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Effect of solidity on aerodynamic forces around straight-bladed vertical axis wind turbine by wind tunnel experiments (depending on number of blades)

Qing'an Li [a], [*], Takao Maeda [b], Yasunari Kamada [b], Junsuke Murata [b], Kento Shimizu [b], Tatsuhiko Ogasawara [b], Alisa Nakai [b], Takuji Kasuya [b]

[a] *Division of System Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan*
[b] *Division of Mechanical Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie 514-8507, Japan*

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ABSTRACT

The prediction of aerodynamic forces around straight-bladed Vertical Axis Wind Turbines (VAWT) is important for wind turbine applications. This paper focused on evaluating the aerodynamic forces acting on a single blade, depending on the different numbers of blades in wind tunnel experiments. In this study, numbers of blades were from two to five and the cross-sectional shape of the tested airfoil was a NACA0021. Firstly, the power coefficient was measured by a torque meter and a six-component balance. Secondly, pressures acting on the surface of rotor blades were measured during rotation by multiport pressure devices. Then, the evolutions of normal coefficient, tangential coefficient and lift-to-drag ratio C_L/C_D, which were obtained from pressure distributions, were discussed. Finally, the power coefficients calculated by pressure distributions were compared with the experiment data of the torque meter and the six-component balance. The results showed that the pressure difference substantially decreased with the increase of solidity. In addition, the values of six-component balance and torque meter showed smaller values than those calculated by pressure distributions. In words, these results provided theoretical significance towards the development of a simple design for straight-bladed VAWT.

1. Introduction

In recent years, the use of wind turbines has risen rapidly for its potential in power generation since wind energy resources are unaffected by environmental pollution and economic insecurity [1–4]. Wind turbines are classified into HAWTs (horizontal axis wind turbines) and VAWTs (vertical axis wind turbines) based on their axis of rotation. HAWTs are better suited for large scale energy generation on flat land and in mountainous terrain, while VAWTs are better suited for small scale energy generation in urban regions [5–9].

The straight-bladed VAWT is distinguished by its simplicity and relatively low manufacturing cost. In urban regions, wind flow continuously changes direction and is also extremely turbulent [10,11]. Therefore, VAWTs potentially perform better in urban regions than HAWTs due to the fact that VAWTs do not require a yaw mechanism for the inflow. Besides, they can be applied in remote areas such as in street lighting and an independent power generation system for families [12]. All these advantages have driven many universities and researchers to study this type of VAWT. IEC 61400-2 [13] and JSWTA 0001 [14] have a very good description of simple design equations of performance and safety standards of small HAWTs [15]. However, the development of the aerodynamic performance and safety standards for small HAWTs is not suitable in the case of VAWTs. The reason is that the two turbines are totally different. As shown in Fig. 1, the directions of the loads for the blade, support structure, and rotor shaft of the straight-bladed VAWT represent different coordinate systems. Furthermore, for VAWTs, the wind flows into the rotor surface, causing disturbed flow in the downstream region so that large fluctuation torque is generated. Therefore, the performance of VAWT mainly depends on wind flow, airfoil type, turbulence intensity, pitch angle, number of blades and so on [16–20]. In order to have a good master of its operating principle and understand better the influence of different design parameters on its performance, experimental tests are generally

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[*] Corresponding author. ,
E-mail addresses: 434687517@qq.com, li@fel.mach.mie-u.ac.jp (Q. Li).

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Nomenclature

A	swept area of wind turbine [m^2]
c	blade chord length (=0.265) [m]
C_D	drag coefficient ($=F_D/(0.5\rho c\ U_0^2)$)
C_L	lift coefficient ($=F_L/(0.5\rho\ c\ U_0^2)$)
C_L/C_D	lift-to-drag ratio
C_p	pressure coefficient ($=P/(0.5\rho\ U_0^2)$)
C_{power}	power coefficient ($=Q\omega/(0.5\rho DH\ U_0^3)$)
C_Q	torque coefficient ($=Q/(0.5\rho DHR\ U_0^2)$)
C_N	normal force coefficient ($=F_N/(0.5\rho c\ U_0^2)$)
C_T	tangential force coefficient ($=F_T/(0.5\rho c\ U_0^2)$)
D	rotor diameter (=2.0) [m]
F_D	drag force per unit length [N]
F_L	lift force per unit length [N]
F_N	normal force per unit length [N]
F_T	tangential force per unit length [N]
F_x	thrust force per unit length [N]
H	span length of blade (=1.2) [m]
N	numbers of blade (2–5)
P	pressure acting on the surface of blade [Pa]
p_{ref}	maximum dynamic pressure attached the surface of blade [Pa]
P_{ower}	power output (W)
Q	rotor torque [N m]
R	rotor radius (=1.0) [m]
Re	local Reynolds number [$= Wc/\nu$]
U_0	free stream wind velocity [m/s]
U	local wind velocity [m/s]
W	resultant velocity to blade [m/s]
V	tip speed of blade ($=R\omega$) [m/s]
x	longitudinal coordinate [m]
y	lateral coordinate [m]
z	vertical coordinate [m]
α	angle of attack [°]
β	blade pitch angle [°]
ϕ	angle of resultant velocity to the blade [°]
θ	Azimuth angle [°]
λ	tip speed ratio ($=R\omega/U_0$)
ν	kinematic viscosity [m^2/s]
ρ	air density [kg/m^3]
σ	solidity ($=Nc/\pi D$)
ω	angular velocity of rotor [rad/s]

used and have made remarkable achievements recently.

Armstrong S. et al. [21] investigated the effect of airfoil type and blade pitch angle on the power performance and flow characteristics in wind tunnel experiments. The results showed that, compared with straight blades, the installation of fences on the canted blades increased the maximum power coefficient and reduced the optimum tip speed ratio, suggestive of a reduction in spanwise flow on the swept blades. Besides, the effect of blade pitch angle was also presented. It was noted that the fluctuations of power coefficient appeared to be slightly dependent on blade pitch angles. The results were also reported in literature of Li Q. et al. [22,23], Staelens et al. [24], Fiedler A. et al. [25], In SH. et al. [26] and Paraschivoiu I. et al. [16]. In order to have a better understanding of aerodynamic performance prediction of Straight-bladed VAWT in the spanwise direction, Li Q. et al. [27] investigated the pressure acting on the blade surface in the different cross-sections, depending on the pressure measurement system and CFD analyses. They found that the power coefficient illustrated the maximum value at the blade central height, and gradually decreased when approaching the blade tip.

The effect of wind velocity was studied by Song SH. et al. [28], Li Q. et al. [29], Islam M. et al. [30] and Ohlmann HA. et al. [31]. From these studies, it was found that, at the same tip speed ratio, when the wind velocity was higher, the power performance of VAWT was better. The measurements also indicated that wind turbine with higher wind velocity had higher optimum power coefficient and lower optimum tip speed ratio. And then, Li Q. et al. [32] and Carpman N [33] further discussed the power performance with different turbulence intensities. As shown from their research, for low tip speed ratios, the output power fluctuated slightly with the increase of turbulence intensity. Meanwhile, for high tip speed ratios, output power increased as turbulence intensity was raised.

In order to determine the optimum variation, El-Samanoudy M. et al. [18] studied the effect of the design parameters, such as turbine radius, airfoil type and chord length, with some experimental data for comparison and analysis. What the obtained results showed that when the turbine radius was decreased, the performance was decreased greatly, showing a significant effect of the turbine radius. Similar results have been investigated by Beri H. et al. [34], Siddiqui M S. et al. [35] and Ismail MF. et al. [36]. Meanwhile, it was found that symmetrical airfoils had higher power coefficient values compared with that of cambered airfoils. There was a much larger drag coefficient in performance results from using cambered airfoils instead of symmetrical airfoils. Castelli MR. et al. [37], Saeed F. et al. [38], as well as Ismail MF. et al. [36] also arrived at the similar results by wind tunnel experiments or

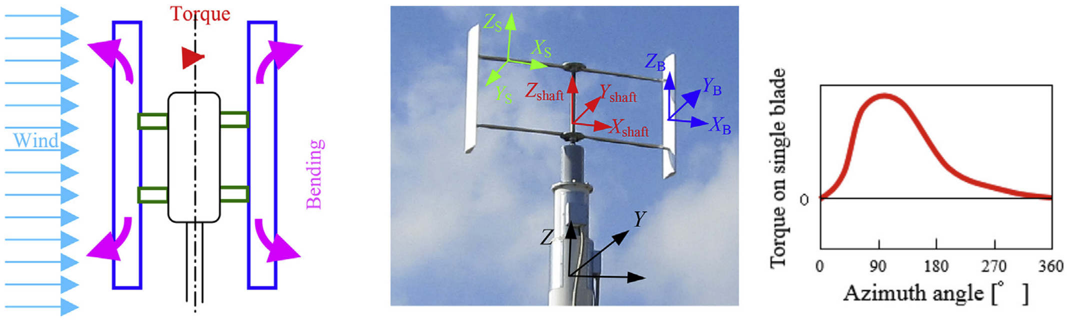

Fig. 1. Blade load in the flap direction of Vertical Axis Wind Turbines.