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Experimental and numerical investigation of a three-dimensional vertical-axis wind turbine with variable-pitch

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ABSTRACT

A combined experimental and numerical investigation is carried out to study the performance of a micro vertical-axis wind turbine (VAWT) with variable-pitch. Three-dimensional numerical simulations are essentially employed, for the VAWT involves a low aspect ratio (AR) three straight blades with struts. The performance of the VAWT is experimentally measured using a wind tunnel, while large eddy simulation (LES) with dynamic smagorinsky subgrid scale (SGS) model is employed to help understand the associated flow structure. The effects of wind speed, turbulence intensity, airfoil shape, and strut mechanism with and without variable-pitch on the performance of the turbine are carefully assessed, both experimentally and numerically. The accuracy of the SGS model in predicting the laminar–turbulent transition is also examined.

1. Introduction

Wind turbines have been historically known to be mounted in open rural areas. However, in recent years, there has been an increasing interest in the deploying these turbine in urban areas. The chief objective is to generate energy on site thereby cutting cables cost and reducing transmission loses (Mertens, 2006). Horizontal axis wind turbines (HAWTs) have long been utilized in large-scale wind farms, for they are known to be more efficient than VAWTs in steady winds. Small scales HAWTs have also been increasingly implemented in built environments. However, various recent studies have shown that VAWTs perform better in urban areas when compare to HAWTs (Mertens, 2006; Ferreira et al., 2007; Hofemann et al., 2008; Stankovic et al., 2009). These advantages are mainly due to various reasons, the most important of which is the VAWTs' ability to function in a multidirectional flow of wind that could continuously change in residential areas. Unlike HAWTs, VAWTs do not need a yaw control mechanism and respond instantly to change in wind speed and direction, which in turn makes them more efficient in turbulent flow regions.

In recent decades there has been a substantial increase in the use of computational fluid dynamics (CFD) to depict performance of VAWTs. This has been mainly driven not only by the increase in availability of user-friendly CFD software and relatively affordable computational cost, but also by the complexity of flow structures associated with VAWTs. Performance of a three-blade wind turbine has been recently investigated using 2-D CFD by Dai and Lam (2009) who compared results against experimental data at a single TSR value. 2-D CFD simulations were also performed for a straight-bladed Darrieus-type cross flow marine turbine by Lain (2010) and favorably assessed their findings against experiments of Dai and Lam's (2009) however, at a single TSR value. Danao et al. (2014) studied the influence of unsteady incoming wind on the performance of a 2-D VAWT. Mesh independent solution by means of Richardson Extrapolation method, Grid Convergence Index method, and the fitting method, was recently investigated for a 2-D VAWT by Almohammadi et al. (2013). Nobile et al. (2014) carried out a 2-D CFD investigation of an augmented VAWT that involved omnidirectional stator located around the VAWT. They reported an increase of around 30 to 35% in torque and power coefficients.

Elkhoury et al. (2013) assessed the influence of various turbulence models on the performance of a straight-blade VAWT utilizing a 2-D CFD analysis. With similar experimental and computational setup to the currently considered test cases, overestimations of power coefficients were predicted by fully turbulent models, a scenario that was deemed to be due to laminar–turbulent transition. Lanzafame et al. (2014) compared predictions of classical fully turbulence models to those of the SST transition model (Menter et al., 2006) for a VAWT utilizing a 2D CFD solver. McLaren et al. (2012) successfully performed a 2D Unsteady Reynolds-Averaged Navier-Stokes (URANS) CFD simulation of a small-scale high solidity wind turbine. Scheurich and Brown

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(2013) used the vorticity transport model to investigate performance and wake dynamics of different VAWT configurations in steady and unsteady wind conditions.

Studies considered previously were all bounded by 2D simulations utilizing 2D flow models, many of which were performed at a specific TSR with scarce experimental data that are essential to validate the models. These recently accomplished studies do not account for connecting rods that tend to have considerable influence on the performance of a VAWT. This important feature cannot be neglected at high TSR (Elkhoury et al., 2013), not to mention blade-rod interference that arises at low TSR. Furthermore, flow over turbines with low AR blades departs from the 2D behavior as blade tip effects become significant, rendering the flow three-dimensional.

To address these limitations, this work capitalizes on such aspects and aims at building a credible 3D CFD model that closely predicts the experimental results. Within this framework, the effects of incoming freestream velocity, turbulence intensity, fixed- and variable-pitch mechanism, and airfoil shape on the power coefficient of the turbine are carefully assessed. LES is employed as the complexity of the flowfield represented by high solidity and low AR. In addition, the interference among the three blades is substantial and would be affected further by the presence of the central shaft and the connecting four-bar linkage mechanism, necessitating a 3-D modeling approach. Furthermore, the ability of LES with dynamic SGS model to predict separation induced transition associated with dynamic stall at relatively low TSRs is examined. It is worth noting that any future attempt to improve this novel design of VAWTs should be facilitated by the use of 3D CFD simulations.

2. Variable-pitch mechanism and experimental system

A 3-D overview of the wind turbine with a variable-pitch angle mechanism is depicted in Fig. 1. The turbine had a diameter of 0.8 m and a height (blade span) of 0.8 m. The turbine had three straight blades each was connected to the rotor's center by three main circular rods with a diameter of 0.02 m each. The pitch of the three straight-blade rotor varies by means of a four-bar linkage mechanism, the top view of which is shown in Fig. 1b.

The pitching axis for the variable-pitch mechanism was located approximately at 15% of the chord from the leading edge. This mechanism has an eccentric rotational center which is different from the main rotational point as shown in Fig. 2. Thus, this mechanism is able to vary blade pitch angle α_p, which is the angle between the blade chord line (i.e., blade-link l_c) and a perpendicular line to the main-link, without actuators. This mechanism is able to make an arbitrary selection of the blade offset pitch angle α_c (i.e., an average of the change of blade pitch angle) and the blade pitch angle amplitude α_w by combinations of the link length. The blade offset pitch angle α_c decreases with increasing length of the second link l_s. The blade pitch angle amplitude α_w increases with increasing length of the eccentric-link l_e. The angle between the main link l_m and the eccentric link l_e is the blade azimuth angle ϕ, and θ_p is the angle between the eccentric-link and the wind direction. The average amplitude of the blade angle of attack for $\theta_p=120^\circ$ is larger than that of the wind turbine of fixed-pitch blade while the variation of blade angle of attack for $\theta_p=0^\circ$ is smaller than that for $\theta_p=120^\circ$. Therefore, an optimum blade angle of attack could be maintained at all azimuthal angles, improving the performance of the VAWT.

The equations governing the motion of the pitch-angle in each quadrant are given as follows

$\alpha_p=\pi/2-(\beta+\gamma)$ for $0<\varphi<\pi$, and $\alpha_p=\pi/2-(-\beta+\gamma)$ for $\pi<\varphi<2\pi$, where

$$\beta=\cos^{-1}\left(\frac{d^2+l_m{}^2-l_e{}^2}{2dl_m}\right),\quad \gamma=\cos^{-1}\left(\frac{d^2+l_c{}^2-l_s{}^2}{2dl_c}\right) \tag{1}$$

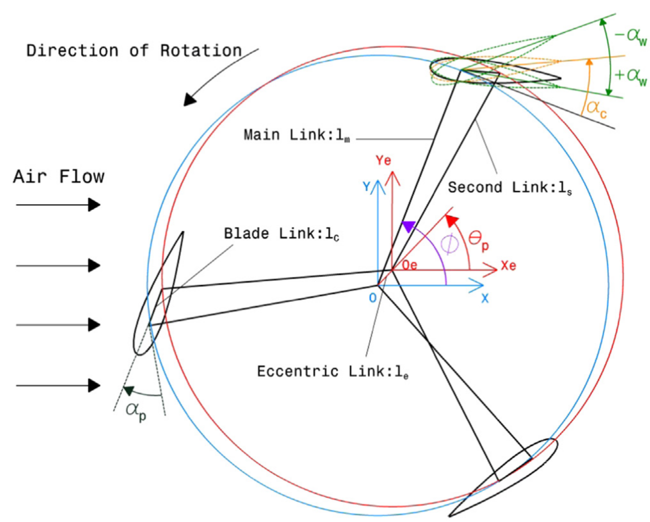

Fig. 2. Schematic diagram of the variable-pitch angle mechanism.

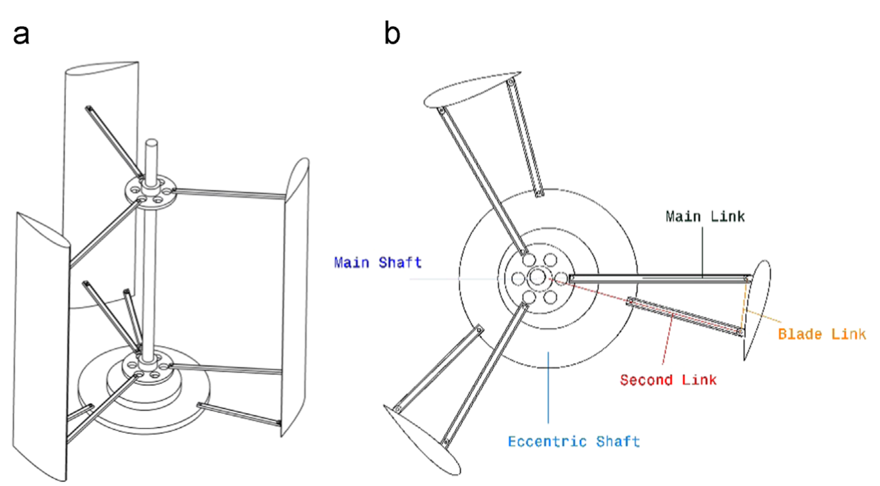

Fig. 1. A 3-D overview of the modeled wind turbine (a) isometric view of the rotor (b) top view of the rotor.