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Unsteady flow simulation of a vertical axis augmented wind turbine: A two-dimensional study

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ABSTRACT

As the integration of vertical axis wind turbines in the built environment is a promising alternative to horizontal axis wind turbines, a 2D computational investigation of an augmented wind turbine is proposed and analysed. In the initial CFD analysis, three parameters are carefully investigated: mesh resolution; turbulence model; and time step size. It appears that the mesh resolution and the turbulence model affect result accuracy; while the time step size examined, for the unsteady nature of the flow, has small impact on the numerical results. In the CFD validation of the open rotor with secondary data, the numerical results are in good agreement in terms of shape. It is, however, observed a discrepancy factor of 2 between numerical and experimental data. Successively, the introduction of an omnidirectional stator around the wind turbine increases the power and torque coefficients by around 30–35% when compared to the open case; but attention needs to be given to the orientation of the stator blades for optimum performance. It is found that the power and torque coefficients of the augmented wind turbine are independent of the incident wind speed considered.

1. Introduction

Although the expansion and installation of wind turbines is mainly focused on rural and open areas, more recently the attention has also moved to the built environment. The benefits are mainly generation of electricity on the site where it is needed, and the reduction in transmission losses and cable costs (Mertens, 2006). The progress of small wind turbines in the built environment has been mainly concentrated on HAWTs, however, several studies have shown that VAWTs are more suitable for urban areas (Mertens, 2006; Mewburn-Crook, 1990; Stankovic et al., 2009; Ferreira et al., 2007a). The advantages are mainly: omnidirectionality without a yaw control; better aesthetics to integrate into buildings; more efficient in turbulent environments; and quieter in operation (Hofemann et al., 2008). Nevertheless, today a number of constraints such as low starting torque, high torque fluctuations and complex flow are holding back the potential market of VAWTs.

Recently, the wind energy sector has seen some researchers explore the concepts of augmented devices (Mewburn-Crook, 1990; Oman et al., 1976; Igra, 1977; Abe et al., 2005; Thomas, 1991). The concept has been around since the late 1960 s without having any industrial success, as most augmenters were unidirectional and added cost to the wind turbine (Mewburn-Crook, 1990). The theory behind augmented wind turbines (AWTs) has been revisited for the built environment in order to accommodate low wind speeds, and high turbulence that are typically found in these surroundings. Pope et al. (2010), in Canada, proposed and analysed an omnidirectional AWT; it is known as Zephyr vertical axis wind turbine, and it has been designed for the built environment. This AWT is composed of a stator–rotor configuration; the power coefficient C_p was proved to be around 0.12. Due to its low C_p values, however, this design was unacceptable for commercial applications. Tong et al. (2010), in order to overcome low wind speed in urban areas, have proposed an innovative power-augmentation-guide-vane (PAGV) design for a VAWT. The PAGV system is mainly designed to guide and increase the wind speed before entering the wind turbine. The geometry was optimised by running several CFD simulations; the numerical results predicted a power increment of 1.25 compared to an open VAWT of the same size. Takao et al. (2009) have proposed and tested a directed guide vane row to increase the performance of a straight-bladed VAWT. The focus was mainly on the geometry of the guide vane row for different combinations of setting angle and gap between rotor and guide vane row. The authors concluded that the peak coefficient is considerably higher than that of a wind turbine without guide

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vane. It was found that for a setting angle of 45° the power coefficient was 1.8 times higher than the open rotor; the gap between rotor and guide vane row did not have any effect on the power of the wind turbine. Similarly, Kirke (2011) has conducted a number of experiments to understand the performance of different hydrokinetic turbines with and without a diffuser. Since the data, for all tests with diffuser, did not consistently show an improvement of the power coefficient; it was concluded that the cost-effectiveness of the diffuser was doubtful.

In this paper a novel vertical axis augmented wind turbine (AWT), developed by Mewburn-Crook (1990) in collaboration with Balfour Beatty Ltd., is examined. The novel AWT, designed for the built environment, consists of a stator and rotor. The stator is composed of eight vertical blades, surmounted top and bottom by conical surfaces; the rotor is composed of three vertical blades that are attached to a central shaft with supporting arms.

In the initial CFD investigation, an open rotor was analysed in order to select the most appropriate mesh, turbulence model, and time step to be implemented for the consecutive numerical simulations. In this part, a CFD validation was performed with secondary data obtained from a similar rotor. Successively, the same rotor was combined with an augmented stator with the aim of increasing the power output of the wind turbine. Finally, a number of CFD simulations were examined with different orientations of the stator blades and different wind speeds, in order to understand how the performance of the augmented rotor is affected. The numerical results are compared and discussed in this paper.

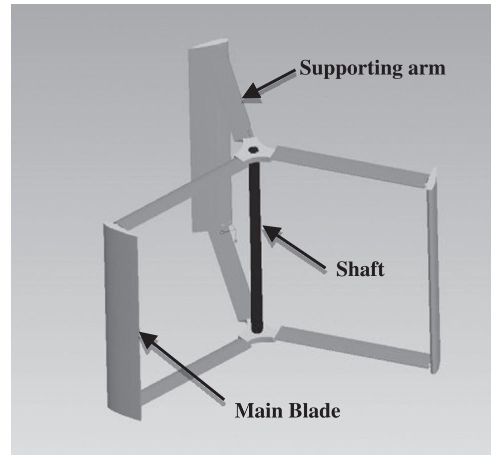

Fig. 1. The 3D open rotor of the AWT.

Table 1
Properties of the rotor.

NACA0018	Chord c (mm)	Thickness t (mm)	Span s (mm)	Quantity N (–)
Rotor blade	490	88.2	2,600	3
Supporting arm	250	45	1,800	6

2. The augmented wind turbine design and computational set-up

2.1. The components of the AWT

The 3D model was generated by using a solid CAD (ProEngineer Wildfire 4.0); the 2D models for both open and augmented rotor were extrapolated from the middle section of the 3D model. The 2D extrapolation was necessary in order to reduce computational time, and understand initially the aerodynamics involved during the operation of the wind turbine. In the present 2D numerical study, the effects from supporting arms and conical surfaces were not taken into consideration.

2.1.1. The rotor

Fig. 1 shows the rotor considered in the numerical study; it is a straight-bladed Darrieus (or Giromill) rotor with a diameter D_r of 4.2 m. The open rotor is composed of three blades, and each blade is attached to a central shaft by two supporting arms. The total number of supporting arms is 6, and the central shaft has a diameter D_{sh} of 0.06 m.

The aerofoil considered, for both vertical blades and supporting arms, is a symmetrical NACA 0018, and its characteristics are listed in Table 1. The rotor solidity σ_r is defined as N_C/R_r and is equal to 0.73. The pitch angle for both vertical and horizontal blades was set to zero degrees. The blade aspect ratio AR of the vertical blade is defined as s_r/c and is equal to 5.3. The pressure centre, in the midsection of the blade, is defined at 0.25c, with c representing the blade chord.

2.1.2. The stator

As shown in Fig. 2, the stator of the AWT is composed of eight straight vertical blades and two conical surfaces. The stator blades form eight identical and converging inlet surfaces to concentrate the mass flow rate next to the rotor; while the outer edges of the conical surfaces promote turbulent mixing above and below in order to reduce the back pressure inside the stator and increase the power output of the wind turbine. The aerofoil profile of the stator blades is also a NACA0018; the geometric properties for both vertical blades and conical surfaces of the stator are listed in Table 2. The internal diameter is 4.8 m, while the external diameter is 6.8 m.

The gap between stator and rotor (stator/rotor clearance) was set to 0.3 m with a stator/rotor turbine diameter ratio of 1.7.

2.2. The computational domain and meshing

As the aim of the present numerical investigation was to determine the operation of an open and an augmented three-bladed rotor of a Giromill wind turbine, the engagement of fixed and rotating domains were required. As shown in Fig. 3, the 2D fluid domain was composed of two distinct domains: a fixed rectangular outer domain with circular aperture; and a circular inner domain to fit into the aperture. The fixed rectangular outer domain was identified as the wind tunnel domain; the circular inner domain was identified as the rotor domain for the open wind turbine and stator–rotor domain for the AWT.

The individual geometries were modelled in ProEngineer Wildfire 4.0 and imported into ANSYS DesignModeler 14.0. The 2D open and augmented rotors were extrapolated from the middle plane of the original 3D model. The mesh was generated by employing the solver ANSYS CFX Meshing 14.0.

2.2.1. The wind tunnel domain

Fig. 4 shows the main dimensions and the boundary conditions employed in the wind tunnel domain. The wind tunnel domain represents the outside fluid around the open or the augmented rotor.

The width of the wind tunnel domain was set to 6 times the rotor diameter; a circular hole was placed in it to fit the rotor or