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Numerical investigation on aerodynamic performance of a novel vertical axis wind turbine with adaptive blades

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ABSTRACT

In this paper, a novel Darrieus vertical axis wind turbine was designed whose blade can be deformed automatically into a desired geometry and thus achieve a better aerodynamic performance. A series of numerical simulations were conducted by utilizing the United Computational Fluid Dynamics code. Firstly, analysis and comparison of the performance of undeformed and deformed blades for the rotors having different blades were conducted. Then, the power characteristics of each simulated turbine were summarized and a universal tendency was found. Secondly, investigation on the effect of blade number and solidity on the power performance of Darrieus vertical axis wind turbine with deformable and undeformable blades was carried out. The results indicated that compared to conventional turbines with same solidity, the maximum percentage increase in power coefficient that the low solidity turbine with three deformable blades can achieve is about 14.56%. When solidity is high and also turbine operates at low tip speed ratio of less than the optimum value, the maximum power coefficient increase for the turbines with two and four deformable blades are 7.51% and 8.07%, respectively. However, beyond the optimal tip speed ratio, the power improvement of the turbine using the deformable blades seems not significant and even slightly worse than the conventional turbines. The last section studied the transient behavior of vortex and turbulent flow structures around the deformable rotor blade to explore the physical mechanism of improving aerodynamic performance. The adaptive blades could obviously suppress the separation of flow from the blade surfaces.

1. Introduction

1.1. Background to the study

Compared with conventional energy sources, wind energy is unexhausted and free of pollution [1]. Reasonable development and utilization of wind power is of strategic importance to economic development of China and the whole world [2]. As one of the most key components in a wind turbine, the rotor blades are responsible for converting the kinetic energy of the wind into mechanical energy first and then into electricity if needed [3]. Wind turbines can be classified into two categories based on the axis about which the turbine rotates: horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) [4]. Recently there is a growing interest in vertical axis wind turbines as they are capable of catching the wind from all directions [5]. In addition, compared to HAWTs, the VAWTs are quieter, more bird and bat-friendly and less expensive to maintain [6]. The lifting-type VAWTs (often referred to as Darrieus turbines) are powered by lift forces which helps it function effectively. Since Darrieus wind turbine with straight blades shows the advantages of lightweight, simple structure and good balance, it shows relatively high wind power coefficient and prosperous application. Therefore, the design research on straight-bladed Darrieus turbines to further improve their power coefficients became one of the hot spots of recent wind power technology development [7].

Intensive computational and experimental studies have made on the aerodynamic performance of novel vertical axis wind turbine concepts. Daynes [8] presented a morphing flap design with a highly anisotropic cellular structure. The experimental validation for morphing flap was conducted with a manufactured demonstrator. Compared with conventional hinged flap, the morphing flap can obviously reduce actuation requirements. Kerho [9] studied an adaptive airfoil design to reduce the negative influences of dynamic stall on rotorcraft blades. His results showed that a higher

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C_{lmax} than that of the baseline section could be achieved for the proposed variable droop/camber compliant leading-edge system. Or else, while maintaining the baseline section's high Mach number, the dynamic stall vortex at a C_l equivalent to the baseline section C_{lmax} could be eliminate. Capuzzi [10] described a novel aeroelastic method to design the blades of large-scale wind turbines. While simultaneously alleviating extreme loading conditions due to gusts, it was found that the turbine's Annual Energy Production increased through tailoring the blade's elastic due to aerodynamic pressure suitably. Hoogedoorn [11] conducted a 2D numerical computation to study the aero-elastic behavior of a flexible blade used in HAWT. It was found that higher lift and lift to drag ratio can be achieved by applying flexible cambered airfoils in HAWT, and thereby this type of airfoils has great potential to improve the turbine performance. Lee [12] designed a novel flexible blade for HAWT. The aerodynamic performance and work capacity for this type of blade were investigated, and the power curve was also obtained. Liu [13] proposed a new design method for wind turbine blade which is based on the topology structure of central axis of leaf vein. By utilizing the similarity of structures and working environment between wind turbine blade and plant leaf, the performance for this bionic designed flexible blade was studied. This type of flexible blade not only widens the range of wind velocity, but it also raises the wind power coefficients. Hua [14] firstly investigated the fly posture and the feather construction for wind turbines. It was found that flow separation hardly occurs on wing surface due to the streamlined configuration on the gull wings surface and the unique feather construction on wings. Therefore, the configuration data of the convex shape and the bending shape of the gull wings were extracted and combined with the requirement of wind turbine blades. Two types of bionic blades with convex shape and front bending shape were designed. According to numerical results, the bionic blade shows better aerodynamic performance than conventional turbine blade.

1.2. A novel vertical axis wind turbine concept

However, all the novel designs of wind turbine blade introduced above have common drawbacks, such as poor aerodynamics, structural stability and difficulty in manufacture. Therefore, a new type of VAWT whose blade shape can be automatically changed according to changes in blade surface pressure is proposed in this paper. According to Huang's research [15], the adaptive reconfigurable airfoil can automatically change its shape according to the pressure distribution over its surface. Thus, this paper adopts Huang's idea of balloon-type airfoil and applies it on the novel VAWT. In order to balance the aerodynamic performance of blades at different phases, most of the current Darrieus wind turbines adopt the symmetrical airfoil. However, based on the basic principle of aerodynamics, the shape of airfoil has great influence on its aerodynamic performance. Normally, if the pressure surface of an airfoil is more flat than the suction surface (like NACA2412 airfoil), this type of asymmetric airfoils then can achieve higher lift-to-drag ratio than that of symmetric airfoils (like NACA0012) at positive angles of attack greater than 0° where no flow separation occurs.

In one revolution, the upper and lower surfaces of a Darrieus wind turbine blade become alternatively the blade suction surface and the pressure surface. In Fig. 1, for blade in the position of $0 < \theta < \pi$, the outside of airfoil is the pressure surface and the inside of airfoil is the suction surface; when blade rotates to the position of $\pi < \theta < 2\pi$, the outside of airfoil turns to the suction surface and the inside of airfoil turns to the pressure surface. Therefore, a new type of airfoil whose shape varies with the surface pressure can be designed. For this type of airfoil, the airfoil surface turns inward due to high pressure, and its shape becomes relatively gentle (such as the pressure surface of NACA 2412). While the airfoil surface turns outward due to low pressure, and the shape of airfoil becomes relatively convex (such as the suction surface of NACA 2412). If the proposed airfoil can deform automatically according to a change of the pressure on its surface as described above, it is expected that incorporation of this new type of airfoil section on the Darrieus VAWT would contribute to high overall efficiency. Aerodynamic performance of this new type of wind turbine was numerically investigated in this paper and discussed in detail in the following sections.

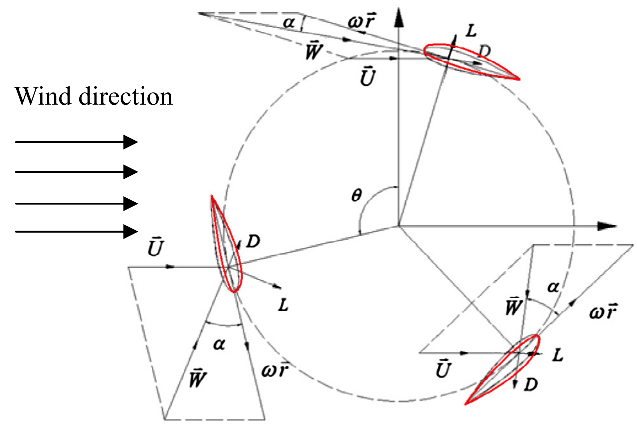

Fig. 1. Forces and velocities acting on a Darrieus turbine for various azimuthal positions.

This paper proposes a new method that the shape of blade airfoil adapts with the surface pressure (VAWTDB). The numerical study for this new type of VAWT is conducted. First of all, the validation of simulation by using the United Computational Fluid Dynamics (UCFD) software was presented. Then, the simulation was carried out for both of the two, three and four bladed conventional VAWT and VAWTDB at different solidities and TSR. Besides, the wind power coefficients of the simulated turbines were summarized and analyzed. After that, three different solidities were chosen for two, three and four bladed VAWT and VAWTDB, and the wind power coefficients at different TSR were compared and analyzed. Finally, the whole flow field of VAWTDB and VAWT with three blades was analyzed from the aspect of vortex, and the tracking analysis of vortex at different positions for the first blade was conducted. In this way, the aerodynamic performance of three-bladed wind turbine with deformable blade was analyzed.

2. Computational methods

2.1. Mathematical model

The UCFD software [16] is adopted in this paper to conduct numerical simulation, and the corresponding control equation and pre-processing technique applied are as follows [17,18]:

Governing equations of fluid mechanics can be expressed as the following general form:

$$\frac{\partial Q}{\partial t} + \frac{\partial (F - F_v)}{\partial \xi} + \frac{\partial (G - G_v)}{\partial \eta} + \frac{\partial (H - H_v)}{\partial \zeta} = 0 \quad (1)$$

for $p = p_0 + p_g$, where p_0 is the atmospheric pressure, p_g is the gauge pressure.