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# Effect of pitch angle on power performance and aerodynamics of a vertical axis wind turbine

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## HIGHLIGHTS

- For the studied turbine, a small negative pitch angle $\beta = -2°$ increases turbine $C_P$ for 6.6% compared to $\beta = 0°$.
- Fixed pitch angle can affect the instantaneous and averaged loading and power conversion for VAWTs.
- Adding a fixed bound circulation (fixed $\beta$) can change the strength of shed vortices and wake generation for VAWTs.
- Fixed pitch angle shifts the instantaneous moment ($C_m$) on turbine blades between the fore and aft halves.
- The shift in $C_m$ proposes individual blade dynamic pitching as a promising power enhancement method for VAWTs.

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## ABSTRACT

Due to growing interest in wind energy harvesting offshore as well as in the urban environment, vertical axis wind turbines (VAWTs) have recently received renewed interest. Their omni-directional capability makes them a very interesting option for use with the frequently varying wind directions typically encountered in the built environment while their scalability and low installation costs make them highly suitable for offshore wind farms. However, they require further performance optimization to become competitive with horizontal axis wind turbines (HAWTs) as they currently have a lower power coefficient ($C_P$). This can be attributed both to the complexity of the flow around VAWTs and the significantly smaller amount of research they have received. The pitch angle is a potential parameter to enhance the performance of VAWTs. The current study investigates the variations in loads and moments on the turbine as well as the experienced angle of attack, shed vorticity and boundary layer events (leading edge and trailing edge separation, laminar-to-turbulent transition) as a function of pitch angle using Computational Fluid Dynamics (CFD) calculations. Pitch angles of −7° to +3° are investigated using Unsteady Reynolds-Averaged Navier-Stokes (URANS) calculations while turbulence is modeled with the 4-equation transition SST model. The results show that a 6.6% increase in $C_P$ can be achieved using a pitch angle of −2° at a tip speed ratio of 4. Additionally, it is found that a change in pitch angle shifts instantaneous loads and moments between upwind and downwind halves of the turbine. The shift in instantaneous moment during the revolution for various pitch angles suggests that dynamic pitching might be a very promising approach for further performance optimization.

## 1. Introduction

VAWTs have recently received growing interest for energy harvesting purposes offshore [1–3] as well as in the urban environment [4–6]. They offer several advantages over HAWTs: omni-directional operation (hence no need for a yaw control mechanism), lower manufacturing costs due to simple blade profile and shape (no twist or taper), lower installation and maintenance costs due to having the generator installed at ground level (or sea level in case of offshore application), good scalability, robustness and lower noise level due to lower operational tip speed ratios (λ) [7]. Early development of VAWTs in the 1970s–1980s [8] could not lead to competitive designs in terms of performance and lifetime compared to HAWTs [7,9], possibly due to insufficient understanding of the complex aerodynamics of VAWTs. Complexities which were later found to play an important in VAWT behavior and performance include temporal/

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## Nomenclature

| | |
|---|---|
| A | turbine swept area, $h \cdot d$ [$m^2$] |
| c | blade chord length [m] |
| $C_d$ | sectional drag coefficient [–] |
| $C_f$ | skin friction coefficient [–] |
| $C_{Fn}$ | coefficient of instantaneous sectional normal force [–] |
| $C_{Fx}$ | coefficient of instantaneous sectional force in x-direction [–] |
| $C_{Fy}$ | coefficient of instantaneous sectional force in y-direction [–] |
| $C_l$ | sectional lift coefficient [–] |
| $C_m$ | instantaneous moment coefficient [–] |
| $C_P$ | power coefficient [–] |
| $C_T$ | thrust coefficient [–] |
| $C_Y$ | coefficient of net force in y-direction [–] |
| CoP | pressure coefficient [–] |
| d | turbine diameter [m] |
| D | sectional drag force [N/m] |
| $F_t$ | sectional tangential force [N/m] |
| $F_n$ | sectional normal force [N/m] |
| $F_s$ | safety factor [–] |
| $F_x$ | sectional force in x-direction [N/m] |
| $F_y$ | sectional force in y-direction [N/m] |
| h | turbine height [m] |
| k | turbulence kinetic energy [$m^2/s^2$] |
| K | reduced frequency [–] |
| L | sectional lift force [N/m] |
| M | moment [N m] |
| n | number of blades [–] |

| | |
|---|---|
| P | power [W] |
| q | dynamic pressure [Pa] |
| R | turbine radius [m] |
| *Re* | chord-based Reynolds number, $U_{exp} \cdot \rho \cdot c/\mu$ [–] |
| $Re_\theta$ | momentum-thickness Reynolds number [–] |
| t | time [s] |
| T | thrust force [N] |
| $U_{exp}$ | experienced velocity [m/s] |
| $U_{ind}$ | induced velocity [m/s] |
| $U_\infty$ | freestream velocity [m/s] |
| $\alpha$ | experienced angle of attack [°] |
| $\alpha_d$ | experienced angle of attack on downstroke (decreasing $\alpha$) [°] |
| $\alpha_{geo}$ | geometrical angle of attack [°] |
| $\alpha_{ss}$ | static stall angle [°] |
| $\alpha_u$ | experienced angle of attack on upstroke (increasing $\alpha$) [°] |
| $\beta$ | blade pitch angle [°] |
| $\gamma$ | intermittency [–] |
| $\Gamma$ | circulation [$m^2/s$] |
| $\theta$ | azimuth angle [°] |
| $\lambda$ | tip speed ratio, $\Omega \cdot R/U_\infty$ [–] |
| $\mu$ | dynamic viscosity of air [kg/m s] |
| $\varphi$ | flow angle [°] |
| $\rho$ | density of air [$kg/m^3$] |
| $\sigma$ | solidity, $n \cdot c/d$ [–] |
| $\omega$ | specific dissipation rate [1/s] |
| $\Omega$ | rotational speed [rad/s] |

azimuthal variations of bound vorticity on the blades [10,11], blade-wake interactions and 3D wake characteristics [12,13], dynamic stall [14,15] and flow curvature [16,17]. Better understanding of these effects is essential for optimization of VAWT performance [18]. Research activities focused on this topic have employed various techniques. These include low-fidelity modeling which are typically momentum-based models such as the double multiple streamtube model [7]. Potential flow, cascade, vorticity and vortex transport models [19–21] are among the moderate-fidelity inviscid methods. Viscous CFD simulation is a high-fidelity method [22–26] which can provide much insight into the complete flow field although the accuracy of the results is very much dependent on computational parameters such as the number of turbine revolutions before data sampling, domain size, grid layout and resolution, and other numerical settings [25–27]. Wind tunnel measurements [28–31] and field experiments [32] have also been utilized both to provide an understanding of the flow physics and to provide validation data for modeling methods. These methods have been used to improve the performance of VAWTs where both the effect of geometrical parameters such as airfoil shape [33–35], blade solidity [36], blade pitch angle [37] and turbine tower [38], and of operational characteristics such as tip speed ratio [39] and freestream turbulence intensity [40,41] have been studied.

Among the aforementioned parameters, blade pitch angle ($\beta$) is very promising for performance optimization of VAWTs since it is very simple to apply in practice and does not introduce high manufacturing, installation or maintenance costs. The effect of pitch angle for VAWTs was studied by several authors [37,42–45] using the Double Multiple Streamtube Model [7]. However, the inaccuracy of this low-fidelity model for the prediction of the complex aerodynamics and performance of VAWTs was highlighted by Simão Ferreira, et al. [20]. Simão Ferreira and Scheurich [11] employed the moderate-fidelity inviscid 2D panel and 3D vorticity transport models in order to investigate the effect of fixed pitch angle. The study investigated pitch angles of −3°, 0° and +3° (see Fig. 1) and reported that although a shift in the instantaneous loads and moments was observed between the upwind and downwind sides of the turbine, the effect of pitch angle on the average loading, $C_P$ and $C_T$, was negligible. The effect of fixed pitch angle was studied using high-fidelity viscous CFD simulations by Hwang et al. [46], Chen and Kuo [47], Zhang et al. [48] and Bose et al. [49]. However, numerical settings employed in the work of Hwang et al. [46], Chen and Kuo [47] and Bose et al. [49] did not meet recently derived minimum requirements for accurate assessment of VAWT performance [27] while this information was not reported by Zhang et al. [48]. Shortcomings included a too small domain size (small distance between the turbine and the inlet and/or outlet, high blockage ratio), large azimuthal increment (d$\theta$) and a small number of revolutions of the turbine before data sampling.

The effect of fixed pitch angles −7°, −4°, −2°, −0.5°, +1° and +3° on $C_P$ was studied by Klimas and Worstell [32] for a 5-m Darrieus VAWT in an open-field experiment where −2° was found to be the

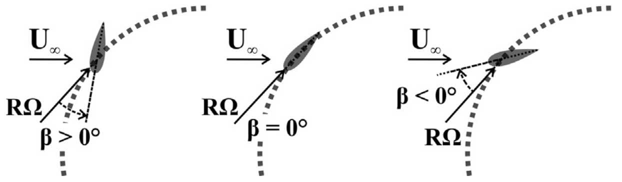

**Fig. 1.** Schematic showing the pitch angle for a VAWT blade.