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Influence of Airfoil Maximum Thickness on Aerodynamic Performance of Vertical Axis Wind Turbines

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ABSTRACT

Airfoil shape can significantly influence the aerodynamic performance of vertical axis wind turbines (VAWTs). However, while the symmetric NACA airfoil series are widely used for VAWTs, the effect of parameters, which define the shape of an airfoil, on the aerodynamic performance of VAWTs has not yet been extensively studied. The current study, therefore, intends to systematically investigate the effect of airfoil maximum thickness t_m on the aerodynamic performance of VAWTs for different tip speed ratios (λ). Unsteady Reynolds-Averaged Navier-Stokes (URANS) calculations are performed on high-resolution gird. The results show that the optimum t_m decreases from 24%c (airfoil chord) to 12%c when λ increases from 2.5 to 5.5. As higher λ corresponds to lower variations of angle of attack (α) of the blades, the better performance of thinner airfoils at such λ is associated to their higher C_l/C_d at such α. Higher stall angle could explain the higher C_P of thicker airfoils at low λ. The current findings could support the optimization of airfoils for VAWTs.

1. Introduction

Vertical axis wind turbines (VAWTs) have recently received growing interest. The renewed interest, which is mainly for offshore applications [1] and in the built environments [2], stems from advantages including omni-directional capability, low manufacturing, installation and maintenance costs, lower noise, robustness, reliability and scalability. Many studies have focused to further clarify the underlying physics of VAWTs, which is highly driven by complex flow phenomena such as dynamic stall and blade-wake interactions [3].

Characterization and improvement of the aerodynamic performance of VAWTs have also been the center of attention where many operational and geometrical parameters such as tip speed ratio λ [4, 5], solidity [6, 7], number of blades [8], pitch angle [9], turbine shaft size [10] have been studied. Earlier studies have shown the important impact of the airfoil shape as it can significantly influence the aerodynamic performance of VAWTs. However, the employed airfoils for VAWTs are mainly the symmetric NACA airfoil series, which have been originally designed for aeronautical applications, i.e. helicopters. An extensive literature study shows that high-fidelity numerical studies on airfoil shapes for VAWTs have been performed for random lists of airfoils. Singh et al. [11] and Asr et al. [12] experimentally studied three different airfoils on VAWTs while their focus was on starting behavior of the turbine rather than characterizing the effect of the airfoil shape on the aerodynamic performance of the turbine. Mohammad [13] and Elkhoury et al. [14] numerically studied several symmetric and asymmetric airfoils for VAWTs, while the comparison of the computational settings employed in these studies were not in line with the minimum requirements for computational settings suggested by CFD guidelines in the literature [15, 16] which have compromised the accuracy of these calculations.

To the best of our knowledge, therefore, a systematic analysis of the effect of parameters defining the shape of the airfoil on aerodynamic performance of VAWTs for different operating conditions has not yet been performed. These important parameters include airfoil maximum thickness t_m, position of maximum thickness, leading edge radius, maximum camber and position of maximum camber.

The current study, therefore, intends to investigate the effect of t_m on the aerodynamic performance of VAWTs for different λ values from 2.5 to 5.5. t_m varies from 10 to 24% corresponding to NACA0010-NACA0024 airfoils. The evaluation is based on extensive verification and validation.

The outline of the paper is as follows: the computational settings and parameters are presented in section 2 where the geometrical and operational characteristics of the turbine, computational domain and grid, solver settings and verification and validation studies are discussed. Section 3 presents the CFD results. The conclusions are provided in section 4.

2. Computational settings and parameters

The geometrical and operational characteristics of the wind turbine are described in Table 1. To simulate the turbine rotation, a computational domain with a rotating core is created where a sliding grid interface with the surrounding fixed domain is employed. The domain width, the distance from the turbine center to the domain inlet and outlet are 20d, 10d and 25d, respectively. Note that the dimensions of the computational domain are chosen based on the CFD guidelines in the literature [15, 16]. The diameter of the rotating core is 1.5d. A high-resolution computational grid consisting of approximately 400,000 quadrilateral cells is generated where the maximum y^+ on the blade walls are below 4 for all cases. The commercial CFD code ANSYS Fluent 16.1 is used to perform the simulations. Incompressible unsteady Reynolds-averaged Navier-Stokes (URANS) simulation are performed in combination with the 4-equation transition SST model [17]. Second-order temporal and spatial discretization and the SIMPLE pressure-velocity coupling scheme are used. The azimuthal increment is 0.1° and the data sampling is initiated after 20 turbine revolutions to reach a statically steady solution. The boundary conditions are uniform velocity inlet, zero gauge pressure outlet, symmetry sides and no-slip walls. The computational settings are according to the guidelines by Rezaeiha et al. [15, 16]. The evaluations are based on extensive verification and validation [9, 10, 15].

Table 1. Geometrical and operational characteristics of the VAWT.

Parameter	Value	Parameter	Value
Number of blades, n	2	Airfoil chord, c [m]	0.06
Diameter, d [m]	1	Shaft diameter [m]	0.04
Height, H [m]	1	Freestream velocity, U_∞ [m/s]	9.3
Solidity, σ [-]	0.12	Freestream total turbulence intensity	5%

3. Effect of airfoil maximum thickness

Symmetric NACA airfoil series with $10\%c \leq t_m \leq 24\%c$ (see Fig. 1) are employed to investigate the effect of airfoil maximum thickness on the aerodynamic performance of VAWTs within a wide range of λ values from 2.5 to 5.5. The airfoils have their maximum thickness at 30% of the chord from the leading edge.

Turbine power coefficients C_P calculated for the last turbine revolution with the different airfoils, shown in Fig. 1, are depicted in Fig. 2a for different values of λ. The comparison shows that at high λ (≥ 3.5), thinner airfoils outperform the thicker airfoils while this reverses for $\lambda < 3.5$ where thicker airfoils yield in higher C_P. To further clarify the effect of t_m on C_P, Fig. 2b shows the variations of C_P versus t_m for different λ values. It can be seen that for $\lambda = 2.5$, as t_m increases, C_P monotonically increases. The improvement of 294% is achieved when t_m increases from 10% to 24%. For $2.5 < \lambda \leq 5.5$, however, there exists an optimal t_m ($t_{m,opt}$). By increasing λ from 3.0 to 4.5, the $t_{m,opt}$ asymptotically reduces from 18%c to smaller value of 12%c (see Fig. 3).

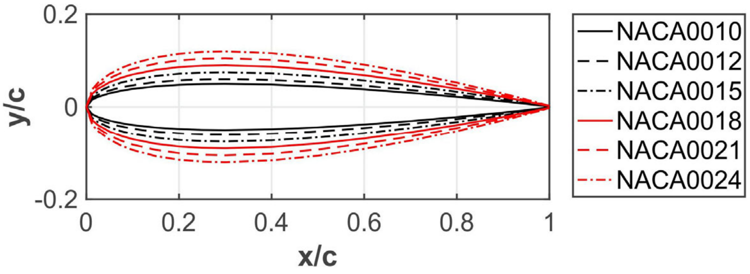

Figure 1. Profiles of the studied airfoils.

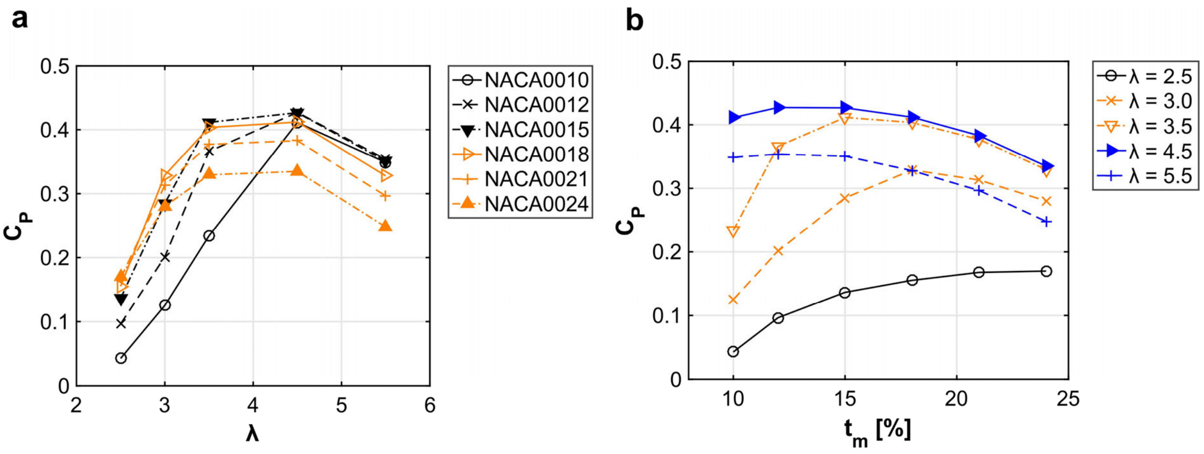

Figure 2. Power coefficient for the last turbine revolution (a) versus tip speed ratio for airfoil with different maximum thickness, 10-24%; (b) versus airfoil maximum thickness for different tip speed ratios, 2.5-5.5.

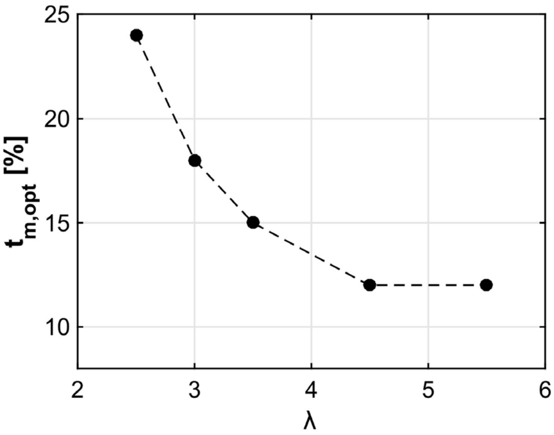

Figure 3. Optimal airfoil maximum thickness versus tip speed ratio.

Turbine instantaneous moment coefficient C_m during the last revolution for turbines with different airfoils at is illustrated in Fig. 4 for different values of λ. It can be seen that the higher C_P corresponding to thicker airfoils at low λ (< 3.5) could be mainly associated to their higher stall angle. This is inferred from later drop of C_m for thicker airfoils within $45° \leq \theta \leq 90°$. In addition, the softer stall behavior of these airfoils also is influential on variation of C_m within the aforementioned θ: the thinner airfoils go through a sudden drop in C_m while this drop is more gradual for thicker airfoils. The better performance of thinner airfoils at $\lambda > 3.5$ is mostly attributed to their higher C_l/C_d prior to stall. Note that $\lambda > 3.5$ corresponds to smaller variations of angle of attack on blades, which means that the blades mostly operate prior to stall and the flow is mostly attached.

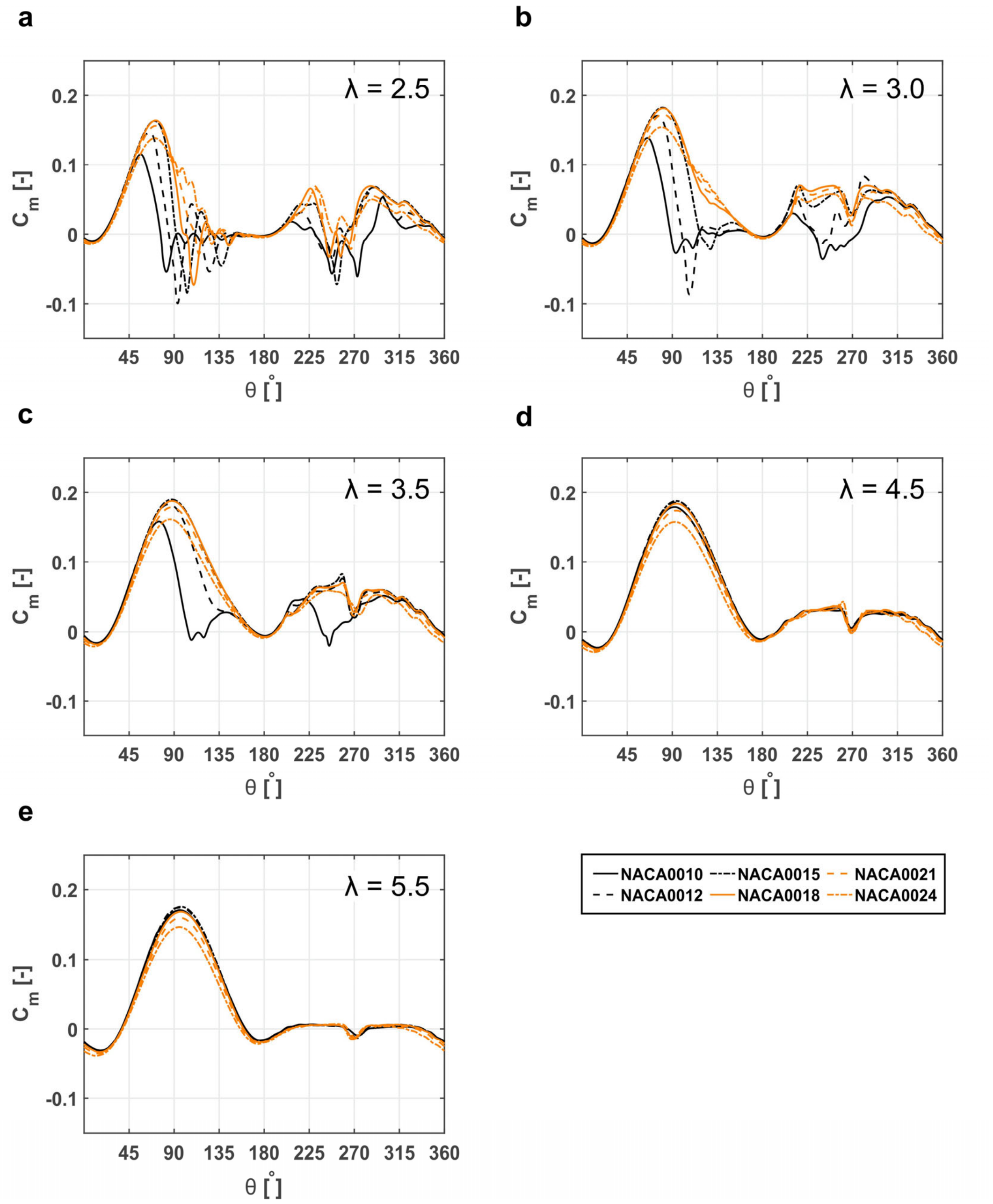

Figure 4. Instantaneous moment coefficient (during the last turbine revolution) at different tip speed ratios for airfoils with different maximum thickness, 10-24%.

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5. Conclusions

CFD simulations are performed to systematically investigate the effect of airfoil maximum thickness on aerodynamic performance of VAWTs at different tip speed ratios. The results reveal that the optimum t_m asymptotically decreases from 24%c at $\lambda = 2.5$ to 12%c at $\lambda = 5.5$. The better performance of thicker airfoils at small λ could be a result of their higher stall angle and soft stall behavior while higher C_l/C_d of thinner prior to stall explains their improved C_P at higher λ. The Weibull distribution of wind speed at potential installation locations, e.g. urban or sub-urban areas, can be employed to identify the most dominant wind speed regime and the corresponding λ so that the airfoil that yields the highest annual energy power (AEP) can be selected. To fully characterize the influence of airfoil shape on the aerodynamic performance of VAWTs, our future studies will investigate the effect of other important parameters defining the shape of the airfoil such as position of maximum thickness, leading edge radius, maximum camber and position of maximum camber.

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