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Design and analysis of a 1 kW Darrieus vertical axis wind turbine with straight composite blades

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Abstract

Currently, energy production from clean sources such as wind is receiving increasing attention from researchers and industry professionals. Vertical axis wind turbines (VAWTs) are a type of wind turbine that is often used for urban and low-power applications. This study aimed to design and analyze a vertical-axis wind turbine. A 1 kW Darrieus-type VAWT with straight blades was aerodynamically and conceptually designed for a region with an average wind speed of 10 m/s. After determining the turbine's dimensions and geometry, the structural design and composite stacking sequence of the blades were developed to withstand extreme wind forces while maintaining blade lightness. This was achieved through an analytical method and the PreComp code. The designed turbine features a rotor diameter of 2.5 m, three blades, a rotational speed of 240 rpm, a blade height of 2.18 m, a chord length of 0.11 m, and an airfoil of DU06-W-200. The blade structure included an optimized sectional composite lay-up, consisting of unidirectional and bidirectional composite materials, a core, bonding layers, and a gel coat. Each blade weighed approximately 600 g, showcasing the advantages of using composite materials. The structural design, validated through FEA, demonstrated a 3% error.

Keywords: Darrieus VAWT; Aerodynamic-conceptual design; Structural design; FEA; Composite materials.

1. Introduction

Vertical axis wind turbines (VAWTs) are generally classified into two main categories: Savonius and Darrieus. The Savonius type operates based on drag force, whereas the Darrieus type is driven by lift force. Darrieus turbines exhibit better performance than Savonius turbines, achieving approximately 20% higher efficiency than the Savonius model [1].

Sun et al. [2] designed, simulated, and tested a vertical axis wind turbine (VAWT) of the Darrieus type with blades made of carbon fiber-reinforced composite. This turbine demonstrated self-starting capability and stable operation at low wind velocities, outperforming similar turbines with resin-based blades. However, the study by Sun et al. did not address the optimization of composite lay-up design. Xue et al. [3] conducted a study on the mass optimization of composite blades and the structural design of VAWTs using a parametric finite element model and genetic algorithm optimization, achieving good results. They also proposed using truss structures to connect arms to the central shaft of small wind turbines. Similarly, Wang et al. [4] employed a finite element model and genetic algorithm to optimize parameters such as the number of unidirectional composite layers, spar cap location, and shear web thickness. Their efforts resulted in a 17.4% reduction in turbine weight compared to the initial design. Castro et al. [5] investigated and simulated a VAWT with eco-friendly, biodegradable fique/epoxy composite blades. Their findings indicated that such biodegradable composites could be a viable alternative to traditional glass or carbon fiber composites.

Given the development-oriented trend of vertical axis wind turbines (VAWTs) for low-power urban and residential applications and the research gap in the cost-effective design and analysis of low-power VAWTs, this study aims to present a comprehensive design and analysis process for a low-power Darrieus-type VAWT with straight blades. The aerodynamic and conceptual design process is initiated by considering the average wind velocity and the required output power as design inputs. Key design parameters, including blade solidity, number of blades, pitch angle, blade aspect ratio, and airfoil type, are determined.

Once the turbine's geometric parameters are established, the structural design of the blades and the optimization of composite lay-up for the turbine blades are carried out, taking into account the various blade components, their roles, and their performance requirements. Following the structural design, finite element analysis (FEA) of the designed blade is conducted using the commercial software Abaqus to validate the proposed design and extract critical results.

2. Design and optimization process

In the aerodynamic-conceptual design of the vertical axis wind turbine, the following parameters need to be determined:

Solidity represents the ratio of the total blade area to the swept area of the turbine and is defined by the following equation:

$$\sigma = \frac{Nc}{R} \tag{1}$$

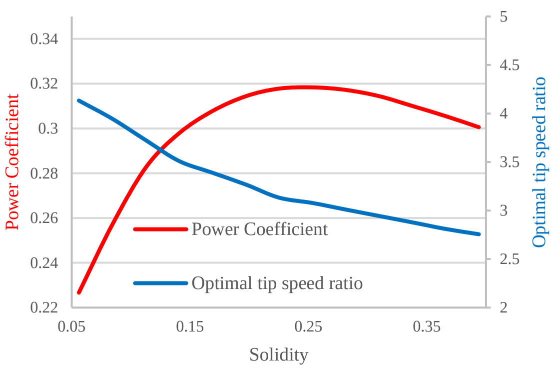
where N, c, and R denote the number of blades, blade chord length, and turbine radius, respectively. This parameter essentially indicates the tip speed ratio at which the turbine achieves its maximum efficiency [6]. The blade tip speed ratio is another critical design parameter for wind turbines and is defined by the following equation:

$$\lambda = \frac{R\omega}{U_\infty} \tag{2}$$

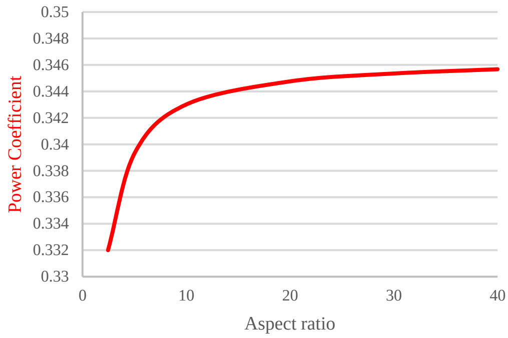
where R, ω, and U_∞ represent the rotor radius, the rotational speed of the rotor, and the wind velocity, respectively. The power coefficient indicates the efficiency and performance of a wind turbine and is expressed by the following equation:

$$C_P = \frac{P_{gen}}{0.5\rho A V^3} \tag{3}$$

where P_{gen} is the power extracted by the turbine, ρ is the air density, A is the swept area of the turbine, and V is the wind speed. Figure 4 illustrates the effect of blade solidity and aspect ratio on the performance of the wind turbine, which helps in selecting the unknown design parameters. The pitch angle, aspect ratio, and airfoil type must also be determined to complete the turbine's specifications.



(a)



(b)

Figure 1. The effect of (a) solidity and (b) aspect ratio of the blade on the turbine performance [7].

The design of a blade requires a compromise between aerodynamic and structural considerations. Wind turbine blades are made of composite materials with various components and properties, resulting in lighter and longer blades with an optimized aerodynamic shape. Figure 2 shows the appropriate structural layout for composite turbine blades to withstand the forces generated by the wind.

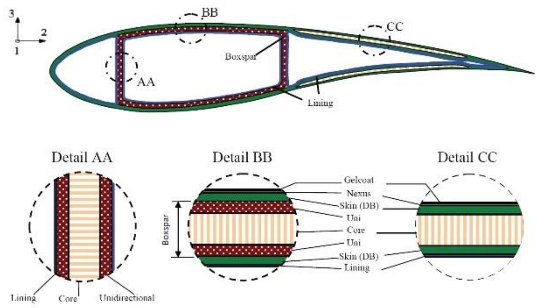


Figure 2. The composite structural lay-up at a section of the blade [8].

The IEC 61400-01 standard specifies the safety requirements for wind turbines. This standard provides a table that can be used to select the critical wind speed for a region based on classification and the average wind speed for design and analysis purposes. Subsequently, with the wind speed available, the drag force can be calculated. With the drag force available, the safety factors provided by the Germanischer Lloyd standard and the material's allowable strains will serve as the appropriate failure criteria.

By modeling the turbine blade as an Euler beam and using the allowable strains of the materials, the required bending stiffness for the blade is obtained. Using the PreComp [9] code and employ a trial-and-error method to determine the optimal blade lay-up by comparing the number of layers in different sections of the blade.

3. Results and Discussion

Figure 1-a shows that the turbine achieves the highest

efficiency with a solidity of 0.263 at a tip speed ratio of 3.14. Additionally, as shown in Figure 4-b, as the blade aspect ratio increases beyond 20, the performance growth rate decreases significantly. Therefore, the optimal blade aspect ratio is considered to be 20. By substituting the values into equations (1) to (3) and the blade aspect ratio and solving the resulting system of equations, the unknown geometric parameters of the conceptual design are obtained. The specifications of the designed wind turbine are presented in Table 1.

Table 1. Final specifications of the designed wind turbine.

Turbine type	H-Type Darrieus	
Airfoil	DU06-W-200	
Output power	P (kW)	1
Rotor diameter	D (m)	2.5
Number of blades	N	3
Pitch angle	λ (degree)	-2
Rotor angular velocity	Ω (rpm)	240
Wind velocity	U_∞ (m/s)	10
Height of blade	H (m)	2.18
The Chord length of the blade	c (m)	0.11
Tip speed ratio	λ	3.14
solidity	σ	0.263

With the geometric specifications of the blade, the drag force can be calculated using the previous information. For an average wind speed of 10 m/s, a critical wind speed of 70 m/s is considered. Based on the blade geometry of this turbine, the drag coefficient can be approximated, assuming the blade is treated as a flat plate. Given the blade height-to-chord ratio of 20, the drag coefficient for this blade is 1.5. The applied drag force on the pressure side of the turbine blade is 1.457 kN. By dividing this force by the height, the distributed force along the height is calculated to be 668.35 N/m. The turbine blade can be modeled as a beam with two simple supports and a distributed applied force. According to the shear force and bending moment diagrams derived from the free body diagram of the assumed beam, the maximum bending moment applied to the blade is 79.41 N.m, which acts on the midsection of the blade.

Considering the minimum allowable strain of the material along the longitudinal direction and using the Euler beam equation, the required bending stiffness around the axis aligned with the airfoil chord is EI = 167 N.m^2. Since the number of layers for the core material and the unidirectional layers is unknown, it is necessary to determine the lay-up through trial and error. Several attempts using the PreComp code can be made to achieve a lay-up that, with the least mass, maintains a bending stiffness higher than the required value. Since the PreComp code provides output in a fraction of a second, an optimal design can be achieved with minimal time cost. In contrast, finite element software has higher time and financial costs and does not provide an exact (analytical) solution.

Based on the results from the PreComp code, the optimized lay-up for the blade is when the main beams consist of four unidirectional layers, two bidirectional layers, and one core layer. Additionally, the shear webs consist of two unidirectional layers. The leading edge consists of one bidirectional layer, and the trailing edge consists of two bidirectional layers. Based on this lay-up, the mass of each blade is 594 grams.

A finite element analysis was performed on the designed blade. All the failure criteria extracted from the finite element analysis indicate that the blade will be safe under the applied loading, and the design based on the analysis and PreComp code is validated with a 3% error.

4. Conclusions

In this study, critical aerodynamic parameters were optimized for a wind speed of 10 m/s and an output of 1 kW. The turbine's solidity was set to 0.263, with a tip speed ratio of 3.14, three blades, and a pitch angle of -2 degrees. The optimal aspect ratio was 20, and the DU 200-W-06 airfoil was selected. Blade dimensions included a height of 2.18 meters, a chord length of 11 cm, a rotor diameter of 2.5 meters, and a rotational speed of 240 rpm.

The structural design used the PreComp code to optimize the composite lay-up, considering components like the spar cap, sides, and shear webs. The blade weight was 600 grams, and finite element analysis confirmed the safety and accuracy of the design with a 3% error.

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