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Optimization of blade pitch in H-rotor vertical axis wind turbines through computational fluid dynamics simulations

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HIGHLIGHTS

- The pitch control for VAWTs is parametrized in consideration of blade aerodynamics.
- The parametrization enhanced the optimization efficiency of pitch control.
- An efficient optimization platform for variable pitch control is developed.
- The optimal pitch control enhances average power coefficients of VAWTs effectively.

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ABSTRACT

Blade pitch control is a well-developed and widely-used approach in modern horizontal axis wind turbines in operation. However, its application in vertical axis wind turbines (VAWTs) is restricted by the ambiguities in its functional mechanism. A generic formulation that uses five governing parameters to represent the solution space of the optimal blade pitch control is developed through an in-depth analysis of the relationship between blade pitch and the output power of VAWTs. Subsequently, a variable blade pitch automatic optimization platform (VBPAOP) composed of genetic algorithm and computational fluid dynamics (CFD) simulation modules is built to search for optimal blade pitches that can maximize turbine power. A 2D unsteady CFD model is used as a performance evaluation tool because of its high computational efficiency, and its accuracy is validated through wind tunnel experiments prior to its application in optimization. Results show that in a wide range of tip speed ratios (TSRs), the optimized blade pitches can increase the average power coefficients by 0.177 and 0.317, respectively, in two simulated VAWT models with different chord lengths. At stages below the rated TSR, stall-induced torque losses are delayed or even avoided by the proposed optimized pitch control. At stages beyond the rated TSR, energy extraction in the downwind zone is improved due to increased upwind wake velocity.

1. Introduction

Vertical axis wind turbines (VAWTs) have reemerged as promising energy conversion devices owing to a variety of brand-new methods that can put forward the efficiency limit [1–6]. To improve the efficiency and competitiveness of VAWTs, much effort has been exerted to obtain an in-depth understanding of their complex aerodynamic behavior, which may involve pre/dynamic/deep stall when blades encounter a flow with a dynamically varying angle of attack [7,8] and blade–wake interactions [9,10]. High-fidelity simulations of these aerodynamic effects are essential in optimizing the performance of VAWTs [11–14]. Although the capabilities of blade pitch control have been illustrated in modern horizontal axis wind turbines (HAWTs), the efficacy of blade pitch control in VAWTs has not been fully demonstrated [15], and ambiguities remain in the optimal pitch control regimes of VAWTs [16]. With the development of active and passive pitch control devices [17–22], it was reported that blade pitch control can enhance the self-starting capability, maximize the power output, and mitigate the structure oscillation of VAWTs. However, the majority of these studies have focused on fixed pitch [23–27] or the superposition of harmonic pitch [22,28–36]. Limited efforts have been exerted to develop real-time optimal active pitch control in a complete azimuthal regime. In fact, the study on the blade pitch control to maximize the power output for H-rotor VAWTs will not only offer insights to the

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Nomenclature

A	amplitude for sinusoidal pitches
a	induction factor
c	chord length
C_P	power coefficient of the turbine
C_T,C_N	coefficients of tangential and normal forces on one blade
F_T,F_N	tangential and normal forces on one blade
$g()$	an implicit function to construct blade pitch
H	height of blades
k	reduced frequency of rotor
N	number of blades
r	radius of the rotor
r_1,r_2	adjustable ratios, represent the percentage of the control points used in the upwind and downwind zones
T	period of the rotor
Δt	time step size of unsteady CFD simulation
V_{in}	incoming flow velocity
V_e	“equilibrium” incoming velocity in the downwind zone
W	resultant velocity, the relative flow velocity that a blade encounters
α	angle of attack, the angle between the resultant velocity and blade chord line
β	pitch angle, the angle between the tangential velocity direction and the chord line
φ	flow angle, the angle between resultant velocity and tangential velocity on the rotor plane
λ	tip speed ratio
θ	azimuth of the rotor
ρ	air density
τ	non-dimensional time step
ω	angular velocity of the rotor
Ω	rotation frequency

mechanism and impact of blade pitch, but also facilitate the parameter optimization in both active and passive pitch control in practical implementations.

The optimal pitch angle in each stream tube (azimuthal position) that can generate maximum torque can be solved analytically with the double–multiple stream tube model (DMST) [33,37]. However, the obtained analytical solution is potentially problematic and disadvantageous. First, the accuracy of the solution is relatively low due to excessive simplifications in DMST. Second, the optimal pitch is discontinuous because the aerodynamic interference effects of adjacent stream tubes are disregarded in DMST. Considering these two facts, computational fluid dynamics (CFD) simulation, which is a state-of-the-art approach for numerically solving the dynamic essence of turbulent flows around turbine blades [38–40], is adopted in this study. Unlike DMST, CFD needs to individually assess the performance of VAWTs with different pitch variation strategies in one cycle; thus, searching for optimal variable pitch curves involves iterations. Considering the large computational cost of CFD and the large number of trial simulations required, a rational formulation with a limited number of design variables and an efficient optimization algorithm need to be developed.

Using the superposition of harmonic functions to formulate the pitch variation curves of actively controlled blades is a simple and popular approach [22,28–36], in which the curve functions can be defined with respect to only one or two adjustable variables (e.g., amplitude and phase of sinusoidal functions). However, superposition of harmonic pitch curves lacks flexibility and aerodynamic principle support, and the achievable improvement in efficiency is usually limited. Alternatively, Hwang et al. [17] selected adjustable pitch angles for 12 azimuthal positions evenly distributed in $[0\ 2\pi]$ to form variation curves of blade pitch. However, the constraint ranges of the pitch angles at the control points have to be artificially and progressively reduced in this method to accelerate convergence because of poor optimization efficiency. The low accuracy and efficiency of existing formulation methods are mainly caused by disregarding the underlying aerodynamic mechanism of variable blade pitch. A comprehensive pitch-curve formulation method that employs a limited number of variables to sufficiently cover the optimal solution space is urgently required. Furthermore, a number of well-developed optimization algorithms, including genetic algorithms (GAs) [17,29,34], memetic algorithms [19], exhaustion method [37], and brute-force optimization [41], have been utilized to search for optimal blade pitches.

Considering these facts, we develop a detailed optimization platform that integrates high-fidelity CFD simulations for H-rotor VAWTs whose blade pitches are actively controlled. An equivalent generic formula for blade pitches is established through an in-depth analysis of the underlying relationship between blade pitch and power generation. The proposed formula considers five governing variables. Subsequently, GA is utilized in combination with validated CFD models to determine the ideal regulation parameters for a wide range of tip speed ratios (TSRs). Furthermore, the influence of blade chord length on the optimal blade pitch is investigated.

2. Optimization methodology

2.1. Mechanism of the relationship between blade pitch control and output power

The power output in lift-type wind turbines can be enhanced by increasing blade lift and reducing blade drag. Therefore, increasing blade lift as much as possible is a rational means to maximize power in a specific blade airfoil. The lift force of a rotating blade is defined as the force component perpendicular to the resultant velocity direction of the blade. In practice, aerodynamic force coefficients are usually tabulated based on experimental results for various angles of attack (AOA)

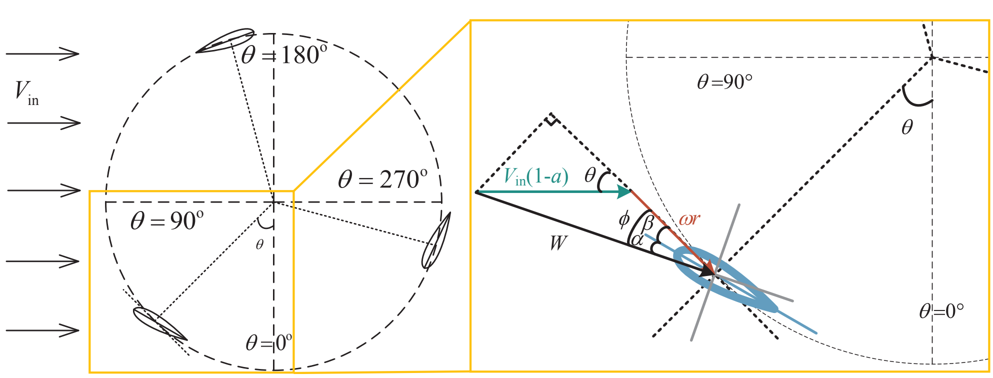

Fig. 1. Schematic of the flow angles of a VAWT.