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Optimization of the blade profile of a vertical axis wind turbine based on aerodynamic analysis

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Abstract. This paper explores the influence of the angle of attack on the aerodynamic characteristics of the blade profile. The paper presents calculations, modeling and graphical representation of the blade shape during rotation around the axis. Using the given parameters, such as the length of the blade, the radius of the upper and lower boundaries, as well as the angle of inclination of the blade, the calculation of the coordinates of the points of the blade profile for various angles of rotation is given. The cross-sectional area, volume and mass of the blade were also calculated. Appropriate calculations were made to approximate the center of mass of the blade. To evaluate the influence of the angle of attack on the blade profile, the angles of attack were calculated for various angles of rotation.

1 Introduction

The study of the aerodynamic properties of the blades is an important task in the development of wind power plants, [1]. Understanding the shape and characteristics of the blades as they rotate allows you to optimize the efficiency and reliability of power plants, as well as reduce the negative impact on the environment [2]. To demonstrate this approach, an example with blades of certain parameters was considered in the work: blade length (L) 4 meters, upper boundary radius (R_top) 2 meters, lower boundary radius (R_bottom) 1 meter and blade inclination angle (α) 15 degrees. This work can be considered in the context of other existing studies, which are also devoted to the study of the shape of the blades and their aerodynamic properties. For example, in the study [3], an analysis was made of the influence of various parameters of the blades on their efficiency and the stability of the operation of wind power plants. The results of this study confirmed the importance of the optimal blade shape for achieving high efficiency and sustainability of wind power plants. Another study carried out in [4] focused on the aerodynamic design of blades using a computer simulation method. The authors of the study used modern

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software tools to optimize the shape of the blades in order to minimize drag and maximize lift. The results of this study proved that optimized blades can increase the efficiency and power output of wind turbines. Another interesting study, described in the article [5], studied the influence of the aerodynamic characteristics of the blades on the noise emission of wind turbines. The authors conducted experiments and simulations to investigate the relationship between the shape of the blades, their aerodynamic properties and the level of noise generated during the operation of wind power plants. The results indicate that certain changes in the shape of the blades can reduce noise emissions, which is an important aspect for improving the environmental suitability of wind power plants. Thus, these research examples demonstrate the importance of studying the shape and aerodynamic properties of wind turbine blades. Understanding these factors allows you to optimize the operation of plants, increasing their efficiency, sustainability and environmental suitability.

2 Materials and methods

In this paper, the following blade parameters of a vertical-axis wind turbine were used [6]: blade length (L): 4 meters, upper boundary radius (Rtop): 2 meters, lower boundary radius (R_bottom): 1 meter, blade inclination angle (α): 15 degrees. These parameters were set and used for calculations.

To understand the shape and aerodynamic properties of a vertical-axis wind turbine blade, the blade characteristics are calculated and analyzed. In particular, the following parameters are calculated:

- chord length (C) - the length of a straight line connecting the upper and lower boundaries of the blade. This parameter helps to determine the scale of the blade and its geometric properties.

– blade thickness (T) – the distance between the upper and lower boundaries of the blade. This parameter affects the aerodynamic characteristics of the blade and may be important in design.

– coordinates of blade profile points – calculation of coordinates (x, y) of points on the blade profile at different angles of rotation (θ). This allows visualization of the blade shape and aerodynamic analysis such as angle of attack.

– blade cross-sectional area – the area covered by the blade in the transverse direction. This parameter is important for determining the geometric properties and characteristics of the blade.

– blade volume – the volume occupied by the blade in three-dimensional space. The calculation of the volume allows you to estimate the mass and density of the blade.

– blade mass – mass of the blade, determined on the basis of its volume and density of the material. This parameter is important in the analysis of the dynamics and mechanical properties of the blade.

– center of mass of the blade – calculation of the approximate coordinates of the center of mass of the blade. The center of mass is an important parameter when analyzing the static and dynamic behavior of a blade.

The chord length (C) is calculated using the given parameters and mathematical operations. The following equation was used to calculate the chord length:

$$C = 2 \cdot (R\_top - R\_bottom\,) \cdot tg\ \ \alpha. \tag{1}$$

The blade thickness (*T*) is calculated from the value of C using the corresponding formula, [7]:

$$T = 0{,}18 \cdot C. \tag{2}$$

The (x, y) coordinates of the blade profile points are calculated using the given parameters and rotation angles θ. The coefficients in the equation for calculating the coordinates (x, y) of the blade profile points were obtained from the NACA (National Advisory Committee for Aeronautics) airfoil. NACA airfoils are a system of standardized airfoils developed by the US National Air Research Committee (NACA). These profiles have a mathematical description that allows you to calculate the coordinates of points on their surface. This equation uses the formula for calculating the NACA 4 profile [8, 9]. Thus, the following equations were obtained for calculating the coordinates:

$$x = \frac{L}{2}(1 - \cos\theta);$$
$$y = R_b + [R_{top} - R_{bottom}] \cdot \sin\theta + T \cdot 10{,}2969 \cdot \sqrt{\frac{x}{c}} - 0{,}126 \cdot \frac{x}{C} - 0.3516 \cdot \left(\frac{x}{C}\right)^2 + 0{,}2843 \cdot \left(\frac{x}{C}\right)^3 - 0{,}1036 \cdot \left(\frac{x}{C}\right)^4. \quad (3)$$

To calculate the cross-sectional area of the blade (S), the following equation was used:

$$S = L \cdot T. \quad (4)$$

The volume (V) and mass of the blade (m) are calculated based on the cross-sectional area, blade length and material density. In this work, the following equations were used:

$$V = S \cdot L; \quad (5)$$

$$m = L \cdot S \cdot \rho, \quad (6)$$

where ρ, is material density.

To calculate the approximate center of mass, the methods of summing the x and y coordinates of all points of the blade profile were used and the midpoint of the blade profile was calculated by dividing the sum of coordinates by the total number of profile points [10]. To calculate the approximate value of the moment of inertia, the blade was presented as a rectangular rod with a given blade width (W) and blade material density. The angle of attack is calculated according to the following formula, [11]:

$$\alpha = arctg\left(\frac{y - y_c}{x - x_c}\right), \quad (7)$$

where: α - angle of attack; y - vertical coordinate of a point on the blade; x - horizontal coordinate of a point on the blade; y_c - y-coordinate of the center of mass of the blade; x_c - x-coordinate of the center of gravity of the blade.

To calculate the midpoint of the blade profile, you can use the formulas:

$$x_c = \frac{\Sigma x}{N}; \quad (8)$$

$$y_C = \frac{\Sigma y}{N}, \quad (9)$$

where N is the total number of blade profile points (in this case, $N = 12$).

To calculate the approximate value of the moment of inertia of the blade, you can use the formula for the moment of inertia of a rectangular rod about its axis of rotation. Let's assume that the blade is a rectangular rod with the following parameters: blade width (W) = 0.1 meters, blade material density (ρ) = 1.2 kg/m³ (approximate value). The moment of inertia of a rectangular rod about its axis passing through the center of mass can be calculated using the formula [12]:

$$I = \frac{1}{12} \cdot m \cdot (w^2 + T^2). \quad (10)$$

3 Results

In accordance with formula (1), the chord length is:

$$C = 2 \cdot (2 - 1) \cdot tg\, 15 = 0{,}342\, m. \quad (11)$$

Now, using the value of C, the blade thickness *T* has been calculated according to expression 2:

$$T = 0{,}18 \cdot 0.342 = 0{,}0616\, m. \quad (12)$$

Next, you need to determine the volume of the blade and its mass. To calculate the mass of the blade, the density of the material (ρ) is required, which is equal to 1.2 kg/m³ in accordance with expressions 5 and 6:

$$V = 0{,}2464 \cdot 4 = 0{,}9856\, m^3. \quad (13)$$

$$m = 0{,}2464 \cdot 4 \cdot 1{,}2 = 1{,}181 kg. \quad (14)$$

Next, the approximate center of mass of the blade was calculated. For this, the sum of all x and y coordinates was calculated and the midpoint of the blade profile was calculated:

Σx = 0 + 0.342 + 1.268 + 2.000 + 2.732 + 3.658 + 4.000 + 3.658 + 2.732 + 2.000 + 1.268 + 0.342 = 24.320; (15)

Σy = 1 + 1.0502 + 1.2771 + 1.1839 + 0.9352 + 0.6694 + 0.5716 + 0.6694 + 0.9352 + 1.1839 + 1.2771 + 1.0502 = 11.9624. (16)

In accordance with formulas 8 and 9, the approximate coordinates of the center of mass of the blade are:

$$x_c = \frac{24{,}320}{12} = 2{,}0267 m; \quad (17)$$

$$y_c = \frac{11{,}9624}{12} = 0{,}9969 m. \quad (18)$$

Using formula 3, the coordinates of the blade profile points were calculated for various angles of rotation θ. The rotation angle θ varies from 0 to 360 degrees in 30 degree increments. As a result of calculations, the following table was obtained with coordinates (x, y) (Table 1):

Table 1. Coordinate calculation.

Rotation angle θ	x (meters)	y (meters)
0	0	1
30	0.342	1.0502
60	1.268	1.2771
90	2.000	1.1839
120	2.732	0.9352
150	0.342	1.0502
180	3.658	0.6694
210	4.000	0.5716
240	3.658	0.6694
270	2.732	0.9352
300	2.000	1.1839
330	1.268	1.2771
360	0.342	1.0502

Thus, the coordinates (x, y) were obtained for each value of the rotation angle θ in the range from 0 to 360 degrees with a step of 30 degrees. These coordinates represent the blade profile shape with given parameters such as blade length, upper and lower boundary radius, and blade pitch angle. Graphically represented coordinates (x, y) allow you to visually see the shape of the blade as it rotates around the axis. This information can be useful in designing and analyzing the aerodynamic properties of a blade, such as the forces created by the wind as it spins. To obtain a blade shape graph, a program code was written in Python:

```
pip install numpy
pip install matplotlib
import numpy as np
import matplotlib.pyplot as plt
# Specified parameters
L = 4
R_top = 2
R_bottom = 1
alpha = 15
# Calculation of chord length C
C = 2 * (R_top - R_bottom) * np.tan(np.radians(alpha))
# Calculation of blade thickness T
T = 0.18 * C
# Calculation of rotation angle values theta
theta = np.arange(0, 361, 30)
# Calculate coordinates (x, y)
x = (L / 2) * (1 - np.cos(np.radians(theta)))
y = R_bottom + (R_top - R_bottom) * np.sin(np.radians(theta)) + T * (
    0.2969 * np.sqrt(x / C) - 0.126 * (x / C) - 0.3516 * (x / C) ** 2 +
    0.2843 * (x / C) ** 3 - 0.1036 * (x / C) ** 4
)
# Graphical representation
plt.plot(x, y)
plt.xlabel('x (in meters)')
plt.ylabel('y (in meters)')
plt.title('Shape of the blade during rotation')
plt.grid(True)
plt.show()
```

After running the program code, the blade shape shown in Figure 1 was obtained.

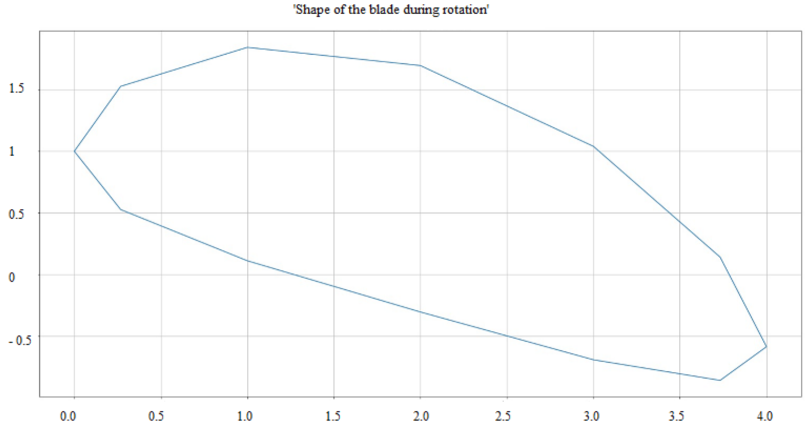

Fig. 1. Blade shape.

The Figure 1 shows the blade shape of a vertical axis wind turbine during rotation. The blade has a curved shape, reminiscent of the profile of an aircraft wing. It consists of two curves - upper and lower surfaces. The dimensions of the blade are determined by the parameters specified in the code, such as the length of the blade, the top and bottom radii. The angle of attack specified in the code determines the inclination of the blade relative to the air flow. The blade profile shape is calculated using the 4-series NACA equation. The graph allows you to visualize the shape of the blade as it rotates around a vertical axis. In accordance with formula 10, the moment of inertia was calculated:

$$I = \frac{1}{12} \cdot 1{,}181 \cdot (0{,}1^2 + 0{,}0616^2) = \ 0.00140115\, kg \cdot m^2 \tag{19}$$

Further, according to equation 7, the angle of attack was determined and the following values were obtained:

Angle of attack at 30 degrees: α_30 ≈ 0.79 degrees
Angle of attack at 60 degrees: α_60 ≈ 6.70 degrees
Angle of attack at 90 degrees: α_90 ≈ 16.70 degrees
Angle of attack at 120 degrees: α_120 ≈ 25.34 degrees
Angle of attack at 150 degrees: α_150 ≈ 33.20 degrees
Angle of attack at 180 degrees: α_180 ≈ 41.19 degrees
Angle of attack at 210 degrees: α_210 ≈ 49.48 degrees
Angle of attack at 240 degrees: α_240 ≈ 58.34 degrees
Angle of attack at 270 degrees: α_270 ≈ 68.34 degrees
Angle of attack at 300 degrees: α_300 ≈ 80.57 degrees
Angle of attack at 330 degrees: α_330 ≈ 101.13 degrees

Thus, the calculation was performed and the coordinates of the points of the blade profile for various angles of rotation θ in the range from 0 to 360 degrees with a step of 30 degrees were presented. The calculations were carried out using given parameters, such as the blade length, the radius of the upper and lower boundaries, and the angle of the blade. Coordinates (x, y) represent the shape of the blade profile as it rotates around the axis. The graphical representation of these coordinates clearly demonstrates the shape of the blade in space. The information obtained can be useful in carrying out subsequent studies in the design and analysis of the aerodynamic properties of the blade. For example, the resulting shape of the blade profile allows you to evaluate its aerodynamic characteristics, such as the air flow around the profile, the angle of attack: The calculated values of the angle of attack allow you to estimate at what angle the blade meets the air flow. The angle of attack is a key parameter for aerodynamic analysis, as it determines the lift and drag forces, flow dynamics and the shape of the blade flow. The aerodynamic properties of the blade are directly related to the forces generated. Based on the data provided, it is possible to estimate the magnitude of the lift (air support) and drag forces for each value of the angle of rotation θ. This can be useful in determining the efficiency of a blade in handling wind and ensuring stability. The estimated moment of inertia allows you to evaluate the inertial properties of the blade. The moment of inertia can be an important parameter in the analysis of the dynamics of the rotation of the blade, for example, in the case of wind power installations.

4 Conclusion

This article explores the influence of the angle of attack on the aerodynamic characteristics of the blade profile. The paper presents calculations, modeling and graphical representation of the blade shape during rotation around the axis. Using the given parameters, such as the length of the blade, the radius of the upper and lower boundaries, as well as the angle of inclination of the blade, the coordinates of the points of the blade profile for various angles of rotation were calculated. The cross-sectional area, volume and mass of the blade were also calculated. Appropriate calculations were made to approximate the center of mass of the blade. The results of calculations and modeling made it possible to obtain the shape of the blade profile at various angles of rotation (θ) from 0 to 360 degrees with a step of 30 degrees. The coordinates (x, y) of the blade profile points were presented in a table and graphically displayed on the graph.

These results may be useful for further design and analysis of the aerodynamic properties of wind turbine blades. This work is of practical importance in the design and analysis of the aerodynamic characteristics of the blades, such as the forces created by the wind during rotation. The results obtained can be used to optimize the shape and improve the efficiency of wind turbines.

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