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Simulation on flow control strategy of synthetic jet in an vertical axis wind turbine

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ABSTRACT

The purpose of present paper is to adopt two-dimensional numerical simulation to investigate the flow field and flow control effect around a straight-bladed vertical axis wind turbine (SB-VAWT) with utilizing synthetic jet active flow control technique which has become a research focus. The numerical simulation results for power coefficients of clean SB-VAWT have been validated by comparing with experimental results. In order to take account of the control effect of orifice quantity, jet momentum coefficient and synthetic jet control strategy, the numerical simulation of the SB-VAWTs with different number of orifices and 5 different control strategy of synthetic jet actuator have been carried out by using unsteady Reynolds-averaged Navier–Stokes (URANS) in ANSYS FLUENT with Realizable k–ε turbulence model and Scalable wall function. The aerodynamic coefficients (power coefficient, torque coefficient) and vorticity field around the blades of the SB-VAWT are comprehensively obtained. The results show that the synthetic jet actuator has positive effect to improve the aerodynamic performance for SB-VAWT. The utilization of synthetic jet actuator with 2 orifices around trailing edge of blades and upward parabola synthetic jet control strategy at 0.035 jet momentum coefficient increases the power coefficient by 15.2%. Besides, this increment in power coefficient decreases with the increasing number of orifices and the synthetic jet actuator brings about more intense load fluctuation than the clean one. Furthermore, the trailing vortices produced and blades less interact with each other, resulting in less vorticity magnitude of shedding vortices and less complexity of flow structure.

1. Introduction

In recent years, the exploitation of renewable wind energy has attracted strong scientific interest and experienced rapid development. The reasonable utilization of wind power shows strategic importance for economic and development of whole world [1]. Vertical axis wind turbines (VAWTs) are the common fluid machineries that convert kinetic energy of wind into electrical power.

Compared with horizontal axis wind turbine (HAWT), VAWT has a number of advantages [2]:

(1) Omni-wind-direction;
(2) Due to the relatively low tip-speed ratio, VAWT is rather quieter than HAWT;
(3) Lower manufacturing cost;
(4) Offering a potential operational safety.

On the other hand, the major disadvantages of VAWT [3]:

(1) A low efficiency;
(2) Difficult self-starting;
(3) Optimal performance occurs at a lower tip-speed ratio (TSR), leading to aerodynamic losses in generator efficiency;
(4) VAWT blades periodically operate within a large range of angle of attack (AOA), resulting in the flow separation which is not yet completely study in aerodynamics;
(5) The trailing vortex produced by the shaft, blades and blade tip interacts with each other, causing the extremely complex flow characteristic.

Due to the disadvantages of VAWT, VAWT urgently requires flow control techniques to improve flow structure. A variety of active flow control (AFC) applications of fluid machinery was developed and investigated [4–6]. Reasonable implementations of AFC consist of the continuous jet actuator (CJA) and the Zero-Net-Mass-Flux actuator (ZNMFA) which is also called the synthetic jet actuator (SJA). A SJA is typically composed of a cavity and a piezoelectric membrane that reciprocating oscillates around its own equilibrium position and it periodically blows/sucks fluid, resulting in no additional fluid to form [7]. Therefore, compared to CJA, a kinetic

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energy transfers from piezoelectric membrane to injection only by utilizing electricity without pulsed-blowing. In addition, its characteristics of low weight, low cost, small size and high jet momentum coefficient also offer a profound engineering practicability [8,9].

The ZNMFA was first used as an active flow control technique in unconventional airfoils and its effect of reducing drag and increasing lift was proved to be reliable [10].

De Giorgi [11] numerically investigated the comparison between SJA and CJA by ANSYS CFD Fluent. The results showed that, at same jet momentum coefficients, reduction of the total pressure losses for the SJA was approximately twice larger than that for CJA. Furthermore, SJA was more profitable from the regaining energy viewpoint.

Meunier [12] carried out an optimized flow control parameters (Position: 64.5% of chord; Injection angle relative to the absolute abscissa: 41.5°; Jet momentum coefficient: 0.051) for a novel airfoil with the slotless hinged flap with synthetic jet by using hybridizing algorithm and Kriging Model. The numerical results showed that a full reattachment of the flap flow was achieved at AOA = 25°, resulting in a dramatic improvement of pressure distribution and lift coefficient.

Shmilovich [13] numerically investigated the effect of number of injections on aerodynamic performance of modified GARTEUR AG08 airfoil with synthetic jet actuator. The results showed that the more synthetic jet actuators which were mounted on flap, the higher lift-drag ratio of airfoil.

Li [14] numerically investigated the effect of blowing directions, actuator position, forcing frequencies and cavity shape on aerodynamic performance of NACA 0015 with leading-edge synthetic jet. The results showed that lift coefficient was sensitive to forcing frequency and actuator positions, but insensitive to blowing directions. Furthermore, different cavity shapes provided acceleration to the fluid at the exit injection, resulting in increasing lift coefficient by 7.5%.

Velasco [15] utilized leading-edge synthetic jet in vertical axis water turbine and numerically investigated the effect of synthetic jet on the aerodynamic performance of vertical axis water turbine. The results showed that average torque coefficient represented an increase of 29% compared to clean vertical axis water turbine.

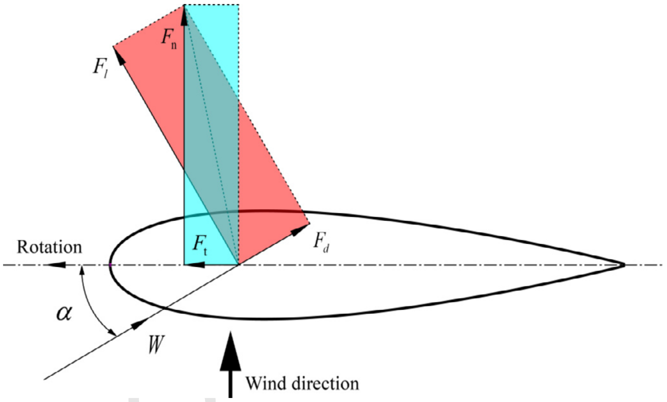
However, it is rare to see the researches about synthetic jet control strategy utilized in VAWT and conventional synthetic jet flow control strategy is not adapted to VAWTs. Therefore, the main purposes of this article are to investigate the effects of number of orifices and different control strategies (jet momentum coefficient versus time for different control strategies) on the flow structure and aerodynamic characteristics improvement. The outcomes of this paper are expected to provide useful reference for reasonable engineering application of vertical axis wind turbine with synthetic jet actuators.

2. Aerodynamic modeling of wind turbine

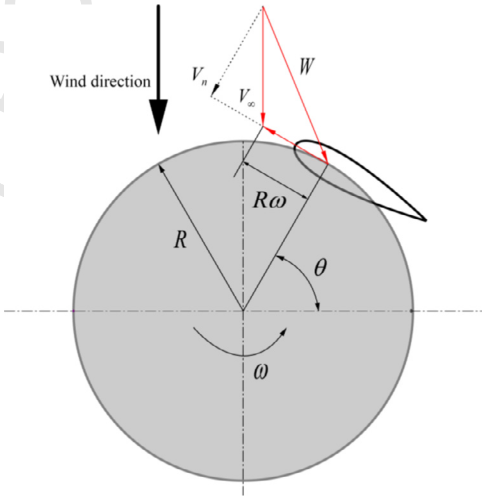
In this section, the aerodynamics of VAWT, VAWT model, synthetic jet actuator model, flow control strategy, rationality of the division of computational domain, meshing strategy, mesh number and reliability of numeric methodology and turbulence model are introduced in detail.

2.1. Aerodynamics of VAWT and physical model

The main aerodynamic performance parameters of airfoils are as follow [16]: (1) Lift coefficient C_l, (2) Drag coefficient C_d, (3) Tangential force coefficient C_t, (4) Normal force coefficient C_n (see Eqs. (1), Eqs. (2)).



(a) Force of airfoil



(b) Velocity triangle of airfoil in VAWT

Fig. 1. Principle of aerodynamics.

$$\begin{cases} C_l = 2F_l/(\rho W^2 \cdot c) \\ C_d = 2F_d/(\rho W^2 \cdot c) \end{cases} \tag{1}$$

$$\begin{cases} C_t = C_l \sin\alpha - C_d \cos\alpha \\ C_n = C_l \cos\alpha + C_d \sin\alpha \end{cases} \tag{2}$$

where F_l = lift, N; F_d = drag, N; ρ = air density, kg/m^3; W = relative velocity, m/s; c = chord length, m; α = angle of attack (AOA), deg.

The principle of force and velocity triangle of airfoil is shown in Fig. 1.

The significant dimensionless design parameter of VAWT is solidity, defined as [17]:

$$\sigma = Nc/(2R) \tag{3}$$

where N is the number of blades.

The AOA of VAWT blades is given as:

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) \tag{4}$$

where θ is the azimuth angle (see Fig. 1(b)), rad; λ is the tip-speed ratio (TSR) of VAWT blades, given as:

$$\lambda = \frac{R\omega}{V_\infty} \tag{5}$$

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