Journal of Wind Engineering & Industrial Aerodynamics 164 (2017) 1–12

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Study on stall behavior of a straight-bladed vertical axis wind turbine with numerical and experimental investigations

Qing'an Li*, Takao Maeda, Yasunari Kamada, Yuya Hiromori, Alisa Nakai, Takuji Kasuya

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

ARTICLE INFO

Keywords:
Vertical axis wind turbine
Flow visualization
Tufts technique
Numerical analysis
Wind tunnel experiment

ABSTRACT

This paper presents a straight-bladed vertical axis wind turbine (VAWT) model for the evaluation of the stall phenomenon associated with unsteady flow around the airfoil surface with numerical and experimental investigations. In wind tunnel experiments, in order to investigate flow visualization, light-weight tufts attached to the inner surface of blade are used to gain insight on the flow characteristics of VAWT during rotation in the low Reynolds numbers. In numerical analysis, a 2D computational investigation on the stall phenomenon and aerodynamic characteristics at the VAWT airfoil is associated with the standard κ–ε model and Shear Stress Transport κ–ω (SST κ–ω) turbulence model. And then, the stall behavior is validated according to compare the results of wind tunnel experiment and numerical analysis. From this study, it is concluded that the numerical simulation captures well the vortex-shedding predominated flow structure which is experimentally obtained and the results quantitatively agree well with the wind tunnel experimental data. Moreover, the flow separation behavior of the airfoil shows the importance of stall phenomenon and the interaction of the separated vortex with the blade as mechanisms in lift and drag coefficients.

1. Introduction

The world is facing enormous challenges because of energy shortage, environmental pollution and greenhouse gas emission, especially the pollution incident of PM2.5 in China (Yang et al., 2003; Luo et al., 2012). As we all know, wind energy is freely available, environ-mental friendly and considered as promising power generating sources due to its independent power generation systems (Almohammadi et al., 2013; Li et al., 2016a). Compared with traditional horizontal axis wind turbines, vertical axis wind turbines (VAWTs) are believed to be able to operate effectively in urban environments (Armstrong et al., 2012; Ismail et al., 2015; Li et al., 2016b). The principal advantages of VAWTs are without yaw control system which can accept the wind from any direction, more aesthetically acceptable to integrate into buildings, more efficient in turbulent environments and with lower sound emissions (Simão Ferreira et al., 2010; Scheurich et al., 2011; Danao et al., 2013; Li et al., 2015).

However, the aerodynamic analysis of VAWTs is very complicated mainly due to the continuous variation of the blade angle of attack during rotation, as shown in Fig. 1, which generates a phenomenon called dynamic stall. The phenomenon is mainly characterized by the development of vortices involving a series of flow separations and reattachments that occur on the airfoil surface and have a substantial impact on the aerodynamic forces and power generation of the VAWTs (Simão Ferreira et al., 2009; Castelli et al., 2012; Wang et al., 2012; Nobile et al., 2014; Li et al., 2014). A typical dynamic stall process can be classified into four key stages as follows (Wernert et al., 1996; Simão Ferreira, 2009; Wang et al., 2010):.

- An attached flow at low angles of attack slightly above the static stall angle;
- The development of leading edge vortex (LEV);
- The shedding of the LEV from the airfoil surface causing the full stall of rotor blade;
- The reattachment of flow to the airfoil surface.

In the process of dynamic stall, large separated vortices are formed at the leading edge, resulting in the reduction of lift coefficient, until the flow reattached on the surface of airfoil (Simão Ferreira et al., 2009; Castelli et al., 2012; Wang et al., 2012; Nobile et al., 2014; Li et al., 2016b). Therefore, the presence of stall phenomenon is an inherent effect of the performance of VAWTs, especially at low tip speed ratios. Most of the previous researches on dynamic stall have been devoted to flows based on some specific technologies such as analytical methods, computation-al fluid dynamics (CFD) and wind tunnel experiments. The effect of dynamic stall on the evolution of forces on the airfoil has

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

http://dx.doi.org/10.1016/j.jweia.2017.02.005
Received 1 April 2016; Received in revised form 26 January 2017; Accepted 3 February 2017
0167-6105/

Nomenclature

A	Swept area of wind turbine [m^2]
c	Blade chord length [m]
C_D	Drag coefficient (=$F_D/(0.5\rho c)$)
C_L	Lift coefficient (=$F_L/(0.5\rho)$)
C_P	Pressure coefficient (=$P/(0.5\rho)$)
D	Rotor diameter [m]
F_D	Drag force per unit length [N/m]
F_L	Lift force per unit length [N/m]
H	Span length [m]
N	Number of blade
P_n	Normal force [N]
p_i	Pressure of measurement tap [Pa]
p_0	Static pressure [Pa]
P_{ower}	Power output (W)
Q	Rotor torque [N·m]
R	Rotor radius [m]
Re	Local Reynolds number
s_i	Distance connecting the midpoint of pressure measurement tap adjacent to each other [m]
u	Wind velocity in the x-direction [m/s]
U_0	Mainstream wind velocity [m/s]
v	Wind velocity in the y-direction [m/s]
V	Tip speed of blade (=$R\omega$) [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 [deg]
β	Blade pitch angle [deg]
θ	Azimuth angle [deg]
θ_I	Inclination angle of the pressure measurement taps in the position of [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]
Ω	Vorticity

been extensively studied by many researchers and universities, and the general features of aerodynamic characteristics have been investigated.

In most previous studies, the effects of stall phenomenon on straight-bladed VAWT aerodynamics and power performance at low tip speed ratios have been widely described with many analytical methods. Some of the most successful methods are the vortex models (Strickland et al., 1979; Cardona, 1984; Laneville and Vittecoq, 1986; Vandenberghe and Dick, 1987) and double–multiple streamtube theory (Paraschivoiu, 1988) in predicting blade aerodynamic forces and wind turbine performance for low solidity operating at the case of the high tip speed ratio. These models pointed out that, if an ideal rotor were designed and operated such that the wind velocity at the rotor were 2/3 of the mainstream wind velocity, the maximum power coefficient of wind turbine can reach 16/27. The maximum achievable value of the power coefficient was well known as the Lanchester-Betz limit (Burton et al., 2001; Manwell et al., 2010). However, these models failed at low tip speed ratios, ostensibly due to the effects of dynamic stall, and correction models were made by Paraschivoiu (1988), Mandal and Burton (1994), as well as Magill and McManus (1998).

With the development of computer technology and numeric computing technology, CFD has been widely applied in designs and analysis of dynamic stall on airfoil. To account for the complex dynamic flow effects, Simão Ferreira et al. (2007a, b) predicted the generation and shedding of vorticity and its convection with DES model and found that the tangential and normal forces reached the maximum at lower values of azimuth angle with unsteady Reynolds averaged Navier-Stokes (URANS) model. Moreover, the influence of turbulence model in the simulation of the vortical structures spread from the blade itself. Also, the effect of dynamic stall was investigated by Castelli et al. (2011) focusing on the phenomena of VAWT performance and aerodynamic forces at different tip speed ratios based on CFD. The obtained results have shown the reduction of blade relative angles of attack passing from lower to higher tip speed ratios, due to the increasing influence of blade translational speed in the near-blade flow field. Martinat et al. (2008), Qin et al. (2011), as well as McLaren et al. (2012) focused on the effect of blade tip losses for power performance based on the URANS equations. In their study, two-dimensional simulations predicted higher values as blade tip losses and support shaft effects

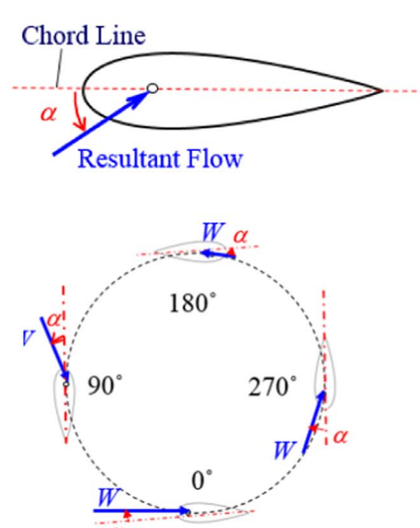

Fig. 1. Wind turbine prototype mounted within the wind tunnel cross-section test airfoil in two-dimensional sketch and the continuous variation of the blade angle of attack.