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Numerical Analysis of the Influence of Number of Blades on the Power Performance of Vertical Axis Wind Turbines

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ABSTRACT: The current study systematically analyzes the impact of number of blades (n) on the aerodynamic performance of 2-, 3- and 4-bladed Darrieus H-type vertical axis wind turbines (VAWTs). A large number of operational parameters, i.e., tip speed ratio (λ), Reynolds number (Re), turbulence intensity and reduced frequency (K) are investigated to provide a deeper insight into the impact of n on the dynamic loads on the blades, the turbine performance and the wake. High-fidelity unsteady Reynolds-averaged Navier-Stokes (URANS) simulations, extensively validated with experiments, are employed. The results show that (i) within the turbine optimal operational range, the turbine power coefficient (C_P) is almost independent of n; (ii) when dynamic stall is present, C_P values are dependent on n due to the impact of K; and (iii) decreasing n leads to an increase in the maximum lift coefficient, while the drag coefficient of the blade(s) reduces due to the higher K. The present findings support the optimal aerodynamic design of small- to large-scale VAWTs.

KEYWORDS: VAWT; Urban; Offshore; Optimal Design; CFD; URANS.

INTRODUCTION

Vertical axis wind turbines (VAWTs) have recently received renewed interest for wind energy harvesting in two new potential locations, i.e., far offshore and in urban environments [1-6]. VAWTs have several advantages compared to horizontal axis wind turbines (HAWTs) [7]: omni-directionality, low noise, simple design and low costs. However, their aerodynamic performance is currently lower than HAWTs. Therefore, to benefit from their many advantages, their aerodynamic performance needs to be further improved. To improve their aerodynamic performance, the impact of operational [8, 9] and geometrical [10, 11] parameters needs to be well understood. Number of blades is an important geometrical parameter, which significantly affects the aerodynamic performance of VAWTs. However, to the best of our knowledge, its impact on the turbine performance and the dynamic loads of the blade is not well understood. Therefore, in this paper, such an impact is studied for 2-, 3- and 4-bladed turbines for different solidities and within a wide range of operational parameters. The evaluation is based on high-fidelity CFD simulations, extensively validated with experiments. The computational settings and parameters are described in Section 2. The results and conclusions are presented in Section 3 and 4, respectively.

CFD SIMULATIONS

The reference turbine is a Darrieus H-type VAWT with the characteristics shown in Table 1. The blade cross-section is the NACA0018 airfoil. The 2D computational domain is 35d × 20d and consists of a rotating core and a fixed domain surrounding the core. The size of the computational domain is based on the guidelines for CFD simulations of VAWTs [12, 13]. The computational grid consists of approximately 395,851 quadrilateral cells with a maximum y^+ of 3.8. The grid is based on a grid sensitivity analysis using three uniformly refined grids. Further details of the grid study is presented in Ref. [13]. The boundary conditions at the inlet and outlet of the domain are a uniform velocity inlet and zero gauge static pressure outlet. Symmetry conditions are used for the side faces. No-slip condition holds on the airfoil and shaft walls. Sliding grid interface is employed for the interface between the rotating and fixed grids. In the CFD simulations, the approach-flow (i.e. inlet) total turbulence intensity is 5% with a turbulence length scale equal to the turbine diameter, i.e., 1 m. The incident-flow total turbulence intensity is 4.42% representing the real value experienced by the turbine [14]. The four-equation transition SST model [15] is employed to model the turbulence [16-18]. Incompressible unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations are performed using the ANSYS Fluent 16.1 with the SIMPLE scheme for pressure-velocity coupling and the second-order temporal and spatial discretization. The azimuthal increment, $d\theta$, is 0.1°, which is based on CFD guidelines for VAWTs [12, 13]. The number of iterations per time step is 20. A number of 20 turbine revolutions are performed, and the results are sampled at the 21st turbine revolution. This value is based on a comprehensive convergence analysis and allows the results to reach a statistically steady-state condition [12, 13]. Two sets of validation studies have been performed and presented in detail in Ref. [1, 13].

Table 1. Geometrical and operational characteristics of the reference turbine.

Parameter	*Value*	*Parameter*	*Value*
Number of blades, n	2	Airfoil chord, c [m]	0.06
Diameter, d [m]	1	Shaft diameter, d_s [m]	0.04
Height, h [m]	1	Freestream velocity, U_∞ [m/s]	9.3
Swept area, A [m^2]	1	Rotational velocity, Ω [rad/s]	27.9 – 102.3
Solidity, σ	0.12	Tip speed ratio, λ	1.5 – 5.5
Blade aspect ratio, h/c	16.67	Chord Reynolds number, Re_c	$0.69\times10^5 – 2.14\times10^5$

RESULTS

Fig. 1 shows the power coefficient versus tip speed ratio and solidity for 2-, 3-, and 4-bladed VAWTs with constant Re_c at identical solidities and tip speed ratios. It can be seen that except for $\lambda < 2.5$, the turbine C_P is weakly sensitive to the number of blades. In the optimal operating range of turbines with different solidities, i.e. in the vicinity of λ_{opt}, C_P is almost *n*-independent. This is an important finding which implies that for variable-speed VAWTs maintaining their λ_{opt} at a given constant Re_c, the number of blades could be selected based on the other design parameters such as uniformity of the output power, structural loads and vibrations, and cost. The same applies to constant-speed low-solidity urban VAWTs, at a given constant Re_c, frequently operating at moderate to high λ where the C_P is almost insensitive to the number of blades. Note that the urban VAWTs need to have a low solidity due to their dominant moderate to high λ.

However, in practice for small- to medium-scale turbines due to the low mean wind speed, e.g., in the urban environment, Re_c is typically in the low to moderate regime, $\leq 2\times10^5$, where Re number effects are significantly influencing the turbine C_P [8]. Therefore, to avoid the low Reynolds number effects, the blade chord length needs to be sufficiently large. Hence, from an aerodynamic point of view and for a given solidity, the smaller number of blades will yield a higher C_P due to the Reynolds number effect. Therefore, the choice of the optimal number of blades with respect to the turbine C_P needs to consider the Re_c. Note that to select the number of blades there exists other important considerations, i.e., uniformity of structural loads, turbine vibrations, power uniformity, and cost.

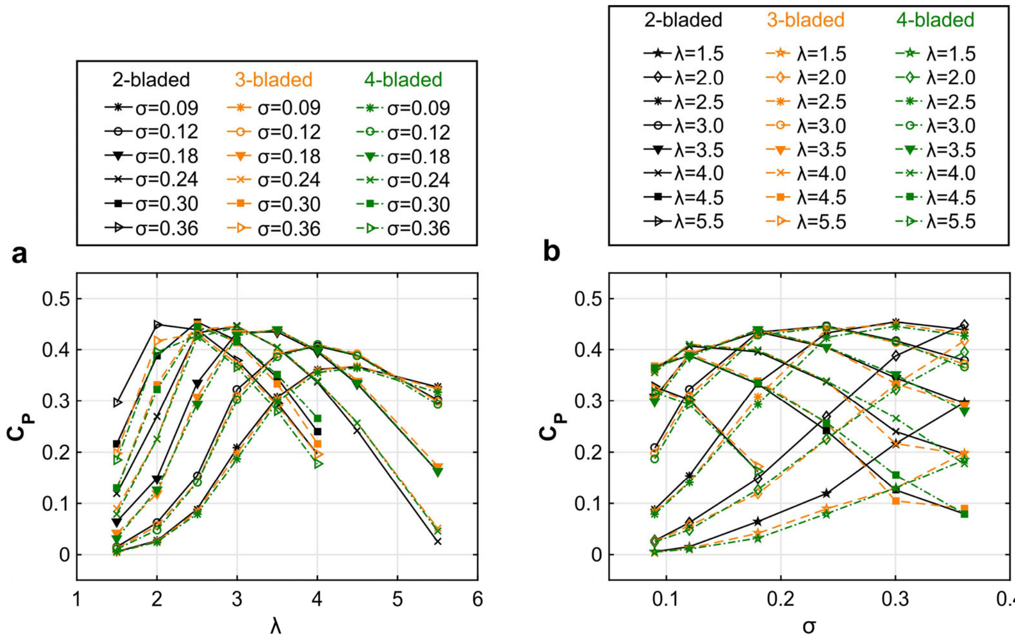

Figure 1. Power coefficients versus tip speed ratio and solidity for 2-, 3-, and 4-bladed VAWTs with fixed Re_c at identical $\lambda - \sigma$ positions (TI = 5%).

In addition, at a given solidity, the turbine with less number of blades will operate at a higher reduced frequency *K* due to the larger blade chord length. The higher *K* will improve the turbine aerodynamic performance at low λ by delaying/avoiding the flow separation and dynamic stall and the consequent load fluctuations. The higher C_P for the turbine with less number of blades at $\lambda < 2.5$, therefore, could be a result of the higher *K*. For instance, this is more pronounced for the 2-bladed turbine compared to the 3- and 4-bladed turbines at $\lambda = 1.5$ and 2.0, see Fig. 1b.
In the full paper, further results analyzing the impact of number of blades on the dynamic loads of the turbine blade at constant Re_c will be presented and discussed in detail.

CONCLUSIONS

Number of blades *n* is an important geometrical design parameter for vertical axis wind turbines. The selection of the number of blades for a turbine is a function of several parameters, namely uniformity of output power, turbine loads and vibrations, cost as well as turbine aerodynamic performance. The focus of the present study is confined to the aerodynamic performance of the turbine to provide a profound understanding and to help the designers/manufacturers with this aspect of the design. In the present study, high-fidelity CFD simulations, extensively validated with experimental data, are employed where the main findings of the study can be summarized as follows: (i) at a given Re_c, the turbine C_P is independent of *n* within the optimal operational range, i.e., in the vicinity of λ_{opt}; (ii) for a given σ and at low λ where dynamic stall is present, C_P values are dependent on the number of blades due to the impact of *K*. This means that at a given solidity, the smaller number of blades (higher chord length) delivers a higher *K* and thus a higher C_P; and (iii) decreasing the *n* is found to increase the $C_{l,max}$ and reduce the C_d due to the higher *K*. From an aerodynamic point of view, at a given σ, the less number of blades is favorable due to the higher Re_c and *K*. However, as discussed above, the choice of the number of blades is also driven by several other important design parameters, such as uniformity of output power and structural loads and cost. A larger number of blades yields more uniform instantaneous loads and power during the revolution while the length scale of the load fluctuations is also comparatively smaller due to the smaller blade chord length at the given σ.

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