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Leading-edge serrations for performance improvement on a vertical-axis wind turbine at low tip-speed-ratios

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HIGHLIGHTS

- Sinusoidal wave serrations are implemented on the leading-edge of rotating blades.
- The power coefficient in the improved VAWT model is found to be improved about 18.7% at TSR = 2.0.
- Dynamic stall is observed to be suppressed significantly in the range of azimuth angle from 75° to 160°.

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ABSTRACT

The performance of vertical-axis wind turbines (VAWTs) are substantially affected by the phenomenon of dynamic stall which is induced by the variations of angle of attack of rotating blades, especially at low tip-speed-ratios (TSRs). Large and sudden torque fluctuations are observed to take place when the dynamic stall vortices, formed near the blade leading-edge, are transported downstream. At low TSRs ($\lambda_{TSR} < 4$) and relatively low Reynolds number ($Re < 10^5$), dynamic stall occurs periodically during the rotation of turbine blades. This results in a sharp drop in lift coefficient and therefore rotor torque and power output are essentially reduced. The purpose of the present study is to investigate the concepts for improving the power performance of a conventional H-type VAWT model by implementing sinusoidal serrations on the leading-edge of turbine blades to control the dynamic flow separation at low TSRs. A thorough numerical study has been carried out to obtain the detailed flow fields for analysis and visualization. The power output results show that the improved turbine design with the sinusoidal serration profile of the wave amplitude $h = 0.025c$ and the wavelength $\lambda_s = 0.33c$ not only increases the power generation at low TSRs, but also enhances the capability of wind energy extraction at the optimal TSR in comparison to the baseline model. The flow separation is significantly controlled in the azimuth angle ranges from 75° to 160°, where the positive torque generation is also found to be considerably increased in the improved turbine model. Counter-rotating vortex pairs are generated due to the existence of serrations, which suppress the flow separation, especially in the regions near the peak-serration sections. Additionally, the lift coefficients illustrate a delay of occurrence of dynamic stall and a notable improvement of maximum lift in the improved wind turbine model in comparison to the baseline model. The effects of Reynolds number variation also reveal that the improved model would gain more benefits in power generation at low Reynolds number compared with that at high Reynolds number. The simulated results demonstrate that the leading-edge serration strategy could be an effective solution to control the dynamic stall in the operation of VAWTs.

1. Introduction

Wind energy has become one of the most important sustainable energy resources since the energy crisis of the 1970s. Wind turbines are usually used to convert the wind kinetic energy into electrical power. According to the alignment of rotational axis, wind turbines can be categorized into two main types: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs). Currently, most of the commercial wind turbines are deployed as horizontal-axis configurations because HAWTs are more efficient at large scales and have a longer lifetime in comparison to VAWT designs [1–3]. However, VAWT designs possess several prominent advantages over HAWT

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Nomenclature

α	angle of attack	H	rotor height
c	chord length	N_b	blade number
C_D	drag coefficient	R	rotor radius
C_L	lift coefficient	Re	Reynolds number
C_m	instantaneous moment coefficient	T	torque
C_p	power coefficient	U_∞	incoming freestream velocity
D	shaft diameter	W	relative velocity
F_x	force in x direction	σ	solidity
F_y	force in y direction	ω	angular velocity
h	serration wave amplitude	θ	azimuth angle
		λ_s	serration wave length
		λ_{TSR}	tip speed ratio

configurations, such as insensitive to wind direction, easy to install and maintain, lower noise emission and less dangerous to birds. VAWTs offer a safer, more convenient and economical solution for wind energy harvest in the urban, suburban and rural environments, such as top of buildings and backyards. Furthermore, as we know that the wind speed in these areas is relatively low and highly turbulent [4], while VAWTs require a lower wind speed to self-start, which makes them a good candidate to harness wind energy in the areas with relatively insufficient wind resources.

Before the late 1980s, very few researches were carried out on VAWTs to understand the aerodynamics and flow characteristics in the operation of a wind turbine [5]. Recently, with the unprecedented growing demand on electricity in daily activities, attention is increasingly paid to develop more efficient and stable VAWT systems [6–8]. Although the compositions of VAWTs are relatively simple, the flow characteristics of them are very complicated, including highly unsteady aerodynamics and strong flow interactions between turbine blades, such as dynamic stall, wake interactions [9], wind turbulence intensities [10], and flow curvature effects [3]. Therein, dynamic stall, induced by the large variations in the angle of attack on the blades during each revolution of the turbine rotor at low TSRs ($\lambda_{TSR} < 4$), has vital impacts on both loads and power outputs [11]. When dynamic stall occurs, a noticeable flow separation would generate from the leading-edge of airfoils, introducing excessive structural vibrations, and resulting in a fast drop in efficiency [12].

Dynamic stall is a dominant flow characteristics in VAWT operations and has been extensively investigated by experimental and numerical studies. Nobile et al. [5] investigated the turbulence models applied in a 2D VAWT model, a deep dynamic stall was clearly predicted at low TSRs. However, the dynamic stall behavior for the VAWT blade was significantly distinguished with a pitching airfoil, in which the maximum torque of turbine blade in one revolution was observed at an azimuth angle beyond the static stall condition [13]. As the particle image velocimetry (PIV) technique matures to be an effective methodology to measure the flow field with a high-spatial resolution, it has been widely used in measuring the flow features of wind turbines [2,14]. Simao Ferreira et al. [11,15] employed detailed PIV measurements on the evolution of dynamic stall for a Darrieus VAWT. Their results not only provided a reasonable description of the development of dynamic stall from occurring to dissipating, but also gave a useful estimation of the strength of the shed vorticity, which can be used for validating computational models.

In the past two decades, a large number of studies focused on the flow control techniques have been carried out to control dynamic stall in VAWTs. The flow control methods consist of two categories: active flow control and passive flow control. The active flow control methodology aims to alternate/change a natural flow to a desired flow path by adding auxiliary/external power to guide the flow. Post et al. [16] implemented a plasma actuator to control leading-edge flow separation and dynamic stall vortex on a periodically oscillated NACA0015 airfoil. The results demonstrated significant improvements in the lift coefficient during the pitch-down phase due to the unsteady plasma actuation. Shun et al. [17] and Tran et al. [18] used a synthetic jet to control flow separations and the fluctuating aerodynamic loads associated with dynamic stall, which were demonstrated to provide enhancement in power outputs on wind turbines. However, considering the extra cost on these external power sources, such active flow control strategies are not practical to be adopted on small VAWT systems and are difficult to maintain. As a result, some passive flow control techniques were also introduced to mitigate the dynamic stall occurring on VAWTs. Frunzulica et al. [19] and Joshi et al. [20] investigated the flow performance by attaching Gurney flaps, vortex generators and adding thin channels/slots on wind turbine blades, which were reported to have capabilities to control dynamic stall in some circumstances.

Recently, a passive flow control methodology called leading-edge serration that is inspired from the morphology of humpback whales, is attracting increasing attention [21]. Wei et al. [22] conducted an experimental investigation on the flow separation control of hydrofoils with leading-edge serrations under a Reynolds number of $Re = 1.4 \times 10^4$. They found a counter-rotating vortex pairs was formed over each serration, which essentially changed the flow in the near surface region and mitigated the flow separations at angles of attack (AoA) of $\alpha = 15^\circ$ and 20°. Johari et al. [23] and Hansen et al. [24] observed that the leading-edge serrations could reduce the maximum lift coefficient in the pre-stall regime but increase the lift coefficient in the post-stall regime. Since a deep dynamic stall occurs during each revolution for VAWTs at low TSRs, the leading-edge serration technique would imply a potential to alleviate the dynamic stall at high AoAs. In fact, VAWTs cannot start themselves with a small solidity and cannot reach the optimal operating rotational speeds without applying external forces, due to the nature flow characteristics in VAWTs [9]. Therefore, auxiliary power is needed to drive VAWTs to operate at their optimal TSRs, indicating a more complex control mechanism is required to be installed in VAWT systems. As a result, improving the power outputs at low TSRs is crucial if we aim to design a VAWT without deploying external driving forces.

In the present study, sinusoidal wave serrations were selected and implemented on the leading-edge of a straight blade to improve the power performance of an H-type VAWT at low TSRs. A meticulous three-dimensional numerical study was performed to analyze the effects of various combinations of wavelength (λ_s) and wave amplitude (h) of serration profiles for controlling the dynamic stall on a traditional H-type VAWT model with two straight rotor blades. A comprehensive comparison, including power outputs and detailed flow characteristics, was carried out to compare the performance between the improved and the baseline VAWT models.

2. Method description

2.1. Wind turbine model

The wind turbine model shown in Fig. 1 is a typical two-bladed H-