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Effect of turbulent inflows on airfoil performance for a Horizontal Axis Wind Turbine at low Reynolds numbers (Part II: Dynamic pressure measurement)

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ABSTRACT

The present study aimed at highlighting the influence of turbulence on the dynamic stall characteristics of the Horizontal Axis Wind Turbine (HAWT) with wind tunnel experiments. UMY02-T01-26 airfoil that could efficiently perform at a high Reynolds number had been designed. The turbulence flow was generated by turbulence grids. To experimentally characterize these flows, HAWT blade surface pressures which were used to investigate the dynamic stall phenomenon were acquired by multiport pressure devices. The pressure distribution acting on the blade surface, lift coefficient and drag coefficient against the angle of attack were examined based on different turbulence intensities. For the angle of attack of $\alpha = 13^\circ$, the results indicated that in the increasing direction of the angle of attack, the lift coefficients of dynamic state showed larger values increase than those in the static state. At dynamic stall, in the case of $Re = 1.5 \times 10^5$, the flow was separated at the leading edge of $x/c > 0.1$ in the increasing direction of the angle of attack. In the case of $Re = 2.0 \times 10^5$, the range of the pressure hysteresis loop became narrower than that in the turbulence intensity of $Re = 1.5 \times 10^5$.

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1. Introduction

In the process history for the utilization of wind energy, it evolved from driving ships, pumping water of windmills, and finally to generating electricity. Yannopoulos et al. [1] provided the valuable insights into ancient water lifting technologies with their apparent characteristics of durability, adaptability, and sustainability from wind energy. Generally speaking, natural wind had a strong turbulence intensity that causes dynamic stall phenomena of wind turbines which might result in major changes of dynamic blade loads and failing stall regulation parameters [2–5]. Dynamic stall phenomenon had been confusing many researchers and scientific institutions, because it involved a series of fluid flow attachments, separations and reattachments that occurred on the airfoil surface, when the HAWT was operating at low values of Reynolds numbers in the urban environment with its maximum angle of attack being above its normal static stall angle [6–9]. This phenomenon was usually related to the formation of a leading edge vortex, which was called the dynamic stall vortex. This vortex travelled along with the blade surface as it grew, and finally separated from the airfoil at the trailing edge [7,10–12].

Therefore, it was extremely difficult to have a good understanding of the mechanism of dynamic stall, in particular at relatively high turbulence intensity appropriate to the urban applications of HAWTs. Since this undesirable fact could not be prevented, it was essential to understand the pattern of dynamic stall and in which conditions it was more likely to occur. So, there were a lot of researches focusing on the blade design in the development of wind turbine for electricity generation [2,8,9,13–15].

The unsteady airfoil stall was first investigated in the helicopter industry. Examples of early analytical studies of dynamic stall phenomena were provided by Carta [16,17] and Ericsson [18] in 1967, Chorin [19] and Crimi [20] in 1973. From their study, it was known that the large torsional oscillations of the rotor blades were observed, due to the periodic stall and no-stall of each blade at the backward side of the rotor disk. This was considered to be a very serious phenomenon, which limited the forward speed and weight of the helicopter. Ericsson [21,22] further analyzed the dynamic stall of a helicopter blade section using a quasi-steady theory, and found the Reynolds number had small effect on the normal force

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Nomenclature

B	fluctuation width of the angle of attack
c	airfoil chord length [m]
C_L	lift coefficient
C_p	pressure coefficient
d	mesh width [m]
F_D	drag force per unit length [N/m]
F_L	lift force per unit length [N/m]
f	variations frequency of the angle of attack [Hz]
k	non-dimensional frequency of the free stream wind velocity
M	mesh interval [m]
P	pressure of blade surface [pa]
p_i	pressure of measurement tap [pa]
p_0	static pressure [pa]
Re	Reynolds numbers
T	fluctuation period of the angle of attack
t	variation time of the angle of attack [s]
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_{mean}	variation center of the angle of attack [°]
θ	Azimuth angle [°]
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]
ϕ	yaw angle [°]

and pitching moment coefficients. This result was similar to investigations in McCroskey et al. [23] with wind tunnel experiments.

The effects of dynamic stall on HAWT blades aerodynamics had also been more extensively studied. In 1963, Banks et al. [24] explained the stall delay by the stabilization of the boundary layer against separation due to rotor rotation, through wind tunnel experiments using the transient technique. This work was also later proved by Carr et al. [25] in 1988, Barnsley et al. [26] in 1992, Rasmussen et al. [27] in 1998, as well as Schreck et al. [28] in 2005. Tangler [29], Pape et al. [30] in 2004 and Hu et al. [31] in 2006 compared the stall characteristics of airfoil using the experimental and numerical studies. They found that 3D effects yield delayed stall with lift coefficient higher than 2D near the blade root location. Soltani et al. [32], Hansen [33] and Göçmen [34] confirmed that the maximum lift coefficient of the roughened airfoil increased with Reynolds number. And then, Gharali et al. [4] discussed the effect of erosion on unsteady aerodynamic characteristics of airfoil based on the range of erosion with the realizable $k-\varepsilon$ and SST $k-\omega$ models. As shown in their study, it was found that the shape of the wake velocity profile depended strongly on the location of the positive and negative vortices at high reduced frequencies close to the airfoil. In order to study the effect of airfoil acceleration on the dynamic stall during rotation, Karbasian et al. [9] investigated the turbulence effect on flow field using SST k-ω model. From this study, the authors found that the accelerated flow could significantly influence the aerodynamic loads and dynamic stall trend.

According to the IEC 61400-1 [35] which required design regulation of wind turbines, it was considered that wind conditions such as turbulence and the changes of wind direction had a significant impact on the aerodynamic performance of the blade. Therefore, it was very necessary to evaluate the endurance of a wind turbine such as the load and fatigue, due to the effect of the turbulence intensity.

In order to study the effect of turbulence on a wind turbine airfoil, Devinant et al. [36] observed that the lift coefficient had a significant increase with the increase of turbulence intensity. This result was also confirmed with experiments performed by Amandolese et al. [37] and Sicot et al. [38]. However, Sicot et al. found that the turbulence intensity did not have a significant influence on the power and thrust coefficients of HAWT. After that, Sicot et al. [39] studied the fluctuation of the static stall characteristics using pressure measurements and PIV measurements for flow visualizations. It was showed that the variations in the Strouhal frequency were based on this von Karman vortex shedding and the inflow turbulence level did not significantly affect the loads. Moreover, Sicot et al. [40] further evaluated the effect of turbulence on the separation point position during rotation, focusing particularly on the pressure distribution acting on the airfoil surface. As shown in their study, the lift augmentation seemed to a lower value of the pressure in the separated region rather than that in a stall delay phenomenon. In order to examine the effect of varying turbulence levels on long-term loads, Moriarty et al. [41] focused on loads calculations using a joint probability density function of both mean wind speed and turbulence intensity. It could be seen that the high turbulence intensity had a dramatic effect on the statistics of moment maxima extracted from aeroelastic simulations.

As mentioned above, it was seen that the stall phenomenon can significantly influence on the aerodynamic loads. Airfoils exclusively designed for small HAWT were still limited, due to the lack of data at the low Reynolds numbers No studies were carried out to develop HAWTs which had a high performance of airfoils in the urban area. Although, Sicot et al. [40] evaluated the turbulence on the blade surface during the blade rotation. It was still very difficult to investigate the mechanism of the change of separated flow. As we all know, study on fluid dynamic flow analysis in the 2D case was the basic research of three-dimensional model. The main objective of this study was to consider the effect of airfoil acceleration on the dynamic stall with different turbulence intensities and low Reynolds numbers in the 2D airfoil. The obtained results could help a better understanding of the stall phenomenon, and also provided a very good guidance for the development of this type of HAWT which is suitable for the large turbulence intensity.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

In order to highlight the influence of the turbulence on the performance of the HAWT, dynamic stall phenomenon was investigated by measuring the pressures attached on the blade surface for the different Reynolds numbers. Experiments were measured at the turbulence intensities in wind tunnel. Turbulent inflow was generated by turbulence grids which could control the inflow turbulence intensity. The main experimental apparatus used in this experiment would be introduced in detail as follows.

Small wind tunnel: The experimental study was carried out in a Gottingen circular type small low speed wind tunnel which is shown in Fig. 1. The inlet diameter of wind tunnel was 1.67 m and

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