Numerical performance assessment of a novel Darrieus-style VAWT with auxiliary straight blades

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Abstract. Domestic Vertical Axis Wind Turbines (VAWT) are able to operate also when the wind speed is low and can be installed in the open spaces of housing areas. The Darrieus turbine is the most promising since it is characterized by higher efficiency, even if for applications at higher wind speeds with respect to Savonius VAWTs. Several researchers try to optimize the aerodynamics of the Darrieus rotors, allowing wind turbines to start rotation even in the presence of low wind speeds. In this paper the authors propose a numerical investigation of the flow field around a 1:4 scaled model of a pair of blades installed on an innovative Darrieus-type VAWT. A Reynolds Averaged Navier-Stokes-based CFD model was validated on the basis of the wind tunnel data, and the scaled turbine performance was analysed by numerically evaluating the effect of different geometric configurations and rotation angles on the turbine torque coefficients. The results of the simulations confirmed the capabilities of the proposed configuration to give valuable performance even for low wind speeds.

1. Introduction

Wind turbine can be divided in Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) depending on the rotation axis. Compared to the HAWT the VAWT receive the wind from all angles and the generator can be located at the bottom of the turbine. On the contrary, the VAWT present an angle of attack variable during the day [1] depending from the incoming wind and also the investigation of the turbulence phenomena is more complicated in respect to the HAWT. Typical VAWT are of two typology: i) Savonius, used mainly for small-scale power applications because of their low energy conversion efficiency [1]; ii) Darrieus type presenting difficulties to start but able to convert energy in a better way [2]. For this reason, it is more interesting to study the domestic Darrieus turbines then the large-scales ones, presenting high problems in start-up their rotation [3]. The significant developments of CFD (Computational Fluid Dynamics) techniques in the last years have made this tool of investigation a valid support to experiments on wind turbine, allowing a significant reduction of tests’ times and costs [4]. However, despite the widespread use, CFD-based predictions may be affected by large errors if not properly validated. These errors can be caused by a number of factors including the discretization of the domain, the proper selection of the boundary conditions (e.g. free-stream velocity
and turbulence intensity, model geometry), and too restrictive assumptions in the modelling of the governing laws (e.g. turbulence modelling in RANS simulations of turbulent flows). Hence, a verification and validation procedure of any computer code is required before the code can be applied to practical problems [5]. Looking at the scientific literature review in some publications the authors proposed improvements in VAWT energy conversion from wind.

Singh [2] by CFD analysis was able to indicate a better blades profile to increase the wind turbine performance. In addition Zamani et al. [6], by numerical simulations, realized a torque optimization adopting a J-shaped profile which improves the pressure distribution around the blades. Naccache et al. [7], by using an additional VAWT succeed to increase the blades trading area. Some of the authors of the present paper, in previous research [8] performed numerical and experimental analysis of a novel domestic Darrieus VAWT characterized by six blades (three main and three support). The results of the simulations confirmed the capabilities of the proposed configuration to give valuable performance even for wind speeds below 4 m·s⁻¹. The adopted numerical model was validated using bulk data as torque and power, collected during the wind tunnel experiments. Therefore, the numerical tool results highlighted that the agreement between experimental and numerical data was not obtained in all the analysed conditions [8]. In order to optimize the performance of the numerical model, in the present paper, a more accurate validation, by using PIV (Particle Image Velocimetry) information about the velocity field around the pair of an innovative Darrieus-type VAWT, was performed. In particular, the numerical velocity fields were validated in correspondence of the main and auxiliary profile of the pair of blades, in static conditions (absence of blade rotation and fixed wind velocity). The performances of two different turbulence models (k-ω-SST and Spalart-Allmaras) were also investigated. The validated numerical tool allowed to analyse the numerical performance of the VAWT prototype by determining the flow field around the blades in correspondence of different wind velocity and different rotation angles.

2. Darrieus-type VAWT prototype

The geometric configuration of the innovative VAWT configuration, analysed here by CFD technique, was selected in a previous work in which some of the authors of the present paper found interesting results in terms of the torque and power [8,9]. The wind turbine, illustrated in Figure 1, present three pairs of blades oriented 120° each other and was obtained by modifying the DU06-W-200 profile [10]. α₁ and α₂ represent the attack angles and present a value of 12.5° while C₂ and C₁ are the chord lengths of the two blades; their ratio is 0.60 and C₂ is 40.8 mm; the space between the blades in y direction is of 18.40 mm and the in x direction is 25 mm (see Figure 1). The wind turbine presents a radius equal to 60 mm and a height of 140 mm. The value of the angles of attack was chosen in order to obtain the max value of the lift coefficient. The use of a symmetrical profile ensures the functioning of the blade during a complete system revolution and therefore when the angle of attack from positive becomes negative. A 1:4 scale model was designed by importing the profiles of both the main and the auxiliary blade and extruding them (Figure 2a). The prototype was printed by the Prusa i3 3D printer (Figure 2b). The pair of blades was studied in the wind tunnel chamber equipped by a Particle Image Velocimetry (PIV) system located in the LAMI laboratory of University of Cassino.
3. Mathematical and numerical models

CFD analysis were aimed at analyse the velocity profile around the VAWT blades. They were performed by solving the mass and momentum conservation equations [8,11] and the turbulence with an Unsteady Reynolds Averaged Navier-Stokes (URANS) model by the software OpenFoam. From a preliminary analysis, only the SST $k-\omega$ and the Spalart-Allmaras models were suitable. The SST $k-\omega$ was selected since it showed the best performances for simulating the specific problem under investigation. 2D numerical analysis were performed in unsteady state conditions adopting a time step equal to $1 \times 10^{-5}$. The solver name is the “pimpleFoam” which is adopted for the resolution of transient incompressible turbulent fluid flows. A second order discretization scheme was employed for the upwind scheme ensuring a more accurate solution and convergence of simulations was ensured taking residuals
tolerance of $10^{-6}$. In Figure 3 the computational domain and the boundary conditions employed are illustrated in the reference position in which the angles of attack, $\alpha_1$ and $\alpha_2$, are both fixed and equal to 12.5° (see Section 2). Addition 5 computational domains were realized by rotating clockwise the bladed of 60°, 120°, 180°, 240° and 300°. In this way, the effects of wind speed on the pair of blades were studied by simulating a complete rotation of the wind turbine. For purpose of validation, a constant and uniform x-component of the velocity equal to 10 m/s with a turbulence intensity equal to 0.5% was imposed at the inlet reproducing the same velocity profile as obtained from the PIV measurements, and placing the boundary condition at the same location as in the PIV experiments, which is equal to a distance of 300 mm from the front of the blades. In addition, a symmetry condition was applied on the horizontal surfaces of the computational domain, the pressure was considered equal to zero at the outlet section and a no slip condition was imposed on the blade faces. Three additional inlet velocity equal to 2.5 m/s, 5 m/s and 7.5 m/s were considered in order to numerically investigate the velocity effects of the torque coefficient on the blades.

The whole computational domain has the dimensions of 340 mm of height (equal to 5 times the chord lengths of the main blade) and 680 mm of width (equal to 10 times the chord lengths of the main blade). The reference system is placed at the leading edge of the auxiliary blade, 300 mm from the inlet section.

In Figure 4 the unstructured computational grid adopted for the numerical simulations composed by 1,709,097 elements is reported. A grid sensitivity analysis was made by calculating the relative error between the vertical profiles of horizontal velocity obtained by two consecutive meshes, using a grid refinement factor of 1.5. With the proposed mesh, the mean relative error on the vertical profiles is maintained under 5%. A grid refinement was made on the blades model surface were a boundary layer was applied with a number of layer equal to 10 a size of $9 \times 10^{-5}$ m and a growth rate of 1.1. The maximum computational grid size in the free stream is equal to 1.2 mm.
4. Numerical results

4.1 On-scale numerical model validation

In order to validate the CFD model, in this section the numerical and PIV data (within the uncertainty bars) are compared and analyzed. In particular, the comparisons are shown in terms of horizontal (u) components of the velocity in four different vertical sections across the wind turbine aerofoils, as indicated in Figure 5.

![Figure 5](image)

**Figure 5.** Different sections across the wind turbine aerofoils in which the horizontal and vertical components of the velocity are compared with the PIV measurements.

In Figure 6 comparisons among two investigated turbulence models (SST k-ω and the S-A-Spalart-Allmaras) and PIV data are illustrated. From the analysis of the figure it is possible to observe that the best performance is obtained by the SST k-ω turbulence model, which is able to better reproduce the fluid flow behavior around the blades. In particular, profiles P1 and P2 show similar performance of both the two investigated turbulence models. On the contrary, from profiles P3 and P4 it is evident that, when the flow starts to separate, SST k-ω model give better results while the S-A model do not reproduce correctly such separation. Anyway, the flow pattern on the lower surface of the blades, is correctly reproduced by both the considered turbulence models since in such a zone there is no significant flow separation at the considered angle of attack. Finally, profiles P4 shows that the S-A profile assumes a diffusive behaviour while SST k-ω model once again present a better performance. Therefore, the SST k-ω turbulence model has been chosen and
applied to investigate the numerical performance of the innovative wind turbine, reported in the next sub-section.

![Figure 6. Comparison between CFD and PIV results in terms of horizontal component of the velocity (u) in different vertical sections across the wind turbine blades.](image)

### 4.2 VAWT numerical performance assessment

The novel VAWT has been studied evaluating the variation of the torque generated at the shaft of the turbine as a function of wind speed and rotation angle. The adopted computation domain, boundary conditions and computation grid are reported in Figure 3 and Figure 4. The reference configuration presents the attack angles $\alpha_1$ and $\alpha_2$ equal to $12.5^\circ$ (see Figure 1). In addition, 5 more computational domains were realized by rotating clockwise the blades of $60^\circ$, $120^\circ$, $180^\circ$, $240^\circ$ and $300^\circ$ but not illustrated here for brevity.

In Figure 7 the non-dimensional torque is illustrated as a function of the wind speed in correspondence of for four different wind speed values (2.5, 5, 7.5 and 10 m/s) and as expected the torque value increases as the wind speed increases.
Figure 7. Non-dimensional torque as a function of the wind velocity

For a speed lower than 2.5 m·s\(^{-1}\) the torque is reduced of about 94% in respect to the highest wind speed (10 m·s\(^{-1}\)) but the VAWT can be however employed for a wind speed equal to 5 m·s\(^{-1}\). In Figure 8, the non-dimensional torque is illustrated as a function of the rotation angle, by fixing the wind speed at a value of 5 m·s\(^{-1}\).

Figure 8 shows that the maximum torque is obtained for a rotation angle equal to 120 degrees. Therefore, the couple of blades is able to extract energy from the wind for azimuth angels around 120 degrees, since the torque at the shaft results positive. On the contrary, for azimuth angles between 0 degrees and 60 degrees, and between 180 degrees and 360 degrees, the blades dissipate part of the extracted energy back in the flow, since the torque at the shaft is negative. Since the VAWT is composed by three pairs
of blades, even when the single pair of blades presents a negative torque, the resultant torque will still be positive (supported by the other two pairs). Figure 9 and Figure 10 shows particular configurations of the velocity and pressure contours obtained for the rotation angle for which the torque reaches the upper and lower limits.

Figure 9. Pressure contour (a) and velocity contour (b) obtained for a rotation angle equal to 72.5° and an inlet wind speed of 5 m/s.
Figure 10. Pressure contour (a) and velocity contour (b) obtained in correspondence of an azimuth angle equal to 132.5° and an inlet wind speed of 5 m/s.

Looking at the velocity fields of the 72.5 degrees configuration (Figure 9a), the blades result stalled and the flow velocity in proximity of both the blades is equal to 0 m/s. With the first aerofoils couple at 132.5 degrees (Figure 10), a lift force is generated because the velocity and pressure became minor than zero in proximity of the blades. The pressure contour reported in Figure 10a shows that, by employing a wind turbine presenting two blades, an increasing of the negative pressure region is obtained.

Conclusions
In this paper, the authors propose a numerical investigation of the flow field around a 1:4 scaled model of a pair of blades installed on an innovative Darrieus-type VAWT. The turbine configuration is characterized by six blades (three main and three support) and is able to start rotations also when the wind speed is low. 2D Unsteady Reynolds Averaged Navier-Stokes (URANS) simulations are made out using the open-source OpenFOAM CFD software. Numerical results obtained adopting the Spalart-Allmaras and SST k-ω turbulence models, in terms of horizontal and vertical components of the velocity over the aerofoils surface, are compared with experimental data from wind tunnel investigation made out with Particle Image Velocimetry (PIV) technique. From the numerical analysis, it is possible to state that the SST k-ω turbulence model shows an overall better ability to reproduce the flow pattern around the aerofoils if compared to the PIV measured data. The validated numerical tool is applied to investigate
the torque obtained by ranging the wind speed and the azimuth angle. Numerical simulation results show that the torque value increase as the wind speed increases and the torque reaches the maximum value with the 72.5 degrees configuration. On the contrary, the numerical analysis performed for an azimuth angle of 132.5 degrees shows a negative torque and a nearly zero velocity in proximity of the stalled blades.

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