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Effect of turbulent inflows on airfoil performance for a Horizontal Axis Wind Turbine at low Reynolds numbers (part I: Static pressure measurement)

Qing'an Li*, Yasunari Kamada, Takao Maeda, Junsuke Murata, Yusuke Nishida

Division of Mechanical Engineering, Mie University, 1577 Kurimamachiya-cho, Tsu, Mie, 514-8507, Japan

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ABSTRACT

This paper presented the results of a study to investigate the effect of turbulent inflows on the blade performance of a Horizontal Axis Wind Turbine (HAWT) by employing the experimental measurement at low Reynolds numbers. In order to observe the stall phenomenon, pressures on the rotor surface were measured by a multiport pressure device. Furthermore, for understanding the effects of different turbulence intensities on the aerodynamic performance characteristics of HAWT airfoil, static turbulence grids were used to adjust the turbulence intensity in wind tunnel. In this experiment, aerodynamic forces were discussed with different turbulence intensities and low Reynolds numbers. From comparing the results, it was found that the flow was separated at the leading edge in the case of without grids. On the other hand, in the case of turbulent flow field (with grids), the flow separated region was expanded gradually with the increase of the angle of attack. In the case of $Re \geq 1.5 \times 10^5$, compared with the low turbulence intensity, the lift coefficient was increased significantly at the high turbulent flow field. In addition, the drag coefficient in the turbulent flow field was reduced as compared to the low turbulence.

1. Introduction

The need for the development of renewable energy has been increasing by all over the world because of the increasing awareness of the need for environmentally sustainable for the built environment. Wind energy which was welcomed by society, industry and politics as a clean, practical, economical and environmentally friendly alternative has been more aware of the importance of energy efficiency [1–3]. In the process history for the utilization of wind energy in the past, it evolved from driving ships, pumping water of windmills, and finally to generating electricity. Windmills have been used for at least 3000 years, mainly for pumping water. As early as the thirteenth century, horizontal axis windmills became an important part of the rural economy [4]. However, from the 1920s, the use of wind pumps decreased rapidly because of the economic depression and the use of diesel and petrol engines or electric motors to drive water pumps. From the 1970s, environmental awareness and soaring energy prices led to their reconsideration [5]. Nowadays, the use of HAWTs for electricity generation became the most common application and many researches and universities focused on the airfoil design [6,7].

The minimum type HAWTs which were used in urban areas can reduce the transmission losses due to proximity to the demand center. However, the flow fields encountered by HAWT blades were highly complex due to the high turbulence influences and generated a stall phenomenon [6,8–12]. Therefore, it was very important to predict the aerodynamic performance of wind turbines in the design process of airfoils. As a result, the simple design requirements and standards for wind turbines as defined by the IEC 61,400 [13–15] included specifications for extreme wind loading conditions. However, it was still very different to develop a HAWT with high efficiency in turbulence environment, especially at low Reynolds numbers [16].

In order to highlight the influence of the turbulence on the performance of the HAWTs, many researches have been done on the effect of stall and scale on the airfoil surface. Meanwhile, significant progress has been made in wind tunnel experiments and developing Computational Fluid Dynamics (CFD) methods for fluid flow analysis. The stall mechanism was highly studied, but it was still difficult to understand, especially the airfoil movement in oscillation.

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

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Nomenclature

c	Blade chord length [m]
C_D	Drag coefficient
C_L	Lift coefficient
C'_L	Lift coefficient before correction
C_M	Moment coefficient
C'_M	Moment coefficient before correction
C_p	Pressure coefficient
C'_p	Pressure coefficient before correction
d	Mesh width [m]
de	Effective mesh width[m]
F_D	Drag force per unit length [N/m]
F_L	Lift force per unit length [N/m]
M	Mesh interval [m]
P	Dynamic pressure [pa]
P'	Dynamic pressure before correction [pa]
p_i	Pressure of measurement tap [pa]
p_0	Static pressure [pa]
Re	Reynolds numbers Re
S_F	Solidity factor
S_{Fe}	Effective solidity factor
TI	Turbulence intensity
U_0	Free stream wind velocity [m/s]
U_{ave}	Average 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 [°]
α'	Angle of attack before correction [°]
ε	Correction factor
θ	Azimuth angle [°]
λ	Tip speed ratio
ν	Kinematic viscosity [m^2/s]
ξ	Shape factor
ρ	Air density [kg/m^3]
σ	Standard deviation of local wind velocity

Many researches also focused on predicting of the effect of airfoil on the blade performance at the stall region with variable rotational speed. Miklosovic et al. [17] developed a scale model of an idealized humpback whale flipper. Through the measurement of wind tunnel experiments, it was found that the addition of leading-edge tubercles to this model delayed the stall angle by approximately 40%, while increasing lift and decreasing drag. Miklosovic et al. [18] further manufactured two test models based on the symmetrical airfoil of NACA0020, and improved the stall angle by approximately 50% with increasing lift and decreasing drag. Johari et al. [19] investigated the hydrodynamic loading of the NACA 634-012 airfoil with protuberances experimentally. As can be seen, the separated flow was originated primarily from the troughs and the flow was attached on the peaks of the protuberances at the angles beyond the stall angle of the baseline foil. Huang et al. [20] focused on investigating of the effect of leading edge protuberances on the blade performance at the stall region with variable rotational speed in wind tunnel. From their experiments, the results indicated that the protuberant blades with smaller amplitudes possessed a better performance at the stall region as compared with the baseline model. Moreover, Timmer et al. [21] and Grujicics et al. [22] showed that after stall, the values of lift and drag coefficients mainly depended on the airfoil's leading edge thickness.

The first major study on turbulence was provided by Stack in 1931 [23], the lift and drag forces of several airfoil sections were measured with and without turbulence grids in the wind tunnel. It was found that the turbulence increased the maximum lift and delayed stall for the Reynolds numbers above 1.0×10^5. This result was also confirmed later by Winkelman et al., in 1980 [24], Rhie et al., in 1983 [25], Riziotis et al., in 1996 [26] and Devinant et al., in 2002 [27]. In order to study the time averaged pressure and loads, Devinant et al. predicted that the aerodynamic characteristics of the airfoil could be strongly affected by the turbulence intensity, both qualitatively and quantitatively. A detailed review on the stall phenomenon was also conducted by Holmes in 1988 [28], Kunz et al., in 1992 [29] and Tulapurkara in 1997 [30], which provided a very detailed analysis of instantaneous changes of wind velocity and direction using CFD simulations. The authors pointed out that the change of wind direction exceeded 20° was in a very short time. At the high angles of attack, there was no significant variations in separation point which caused a slight variation of the drag coefficient. Comparing the separation point position from pressure measurement, Sicot et al. [31] found that, for the same angle of attack, the separation point was nearer to the trailing edge with the increase of turbulence intensity. Karbasian et al. [32], Al-Abadi et al. [33] as well as Seddighi et al. [34] also got the very similar conclusion with experimentally or numerically. Moreover, Seddighi et al. [34] further proved that increasing the turbulence intensity delayed stall until higher angles of attack. This result was similar to investigations in Al-Abadi et al. [33], Swalwell et al. [35] and Maldonado et al. [36].

As mentioned above, it could be seen that the stall phenomenon involved a series of flow separations and reattachments that occur on the airfoil surface during rotation and had a substantial impact on the power generation of the HAWTs, especially at the low Reynolds numbers. Many studies have shown that low Reynolds numbers airfoils reduced the suction peak near the leading edge causing decreased in adverse pressure gradients on the upper surface of the airfoil [37]. Furthermore, the thrust coefficient was observed to decrease at the low Reynolds numbers [38]. Driss et al. [39] found the power coefficient also decreased at the low Reynolds numbers when the tip speed ratio was same.

So far airfoils exclusively designed for small HAWT were still limited. Moreover, there was a lack of data at the Reynolds numbers range of 0.5×10^5–2.0×10^5. No studies were carried out to develop HAWTs which had a high performance of airfoils in the urban area, neither did they take into account the turbulence intensity in wind tunnel experiments. Therefore, in an effort to improve the performance of a small HAWT, a new type airfoil of UMY02-T01-26 was developed by our laboratory. In this study, the aerodynamic behavior of HAWT was analyzed by means of multi-port pressure devices, focusing on the development of stall phenomenon at different turbulence intensities and low Reynolds numbers. The obtained results of stall phenomenon can provide rich information for the development of effective design for HAWTs which are suitable for the large turbulence environment.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

To examine the stall characteristics of HAWTs, two-dimensional blade performances were investigated by measuring the pressure attached on the blade surface for the different Reynolds numbers