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Aerodynamic Performance Analysis of Wind Turbine Blades Based on Bézier and Blade Element Momentum

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Abstract. Accurate aerodynamic performance prediction and blade geometry optimization are critical for enhancing wind turbine energy efficiency. This study establishes a Blade Element Momentum (BEM) simulation framework for a wind turbine, focusing on the impacts of correction models, blade parameterization methods, and operating parameters on rotor performance. The results demonstrate that uncorrected ideal Betz models severely overestimate power coefficients, while Prandtl/Glauert corrections yield physically realistic predictions, confirming their necessity in BEM simulations. Comparative analysis reveals that the Bézier curve parameterization achieves a peak power coefficient of 0.4762, significantly outperforming the polynomial method, and is thus selected for blade geometry definition. Further investigation quantifies the combined effects of pitch angle and tip speed ratio, showing that moderate pitch angles optimize aerodynamic loading across operating ranges. Finally, the wind turbine power curve from 4 to 12 m/s is derived, validating the high efficiency of the optimized design. This work provides a systematic reference for wind turbine rotor design and performance evaluation.

Keywords: Wind Turbine Aerodynamics, Blade Element Momentum, Blade Parameterization, Power Coefficient

1. Introduction

As a core component of clean and renewable energy, wind energy is undergoing unprecedented rapid development against the global strategic background of addressing climate change and pursuing carbon neutrality. According to the Global Wind Energy Council (GWEC), the cumulative installed wind power capacity worldwide has grown at an average annual rate of over 12% in the past decade, and wind power has become an important pillar in the power structure transition of many countries [1]. Meanwhile, the proposal of the "Dual Carbon" goal has further strengthened the strategic significance of wind energy development. Improving the aerodynamic conversion efficiency of wind turbines is not only related to the continuous reduction of the levelized cost of electricity, but also directly affects the overall economy and sustainability of wind farms [2]. However, constrained by blade geometric limitations, aerodynamic stall characteristics, and manufacturing capabilities, the power coefficient of practical wind turbines has long been difficult to approach the Betz limit. How to systematically narrow the gap between engineering practice and theoretical limits has become a key scientific issue urgently to be solved in the field of wind energy engineering.

In the field of blade aerodynamic design and performance optimization, researchers worldwide have accumulated extensive achievements. Early studies were mostly based on the Blade Element Momentum (BEM) theory, aiming to achieve aerodynamically optimal blade design by optimizing chord and twist angle distributions. Based on the classical momentum theory, Glauert introduced tip loss corrections, and Prandtl further developed tip and root loss models, which significantly improved the accuracy of theoretical predictions and established a widely adopted framework for engineering design [3]. In recent years, with the advancement of Computational Fluid Dynamics (CFD), numerical simulations based on the three-dimensional Navier–Stokes equations have been widely used to capture complex flow structures and reveal the mechanisms by which nonlinear aerodynamic phenomena such as tip vortices and flow separation affect the power coefficient. Meanwhile, the introduction of parametric blade modeling methods, including Bézier curve and polynomial fitting, has enabled continuous geometry optimization and provided a flexible design space for multi-objective aerodynamic optimization. In terms of operational control, coordinated regulation strategies for the tip-speed ratio and pitch angle have been extensively investigated, and the maturity of variable-speed and variable-pitch control has further promoted high-efficiency operation of wind turbines over a wide range of wind speeds [4].

This paper takes the Bezier curve-fitted blade as the core research object, uses the Betz optimal blade as the theoretical reference and the polynomial-fitted blade as the comparative baseline, and systematically conducts aerodynamic performance analysis within the Blade Element Momentum framework. The research is carried out progressively as follows: first, the necessity of the Prandtl/Glauert correction models for improving BEM calculation accuracy is verified; second, the Bezier curve fitting method is determined as the blade modeling approach; finally, based on the selected blade model and correction method, the influence laws of operating parameters such as pitch angle on blade aerodynamic performance are systematically analyzed, forming a complete research chain from blade modeling to operational optimization [5].

This paper focuses on the aerodynamic design and performance optimization of wind turbine blades. By employing the Blade Element Momentum theory with Prandtl and Glauert corrections, this study compares Bezier curve and polynomial parameterization methods, identifies the advantages of the Bezier-fitted blade in improving aerodynamic efficiency, and quantitatively analyzes the influences of tip speed ratio and pitch angle on wind turbine power performance. The research forms a complete framework from blade geometry modeling and theoretical correction validation to operational parameter optimization, which can provide theoretical support and practical reference for the high-efficiency design and engineering application of wind turbine rotors.

2. Methodology

2.1. Blade element momentum

The aerodynamic performance of the wind turbine rotor is predicted using Blade Element Momentum (BEM) theory. The rotor blade is divided into several independent annular segments along the spanwise direction, where each segment is treated as a blade element. For each element, the local inflow angle, angle of attack, and corresponding lift and drag coefficients are determined iteratively [6]. The aerodynamic forces are integrated radially to compute the thrust, torque, and power coefficients of the entire rotor. Prandtl tip and root loss corrections as well as Glauert correction for heavily loaded conditions are applied to improve the accuracy of the prediction.

2.2. BEM correction models

The Prandtl tip and root loss correction accounts for the three-dimensional flow effects around the blade tip and root, where the blade loading is reduced due to spanwise leakage and vortex shedding. This correction factor is applied to scale the aerodynamic forces and induction factors, restoring the accuracy of the BEM theory for finite-bladed rotors.

The Glauert correction modifies the momentum theory relationship for highly loaded rotors, where the axial induction factor exceeds the threshold for ideal momentum theory. It provides a continuous empirical correction to avoid non-physical predictions and ensures stable convergence of the BEM algorithm in heavily loaded operating states [7].

2.3. Blade geometry parameterization

To investigate the effects of blade shape representation on rotor performance, polynomial functions and Bézier curves are adopted to parameterize the chord and twist distributions along the blade span. Polynomial parameterization provides a simple and computationally efficient means of defining smooth spanwise variations, with coefficients directly determining the overall geometry. Bézier curves, by contrast, offer greater geometric flexibility through control points, enabling smooth and physically realistic blade profiles suitable for aerodynamic design and comparison studies. Both methods are used interchangeably to evaluate how different parameterization strategies influence the accuracy and convergence of the aerodynamic predictions.

The Betz optimum blade distribution is also implemented as a theoretical reference configuration. Derived from ideal flow conditions and maximum theoretical energy extraction, this geometry represents the theoretical performance limit of a horizontal-axis wind turbine rotor. However, such idealized loading assumes uniform, loss-free flow, which significantly deviates from real three-dimensional flow phenomena [8]. By comparing numerical results obtained from the ideal Betz blade with corrected predictions, the importance of Prandtl tip–root losses and Glauert high-loading corrections is clearly demonstrated, as neglecting these effects leads to considerable overprediction of thrust and power coefficients [9].

2.4. Main parameters of wind turbine

Table 1 summarizes the key design parameters of the horizontal-axis wind turbine adopted in this study. The rotor has a radius of 50 m and a hub radius of 10 m, with 3 blades and a DU-95-W-180 airfoil profile. The design wind speed is set to 10 m/s, and the air density is taken as the standard sea-level value of 1.225 kg/m³, which serves as the fundamental input for the subsequent BEM-based aerodynamic performance calculation [10].

Table 1. Wind turbine parameters

Parameter	Value
Rotor Radius	50m
Hub Radius	10m
Number of Blades	3
Design Wind Speed	10m/s
Air Density	1.225 kg/m³
Airfoil Type	DU-95-W-180

3. Results and discussion

3.1. Necessity of correction models

Figure 1 illustrates the effect of Prandtl tip/root loss and Glauert high-loading corrections on the power coefficient (C_p) prediction for a Betz-optimized wind turbine rotor, across tip speed ratios (λ) from 5 to 12. The uncorrected results (red dashed line) represent the ideal theoretical limit, yielding significantly higher C_p values (ranging from ~0.506 to 0.528) that consistently overestimate the rotor's actual power capture capability. In contrast, the corrected results (blue solid line) account for real three-dimensional flow effects, producing physically realistic C_p curves with a peak value of approximately 0.49 at $\lambda = 8$, which aligns with practical wind turbine performance characteristics.

The substantial discrepancy between the two curves clearly demonstrates the necessity of incorporating aerodynamic corrections in BEM-based simulations. Neglecting these corrections leads to severe overprediction of power output. The corrected model, by contrast, provides accurate and reliable predictions that reflect real-world wind turbine aerodynamics, which is critical for validating rotor design and performance optimization.

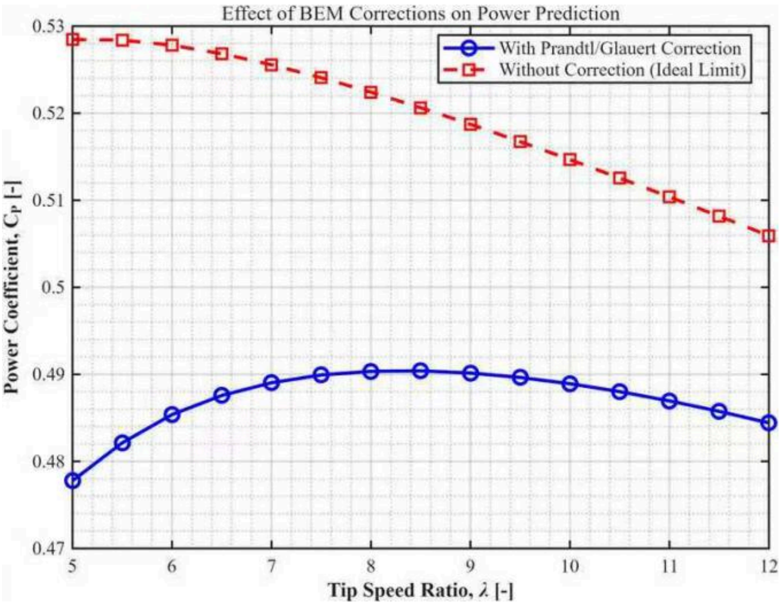

Figure 1. Comparison of the impact of corrections on results

3.2. Selection of blade parameterization methods

Figure 2 presents a performance comparison of two blade parameterization methods—Bézier profile and polynomial profile—for the wind turbine rotor, evaluated across tip speed ratios (λ) from 5 to 12. The Bézier parameterization (blue solid line) consistently delivers significantly higher power coefficients (C_p) across the entire operating range, with a peak C_p of approximately 0.47 at $\lambda = 6$, maintaining values above 0.39 even at the highest tip speed ratio of 12. In contrast, the polynomial profile (green dashed line) exhibits substantially lower aerodynamic efficiency, with a peak C_p of only ~0.42 at $\lambda = 5$, and a continuous, steep decline to just ~0.29 at $\lambda = 12$.

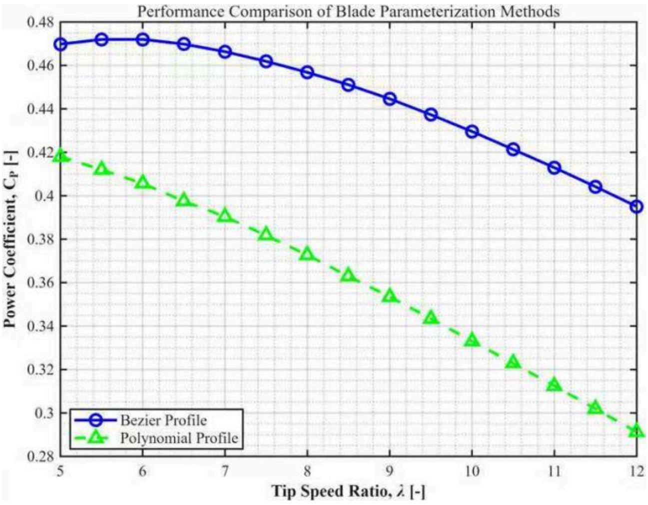

Figure 2. Performance comparison of blade parameterization methods

This pronounced performance gap demonstrates the clear superiority of the Bézier curve method for blade geometry design. The Bézier parameterization enables a more flexible and smooth description of spanwise chord and twist distributions, which better aligns with the optimal aerodynamic loading required for high energy capture. The polynomial method, by contrast, is limited by its rigid, global fitting characteristics, which fail to accurately replicate the ideal blade shape, resulting in severe underperformance, especially at high tip speed ratios. These findings confirm that the choice of blade parameterization method has a critical impact on wind turbine power performance, with the Bézier profile being the more suitable option for high-efficiency rotor design. Subsequent blade parameterization in this study adopts the Bézier curve method.

Figure 3 presents the spanwise chord length and twist angle distributions defined by the Bézier curve parameterization, normalized by the rotor radius (r/R). The chord length decreases smoothly from approximately 7.5 m at the blade root ($r/R = 0.2$) to 2.2 m at the tip ($r/R = 1$), following a continuous, physically realistic gradient that matches the aerodynamic loading requirements of a large-scale wind turbine blade. The twist angle exhibits a similar smooth trend, starting at 15° near the hub and gradually decreasing to -5.5° at the tip, which effectively equalizes the local angle of attack along the blade span, optimizing aerodynamic efficiency across the entire rotor. This parameterization ensures a continuous, smooth blade geometry free of abrupt changes, which is critical for accurate aerodynamic performance prediction.

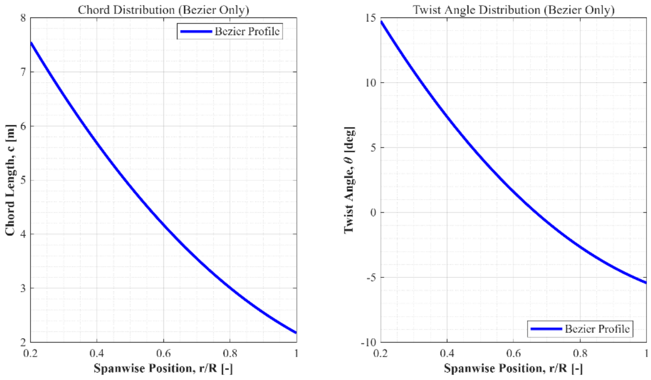

Figure 3. Bézier-defined spanwise chord and twist distributions

3.3. The impact of pitch angle on aerodynamic performance

Figure 4 illustrates the combined effects of pitch angle and tip speed ratio (λ) on the power coefficient (C_p) of the wind turbine rotor. Across all tested pitch angles, C_p exhibits a consistent downward trend as λ increases from 6 to 10, indicating that rotor aerodynamic efficiency degrades when the rotational speed deviates from the optimal operating condition. Notably, the pitch angle has a profound impact on both the magnitude and sensitivity of C_p : at a given λ , C_p increases significantly with rising pitch angle within the range of 0° to 6°. For instance, at $\lambda = 6$, the C_p for 6° pitch reaches ~0.46, while the 0° pitch case only achieves ~0.44; at $\lambda = 10$, the gap widens dramatically, with the 6° pitch maintaining a C_p of ~0.35, whereas the 0° pitch drops to merely ~0.13.

This performance discrepancy arises from the direct influence of pitch angle on the local angle of attack along the blade span. A moderate increase in pitch angle optimizes the inflow angle and aerodynamic loading, particularly at high λ , effectively mitigating flow separation and power loss. In contrast, a 0° pitch leads to excessive angles of attack at elevated λ , causing severe aerodynamic stall and a sharp decline in C_p . These results demonstrate that pitch angle is a critical control parameter for wind turbine performance, and selecting an appropriate pitch angle matched to the operating λ is essential to maximize energy capture and ensure stable rotor operation across varying wind conditions.

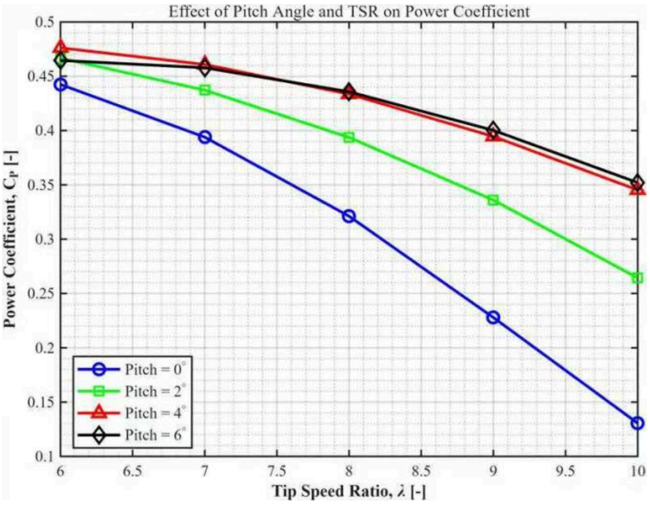

Figure 4. Combined effects of pitch angle and tip speed ratio on power coefficient

3.4. Wind turbine aerodynamic power curve

Figure 5 presents the absolute aerodynamic power curve of the wind turbine rotor across free-stream wind speeds from 4 m/s to 12 m/s, calculated based on a 50 m rotor radius, standard air density of 1.225 kg/m^3, and a maximum power coefficient (C_p) of 0.4762. The power output exhibits a clear cubic growth trend with increasing wind speed, rising from approximately 100 kW at 4 m/s to nearly 4000 kW at 12 m/s, which aligns with the fundamental aerodynamic principle that wind power is proportional to the cube of wind velocity. The curve demonstrates the rotor's consistent energy capture performance across the typical operating wind speed range, with the peak C_p of 0.4762 indicating high aerodynamic efficiency achieved by the optimized Bézier-parameterized blade design. This power curve serves as a key performance indicator for the wind turbine, validating the rationality of the rotor design and providing a basis for power output prediction under real-world wind conditions.

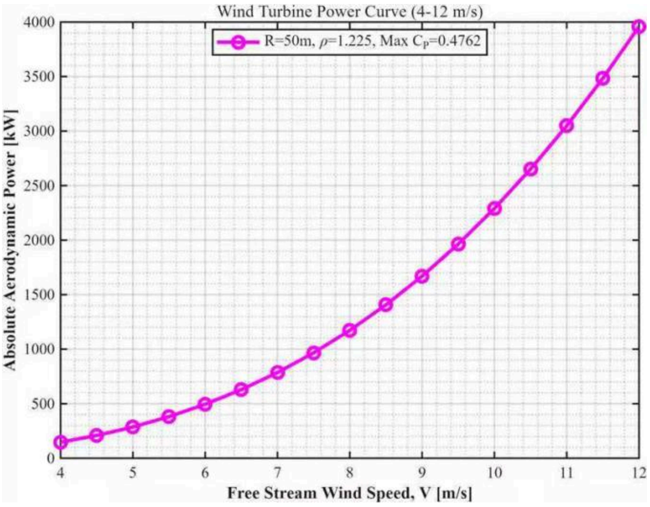

Figure 5. Wind turbine power curve

4. Conclusion

This study systematically investigated the aerodynamic performance of a wind turbine rotor based on the Blade Element Momentum (BEM) theory. The necessity of incorporating Prandtl tip/root loss and Glauert high-loading corrections was verified, as the uncorrected ideal Betz model significantly overestimated the power coefficient, while the corrected model yielded physically realistic performance predictions. A comparative analysis of blade parameterization methods demonstrated that the Bézier curve approach outperforms the polynomial method in achieving higher aerodynamic efficiency, with a peak power coefficient of 0.4762, and thus was adopted for all subsequent blade geometry definitions. The effects of pitch angle and tip speed ratio on power performance were further quantified, revealing that appropriate pitch angle tuning is critical for optimizing energy capture across operating conditions. Finally, the wind turbine power curve was derived, confirming the high efficiency of the optimized Bézier-parameterized blade design and providing a reliable reference for practical wind turbine rotor design and performance evaluation.

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