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Effect of barchan dune guide blades on the performance of a lotus-shaped micro-wind turbine

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ABSTRACT

A lotus-shaped micro-wind turbine has been developed as a decoration for urban and rural areas. This wind rotor consists of guide and semi-circular blades. In this study, barchan dune was used as a model to design the guide blades of the wind turbine. The effects of different skew angles of the barchan dune guide blade on the performance of the wind rotor were studied using computational fluid dynamic simulation methods. The performance of each section of the semi-circular blades was also analyzed. Findings suggest that power coefficients for 15°, 20°, or 25° slope of the rotor are roughly identical at the same tip speed ratio, and their values are relatively larger than those of the other rotors without guide blades or with 0° or 30° slope. Furthermore, their maximum values are approximately 120% of the rotor with null slope or without guide blades. The performance of the wind rotor is minimally dependent on the skew angle of the barchan dune guide blade within the range of $\alpha = 15–25°$.

1. Introduction

Many satisfactory approaches to engineering design have been inspired by natural phenomena. For instance, the tubercles on the flippers of humpback whales (Fish et al., 2011) can be applied to the design of blades to improve the efficiency of wind turbines, computer fans, compressors, and pumps. Reproducing shark skin on the blades of a wind turbine (Reif, 1985) is a way to reduce skin friction. The effect of movable flaps of birds (Alvarez et al., 2001) was used to develop the lift of the blades. A lotus-shaped micro-wind turbine (Wang and Zhan, 2013) has been developed to reduce the visual effect on people based on Savonius wind rotor. The wind rotor consists of static blades (also called "guide blades") and rotor blades (also called "semi-circular blades"). In this study, the structure of barchan dunes was applied to the design of a guide blade, which is different from the guide device at the rotor bottom described in the literature (Chong et al., 2011). The geometric forms of the barchan dunes are visual embodiments of aerodynamics. Relevant literature on barchan dunes was reviewed.

Formation mechanisms of barchan dunes have been studied by a number of researchers, such as Schwämmle and Herrmann (2003), Sauermann et al. (2000), and Hersen (2004). Barchan dunes are characterized by fast and simple dynamics, stable crescentic-shape, and the weak lateral coupling dynamics over the wind direction (Groh et al., 2009). The size and structure of barchan dunes were systematically reviewed in the desert (Durán et al., 2011). The research shows that the barchan dune is the stable shape of dunes. Their shapes will remain stable if barchan dunes have developed. Besides, similar work studied on the variation of subaqueous barchan dunes (Franklin and Charru, 2011). Wu et al. (2011) investigated airflow over barchan dunes and the change of speed-up ratio, and what's more, it was reported in many articles that the model of the barchan dune was applied to practices. Climate fluctuations in the past could be reconstructed using residual dune ridges among barchan dunes to detect climate change (Levin et al., 2009). Gao and Ning (1982) designed a barchan dune vortex generator and studied the stability of its vortex flame. The shape of the barchan dune vortex generator matches that of two natural barchan dunes symmetrically. The aerodynamic shape of a car roof box has also been designed based on the barchan dune (Johnnes and Volkswagen, 2009).

As mentioned, a lotus-shaped micro-wind turbine has been designed based on the Savonius rotor. Relevant literature on the Savonius rotor has been investigated. The shape of the wind turbine in the built environment must be considered to weaken the visual effect on people. However, literature indicating that visual pollution is one of the most important factors in wind turbine design is limited. The lotus-shaped micro-wind turbine we designed in this study is both attractive and practical. The guide blades of this turbine are the counterparts of lotus petals and can sculpt the oncoming wind to improve the performance of the wind turbine. The rotor blades represent the lotus

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Nomenclature

R	rotor radius (mm)
L_u	linear length of the windward side
L_s	length of the slip face
$\eta(x)$	S-shaped profile
T_{total}	total dynamic torque (N m)
$T_{isection}$	ith sectional dynamic torque (N m)
$C_{Tisection}$	ith sectional dynamic torque coefficient
$C_{Paveraged}$	averaged power coefficient

Greeks symbols

α	slope of barchan dune guide blades
β	slope of slip face
ω	rotor angular velocity (rad/s)
θ	blade phase angle (deg)
λ	tip speed ratio
ε	contribution to the total torque from blade's each section

stamens, and can be used to drive a generator through its shaft. Under the same wind velocity, the performance of the Savonius rotor is poor compared with that of horizontal axis wind turbines. The blade of the Savonius rotor is simple and can be maintained conveniently. The wind turbine has low running speed and noise. The Savonius rotor is self-starting, with relatively high power per unit length, and can operate in all wind directions (Menet et al., 2001).

Based on the above advantages, many researchers have put forward and testified various Savonius rotors to improve their performance. Kumbernuss et al. (2012) carried out deep research on the overlap ratio and shift angle for a double stage three bladed vertical axis wind turbine (VAWT). Kamoji et al. (2009) experimented with helical Savonius rotors and, compared with conventional Savonius rotors, the rotor's performance was improved. In addition, the influence of guide blades, located in the upstream of a Savonius rotor, on the performance of the Savonius turbine was analyzed (Daegyoum and Morteza, 2013; Golecha et al., 2011; Irabu and Roy, 2007). However, the use of guide vanes directly in front of the wind rotor not only has complicated structure, but also canceled its capability to accept wind from any direction. The influence of guide blades at the end of the wind rotor on the performance of the wind turbine is rarely discussed. A zephyr VAWT was presented by Pope et al. (2010). It consists of stator blades, along the upstream, and rotor blades. The stator blades are used to reduce turbulence flow. Wind, solar and rain water harvester by a power-augmentation-guide-vane was integrated and can be blended into buildings. However, it is more suitable for urban high-rise buildings (Chong et al., 2011). A novel solar and wind energy extraction system was designed and investigated (Li et al., 2011; Gholamalizadeh and Mansouri, 2013). However, the system is confined to the chimney to use.

In the design process for wind turbines, using computational fluid dynamic (CFD) tools are well-known. McTavish et al. (2012) presented a new VAWT and evaluated its performance through rotating three-dimensional Reynolds-averaged Navier-Stokes (RANS) CFD simulations. In addition, Bahrain World Trade Centre is a more successful exemplar based on a visual delight (Smith and Killa, 2007). The shape of the two towers sculpting the oncoming wind has been designed using CFD. The result indicates that the turbines' potential to generate power is improved. Unsteady two-dimensional RANS CFD simulations were conducted on two and three-bladed Savonius rotors (Mohamed, 2011). Meanwhile, the effect of a certain slope obstacle upstream of the retreating blade on Savonius rotor's performance was investigated to decrease negative torque for the retreating blade.

The geometric forms of dunes are the visual embodiments of aerodynamics. In this study, natural barchan dune was used as a basis to design the aerodynamic shape of guide blades. Validation studies of CFD models were conducted using a Savonius rotor (Saha and Rajkumar, 2006). Rotating three-dimensional simulations were performed to analyze and discuss the dynamic performance of the rotors under conditions of barchan dune guide blades with different skew angles.

2. Mathematical description of barchan dune

The desert is decked with a sea of sand. Sand dunes are considered one of the most beautiful patterns sculpted by wind. They are the visual embodiment of aerodynamics. However, barchan dunes are noted for a stable crescentic-shape and simple dynamics over the wind direction. The barchan dune is divided into two horns, slip face and windward face. The upstream side of the barchan dune has typical slopes between 8° and 21°. Meanwhile, typical slopes of the slip face range from 28° to 34° (Hesp and Hastings, 1998).

A simple geometrical description of the barchan dune is presented in Fig. 1. The length of the slip face L_s depends on the height H (Groh et al., 2008). β stands for the inclination angle of

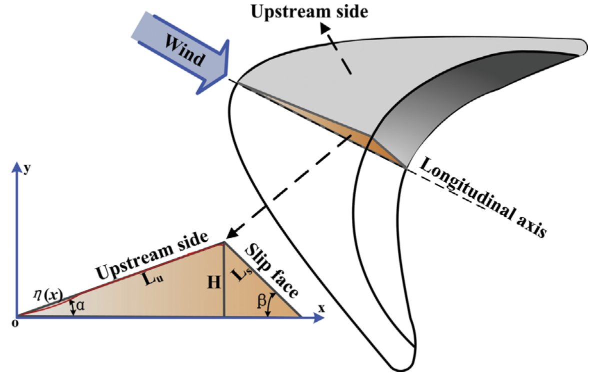

Fig. 1. Simple geometrical form of barchan dune.