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Wind tunnel and numerical study of a straight-bladed vertical axis wind turbine in three-dimensional analysis (Part I: For predicting aerodynamic loads and performance)

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ABSTRACT

This paper presents a straight-bladed VAWT (vertical axis wind turbine) model for the evaluation of aerodynamic forces and inertial contributions to rotor blade deformation. In this paper, a two-bladed VAWT is proposed and analyzed with CFD (computational fluid dynamics) and wind tunnel experiments in three-dimensional (3D) investigation. In wind tunnel experiments, pressure measurement system is presented to measure the pressure acting on a single blade of straight-bladed VAWT in the spanwise direction. In numerical analysis, 3D CFD models have been performed to simulate the aerodynamic forces characteristics of VAWT with k–ε SST (Shear Stress Transport) (k–ε) turbulence model. From comparing the results of the wind tunnel experiments and numerical analysis, it is found that the fluid force decreased with the increase of spanwise positions excluding the position of support structure. Furthermore, according to the result from six-component balance, the waveforms of the power coefficient C_{pw} have similar characteristics and show smaller values than CFD calculations.

1. Introduction

The principal advantage of VAWT (Vertical Axis Wind Turbine) is to enable a design that alleviates the material stress on the tower. VAWT can accept wind energy from any direction without yawing that is required in the horizontal axis design [1–4]. Compared with the horizontal axis design, the progress of VAWT in a built environment has been an increasing interest because the latter has higher efficiency [2,5–9].

However, the VAWT has an inherently non-stationary aerodynamic behavior, mainly due to the continuous fluctuation of the relative velocity with respect to the blade and blade angle of attack during the rotation [3,7,10–14]. This phenomenon has a significant effect both on the aerodynamic forces acting on the rotor and the flow field characteristic around rotor blade. For the VAWT, it is noted that not only the centrifugal loads are caused by the rotation, but also the bending loads are generated from fulcrum. Moreover, high rotational speed of the rotor leads to high centrifugal and bending forces and probability of structural failures increases at the same time [8,15,16]. Therefore, it has been proven challenging due to the complexity of the aerodynamic forces acting on the blade of a small straight-bladed VAWT, especially at a low tip speed ratio.

In recent decades, many numerical and wind tunnel experimental studies have been conducted on aerodynamic forces acting on a single blade of VAWT and great achievements have been acquired. For example, according to CFD (computational fluid dynamics), Roynarin [17] presented a 2D CFD model for the evaluation of lift and drag forces acting on single rotor blade of VAWT. From his study, the results of the lift and drag performance of NACA (National Advisory Committee for Aeronautics) 66–212 and NACA 4421 airfoils have been investigated from the average pressure flow field around a zero angle of attack. The lift and drag coefficients of various shapes of the VAWT blade were also analyzed using the CFD code by Shin et al. [18].

In order to investigate the phenomenon of dynamic stall which has significant impact on both load and power, Ferreira et al. [19,20] predicted the generation and shedding of vorticity and its convection with DES (Detached Eddy Simulations) model. From their study, it can be found that the tangential and normal forces reached

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Nomenclature

A	Swept area of wind turbine [m^2]
c	Blade chord length (=0.265) [m]
C_p	Pressure coefficient ($=P/(0.5\rho U_0^2)$)
C_{pw}	Power coefficient ($=Q\omega/(0.5\rho DHU_0^3)$)
C_{QS}	Single torque coefficient ($=Q/(0.5\rho DHRU_0^2)$)
ds	Minute distance on the rotor surface [m]
D	Rotor diameter (=1.7) [m]
H	Span length (=1.2) [m]
l	Distance between the rotor axis of rotation and the micro-element [m]
N	Number of blade (2)
P_n	Normal force [N]
P_θ	Circumferential force [N]
P_{ower}	Power putout (W)
Q	Rotor torque [N•m]
Q_S	Single blade torque [N•m]
R	Rotor radius (=0.85) [m]
U_0	Freestream wind velocity [m/s]
V	Tip speed of blade ($=R\omega$) [m/s]
W	Inflow velocity to blade [m/s]
x	Longitudinal coordinate [m]
y	Lateral coordinate [m]
z	Vertical coordinate [m]
α	Angle of attack [deg]
β	Blade pitch angle [deg]
θ	Azimuth angle [deg]
λ	Tip speed ratio ($=R\omega/U_0$)
ν	Kinematic viscosity [m^2/s]
ρ	Air density [kg/m^3]
ω	Angular velocity of rotor [rad/s]
Ψ_θ	Angle between the normal and the circumferential force direction at the micro-element blade surface

the maximum at lower values of azimuth angle with URANS (Unsteady Reynolds Averaged Navier-Stokes) model. Their results were similar to investigations in Cheboxarov et al. [21] who also calculated that the power coefficient came close to the Betz limit by a Navier–Stokes numerical simulation. Ferreira et al. [22] also discussed the experimental smoke visualization and hot-wire anemometry results of the tip vortex flow for a two-bladed H-VAWT, considering the three-dimensional effect. The results clearly identified that the inboard motion of the tip vortex generated during the upwind passage, and the outboard motion for regions closed to the leeward and windward segments of the rotation. It was also found by Dixon [6], Tescione et al. [8] as well as Hofemann et al. [11]. Alaimo A. et al. [3], who focused on the effect of RPM (Rotational Speed) on the tip vortex in 3D, found that for higher values of the RPM, the tip vortex diffusion leaded to a deterioration of blade performances on the advancing blade with respect to the straight configuration. To understand the effect of skew on the induction, convection, circulation and loads on the VAWT, Dixon [23] combined the experimental PIV (Particle Image Velocimetry) results with the 3D free-wake panel model simulations. He found that the convection of the wake in the z-direction implied a spanwise asymmetry of the induction of the wake on the blade. Furthermore, Ferreira et al. [24] further studied the effect of 3D on the development of forces and vortices during the rotation. As can be seen from their study, the oscillations in normal force were caused by the generation of strong vortices from the trailing edge and leading-edge separation during dynamic stall.

In order to investigate the effects of parameters such as the blade profile, the Reynolds number, and the solidity on the performance characteristics of a straight-bladed VAWT, Roh et al. [25] evaluated the power performance depending on the design parameters with MST (multiple stream tube) method. The obtained results showed that the symmetrical airfoils had better performance corresponding to maximum power coefficient and minimum drag coefficient compared with that of cambered airfoils. The high-digit NACA00xx airfoil provided higher power coefficient at a low tip speed ratio than the low-digit NACA00xx airfoil. Their results were similar to investigations in Mohamed [26], Islam et al. [27], Danao et al. [28] as well as Castelli et al. [29]. Moreover, it was found that an enhancement of the power production was observed with the increase of the Reynolds number. This work was also performed in Danao et al. [30] and Li et al. [31]. In addition, in the research of Roh S C. et al., it can also be noted that the peak of power coefficient seemed to decrease with the increase of the solidity. However, the enhancement of the power with increasing the solidity in the low tip speed ratio could be recommended. Mohamed [7], Howell et al. [32] and Li et al. [33] also focused on these results.

Castelli et al. [34] presented a CFD model based on BE-M theory for the evaluation of energy performance and aerodynamic forces acting on single blade of straight-bladed VAWT. The obtained results showed the reduction of blade relative angles of attack passing from lower to higher tip speed ratios and the maximum torque coefficients were generated at the upstream side during rotation. The similar results were also discussed by Islam et al. [27], as well as Abu-El-Yazied et al. [35]. Besides, they further compared the fluctuation of torque coefficient against azimuth angle during the rotation by increasing the number of blades [36]. As can be seen from their study, with the increase of number of blades the torque coefficient peak became lower and the frequency of the oscillations in the torque increased. The effect of blade shell thickness on the performance was also discussed by CFD calculation with a FEM (Finite Element Methods) code for the structural design analysis of rotor blades [37]. From this study, the aerodynamic displacements, being proportional to rotor blade deformability, resulted higher values for reduced blade shell thickness.

Recently, some researchers and universities also reported experimental investigations of the aerodynamic characteristics of the straight-bladed VAWT. Song et al. [38], Ohlmann et al. [39] as well as Bravo et al. [40] focused on the effect of wind velocity on the power performance in wind tunnel experiments. From these studies, it was found that at the same tip speed ratio, the wind turbine with the higher wind velocity had higher optimum power coefficient and lower optimum tip speed ratio. The effect of 3D on aerodynamic characteristics have also been discussed on the straight-bladed vertical axis water turbine. Marsh et al. [41] used a commercial RANS (Reynolds-Averaged Navier-Stokes) model to fully capture turbine performance characteristics. In this research, the reduction of power performance was largely due to the high levels of strut drag. Mercier et al. [42] investigated near wake of a Darrieus water turbine using LDV (Laser Doppler Velocimeter) system in the measurement of 3D. As shown in this study, the flapping of the wake could mix quickly the deficit part of the wake with the by-pass flow. Furthermore, this effect produced a quick recovery of the velocity along the symmetry axis.

To investigate the power coefficient of losing from wind and obtaining from straight-bladed VAWT, Li et al. [43] studied with streamtube model and LDV measurement in wind tunnel experiments. According to streamtube model, the power absorbed from