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Effect of turbulence on power performance of a Horizontal Axis Wind Turbine in yawed and no-yawed flow conditions

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ABSTRACT

The purpose of this study was to investigate the effect of turbulence on the power performance at the yawed and no-yawed flow conditions, focusing on the turbulence intensities and boundary layer in wind tunnel experiments. In this study, UMY02-T01-26 airfoil was developed, based on the body type of large aquatic animals. Turbulence inflow was generated by an active turbulence grid. Boundary layer was simulated by a boundary layer tape attached on the rotor surface. Furthermore, the fluctuations of power coefficient against the tip speed ratio were examined during rotation. From the experiments, it could be found that the power coefficients decreased in the case of the extremely low turbulence intensity of $TI = 0.50\%$. However, the power coefficients had a significant improvement in the high turbulence intensity of $TI = 10.0\%$. Moreover, in the case of the yaw angle of $\phi = 30^\circ$, the power coefficients showed larger values than those of $\phi = 0^\circ$ at the low tip speed ratio ranges of $1.5 < \lambda < 2.5$. Therefore, the developed wind turbine model could exhibit sufficient performance at the Reynolds numbers of $Re = 1.5$ and 2.0×10^5 in the natural wind condition.

1. Introduction

Recently, there has been a noticeable increase in interest for wind power generation as a renewable energy because of environmental concerns [1–4]. One of the most important factors which influence the lifetime and reliability of a wind turbine is the aerodynamic forces acting on the blade, which are dependent on the natural environment, such as varying wind velocities, turbulence intensity (*TI*), wind shear and surface roughness of the blades [3,5–9]. These uncertainties should be considered in order to design the optimum wind turbine blade and analyze its performance.

These uncertainties can cause the variations of the blade angle of attack during the rotation and generate the dynamic stall phenomenon [3,6,9–13]. This phenomenon is due to the appearance of a strong or sudden flow separation on the suction side surface of a profile. And then it causes a drastic drop in lift and increases drag for the airfoil [6,10,11,14–16]. Moreover, the wind turbine blades are also submitted in time to degradation in its performance due to the blade surface boundary layer [17,18]. Therefore, the study of wind turbine power performance needs to take into account the coupled effects of turbulence and boundary layer.

The effects of the turbulence on the aerodynamics characteristics of the Horizontal Axis Wind Turbine (HAWT) have been more extensively studied. In 2002, Devinant et al. [19] concerned the effect of turbulence on a wind turbine airfoil and measured free-stream turbulence levels ranging from 0.5% to 16% in wind tunnel experiments. The airfoil was an NACA 65_4–421 and the aerodynamic data for this airfoil were calculated by measuring the pressure along the blade surface. The turbulence intensities were generated by placing turbulence grids at the convergent exit upstream of the test section. From the results, they found that the aerodynamic behavior of the airfoil was strongly affected by the turbulence level, both qualitatively and quantitatively. Moreover, it was also observed that the lift coefficient significantly decreased with the increase of turbulence intensity. This result was similar to investigations by Amandolese et al. [20] in 2004 and Bak et al. [21] in 2008.

In 2006, Sicot et al. [22] showed that these effects of turbulence level do not have a significant influence on the drag coefficient. In their research, the turbulence intensities were 4.4%, 9.0% and 12.0%, which were obtained using a square grid mounted in the wind tunnel nozzle. The wind turbine diameter was 1.34 m and the airfoil was an NACA 65_4–4211 with the chord length of 71 mm. From their

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Nomenclature

A	swept area of wind turbine [m^2]
c	airfoil chord length [m]
C_{pow}	power coefficient
D	rotor diameter [m]
N	number of blades
P	power output [W]
Q	rotor torque [N m]
R	rotor radius [m]
Re	Reynolds numbers
TI	turbulence intensity
U_0	free stream wind velocity [m/s]
W	resultant velocity to blade [m/s]
x	longitudinal coordinate [m]
y	lateral coordinate [m]
z	vertical coordinate [m]
α	angle of attack [°]
β	pitch angle [°]
θ	azimuth angle [°]
λ	tip speed ratio
ρ	air density [kg/m^3]
σ	standard deviation of wind velocity
ω	angular velocity of rotor [rad/s]
ϕ	yaw angle [°]

results, it was known that the turbulence effect on wind turbine power and thrust coefficients could be neglected when the wind velocity was more than 8.0 m/s. This was in good agreement with the studies of Chu et al. [23] in 2014, Chamorro et al. [24] in 2015 and Johnson et al. [25] in 2004. In order to investigate the coupled effects of rotation and turbulence on HAWT blades aerodynamics, Sicot et al. [26,27] in 2007 and 2008 further measured the pressure acting on the airfoil surface at the turbulence intensities from 4.5% to 12%. The pressure distribution at different positions along the blade surface was studied by moving the equipped part with pressure taps. From their study, it could be seen that the rotation had no significant effects on the separation point position. Nevertheless, for the same angle of attack, the pressure acting on the suction surface was significantly lower for the rotating blade.

In 2014, Al-Abadi et al. [28] also investigated the effect on the performance of the HAWT at the turbulence intensities of 0.7%, 1.1%, 2.5%, 3.2% and 11.4%, which were generated by two static squared mesh grids in the wind tunnel experiments. The blade sectional airfoil was SG6043 and the free stream wind velocity was set on 12.0 m/s. From the results, it was noted that the power coefficient increased as the turbulence level increased.

However, in 2016, Li et al. [29] once again examined the effect of turbulence intensities on the performance of HAWT in wind tunnel for the turbulence intensities of $TI = 1.4\%$, 8.0% and 13.5%. The free stream wind velocity U_0 was performed at 7.0 m/s and the turbulence intensities were generated by active turbulence grids which were developed by themselves. The airfoil sections were NACA63 (3)-618 and NACA63 (2)-215 with radial positions of $r/R = 0.2–0.8$ and $r/R = 0.9–1.0$, respectively. They found the turbulence intensity had no significant effects on power performance and this was similar to the observation of Sicot et al. [22], Chu et al. [23], Chamorro et al. [24] and Johnson et al. [25], rather than Al-Abadi et al. [28]. Moreover, Li et al. [29] also found that the power coefficient was strongly dependent on the blade pitch angle and the yaw angle.

In order to investigate the effect of rotation on the blade boundary layer, Du et al. [30] in 2000 used the 3-D integral boundary layer equations with the assumed velocity profiles and a closure model. Several key parameters, such as the momentum thickness and separation location, were calculated and compared at the cases of non-rotation and rotation. It was concluded that the separation point was delayed as a result of increasing rotation speed or decreasing blade spanwise position.

In 2003, Eggers et al. [31] studied the effects of wind shear and turbulence on rotor fatigue and loads control of a large HAWT in variable speed operation from 4 to 20 m/s. Two and three blade rigid rotors were investigated over a range of wind shear exponents up to 1.25 and a range of turbulence intensities up to 17%. They found that the fluctuations of pitching and yawing moments of the blade rotor were substantially less sensitive to wind shear and more sensitive to turbulence level. The effects of higher wind shear and turbulence on the wind turbine life should be mainly accounted for in the fatigue design.

In 2004, Schobeiri et al. [32] experimentally verified the effects of unsteady flow on the development, separation and reattachment of boundary layer along the suction surface. The experiments were carried out at a free stream turbulence intensity of 1.9% with a Reynolds number of 1.1×10^5. In addition to the unsteady boundary layer measurements, blade surface measurements were also performed at the unsteady inlet flow conditions. According to the locations and the heights defining the separation bubble, they found that the location of boundary layer separation was independent of the reduced frequency level.

In 2014, Maeda et al. [33] measured the velocity in the boundary layer on rotating blade surface of an experimental HAWT using the Laser Doppler Velocimeter in a wind tunnel. Three-bladed HAWT model with a diameter of 2.4 m was test at a tip speed ratio of 5.2, corresponding to the maximum power coefficient of 0.45. Velocity field around rotor blade was discussed for $r/R = 0.3$ and 0.7. By the results of velocity profile in boundary layer, the boundary layer for $r/R = 0.7$ transited from laminar to turbulence at $0.3 < x/c < 0.5$.

The effects of the pressure gradient and surface roughness on turbulence boundary layers were experimentally investigated by Shin et al. [34] in 2015. Smooth- and rough-surface turbulent boundary layers without and with favorable pressure gradients were conducted at a Reynolds number of 9.0×10^5 in the wind tunnel experiments. They pointed out that the favorable pressure gradients augmented the roughness effects on turbulence boundary layers.

The reviews and discussions above strongly suggest that further exploration should be focused on the turbulence inflows on the HAWT performance. However, it still lacks systematic and quantitative investigations on the effects of the boundary layer on the power performance operating with low Reynolds numbers. The objective of this study is to measure the power performance with the attached tape to evaluate the effects of the boundary layer in wind tunnel experiments. In this study, the turbulence inflow was generated by an active turbulence grid and boundary layer was simulated by boundary layer tape attached on the rotor surface. Furthermore, the fluctuations of power coefficient were discussed as a function of tip speed ratio during rotation. The results from this review provided a better understanding of the effect of turbulence intensities and blade surface boundary layer on the power performance of wind turbine.