Design and Experiment of a Double-Layer Vertical Axis Wind Turbine

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Abstract. This paper introduces the design and experiment of a double-layer vertical axis wind turbine. This system is mainly oriented to the polar environment as a supplement for mobile robot energy. Firstly, the aerodynamic performance of the wind turbine structural parameters is numerically simulated using CFD software combined with the Uniform Design Experimentation method, the system uses NACA4412 blades to form a double-layer wind turbine. Secondly, ANSYS software is used for modelling and verifying the structure of the main components of the wind turbine. A permanent magnet direct-drive synchronous generator is applied to convert mechanical energy into electrical energy, and charges the battery through a circuit. Finally, the prototype is developed and tested. The maximum conversion efficiency of wind energy can reach 24.66% at the wind speed of 7 m/s.

Keywords: Wind turbine · Numerical simulation · Conversion efficiency

1 Introduction

The global energy problem is severe, and the stroke energy of natural energy is almost endless [1]. In particular, the Antarctic has high wind speeds, long durations and large changes in wind direction [13]. Using wind power as a supplement for mobile robot energy will increase the mobile robot's battery life and radius of activity greatly. Most of the existing wind turbines are horizontal axis wind turbines, which have inherent defects, such as poor wind resistance, weak wind resistance and dynamic stall. Thus, in recent years, vertical axis wind turbines have been valued, and they have many advantages [5–12]:

1. The gear box, generator and controller in the vertical axis wind turbine can be placed on the ground with a low center of gravity, convenient maintenance, long life and stable operation;
2. The vertical axis wind turbine is simplified structure because it can feel wind from any direction without yaw device;
3. When the vertical axis wind turbine is running, the tip speed is smaller, cause less noise.

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The purpose of this article is to design a vertical axis wind turbine for mobile robot s used in Antarctica. Firstly, the Blade Element Theory is introduced. Then four NACA airfoils are selected, and the structural parameters of the wind turbine are optimized using CFD software and Uniform Design Experimentation method. The aerodynamic performance is numerically simulated to determine the optimal performance parameters of the wind turbine. Then a 3D model of the vertical axis wind turbine is established and the static simulation is performed. Finally, a prototype is processed for experimental verification.

2 Blade Element Theory

Blade Element Theory (BET) is one of the most basic theories of wind turbines [3, 4] of which idea is to cut the blades of wind turbines into countless segments, and each segment is called foline. It assumes that the flow on each blade element does not interfere with each other, blade elements can be regarded as a two-dimensional airfoil. A cross-section on the blade is taken to study the force of the blade. Generally, foline is used as the research object to analyze the force and moment on the blade. The analysis of the force on the blade is shown below (Fig. 1):

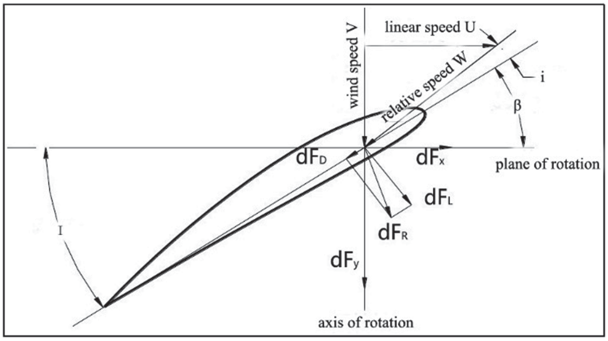

Fig. 1. Analysis of blade stress.

$$dF_L = \frac{1}{2}\rho c W^2 C_l dr \tag{1}$$

$$dF_D = \frac{1}{2}\rho c W^2 C_d dr \tag{2}$$

In the formula above, dF_L is the airfoil lift; dF_D is the airfoil resistance; W is the relative velocity of the airflow to the blade element; L is the airfoil chord length; C_l is the airfoil lift coefficient and C_d is the airfoil drag coefficient; dF_L and dF_D are projected along the axial and circumferential directions of the wind wheel, then we can get:

$$dF_x = dF_L \cos I + dF_D \sin I = \frac{1}{2}\rho LW^2 dr(C_l \cos I + C_d \sin I) \tag{3}$$

$$dF_y = dF_L \sin I - dF_D \cos I = \frac{1}{2}\rho LW^2 dr(C_l \sin I + C_d \cos I) \tag{4}$$

The value of dF_R projected above the axis of rotation of the wind wheel is dF_x, where dF_R is the force acting on the airfoil; the value of dF_R projected along the direction of the rotation surface of the wind wheel is dF_y; I is the gas phase angle, $I = i + \beta$, where i is the airfoil attack angle; β is the installation angle of the blade.

The BET is to divide the whole wind turbine blade into a limited number of leaf elements, find the force and moment on each leaf element, and integrate to obtain the aerodynamic performance of the whole blade. As for the stress performance of leaf element, what we are most concerned about the power is the blade can obtain, which is to maximize the utilization efficiency, so the airfoil characteristics should meet three requirements:

1. Large gradient of lift coefficient;
2. Small drag coefficient;
3. The airfoil can maintain excellent aerodynamic performance during the change of the angle of attack.

3 Numerical Simulation of Aerodynamic Performance of Wind Turbine

3.1 Simulation Analysis Results

Computer Fluid Dynamics (CFD) is a newly developed discipline based on classical fluid dynamics and numerical calculation methods. CFD is used for numerical simulation analysis of fluid dynamics engineering problems, which improves design efficiency greatly [2].

In this paper, a better airfoil is selected by comparing the aerodynamic performance of different airfoils. In the analysis process of optimizing the blade airfoil, the angle of attack is set to 0°, the airfoil and the wind speed are changed. The NACA airfoil is widely used in aerospace and wind energy utilization, so the airfoils NACA0012, NACA0021, NACA4412, NACA23012 are chosen. The lift coefficient C_l, drag coefficient C_d, moment coefficient C_m, and lift-to-drag ratio C_l/C_d of four different airfoils are analyzed when the wind speed varies between 5 and 25 m/s. Figures 2, 3, 4 and 5 show the lift coefficient, drag coefficient, moment coefficient and lift-to-drag ratio of different airfoils at different wind speeds.

As can be seen from the above figures, the lift-to-drag ratio of the NACA4412 is the largest at a wind speed of 5–25 m/s, especially around 17 m/s, its aerodynamic performance is better than other airfoils. NACA4412 has a high lift coefficient and a small drag coefficient, and its excellent aerodynamic performance can be maintained in a large range of angles of attack. Therefore, the NACA4412 is chosen as the blade airfoil of the wind turbine.

3.2 Determination of Other Structural Parameters of the Wind Turbine

After selecting the airfoil, other structural parameters such as the radius, chord length, number of blades and installation angle of the wind turbine are determined by Uniform

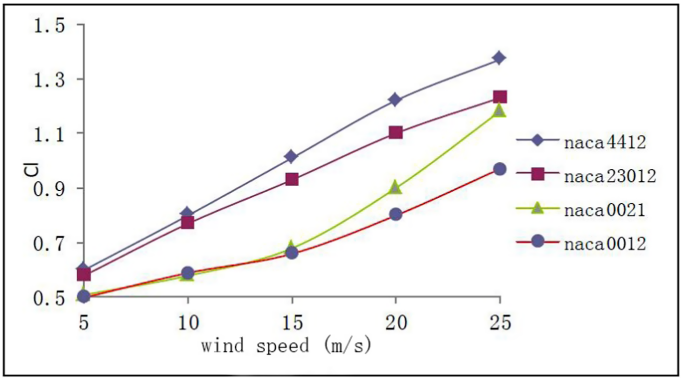

Fig. 2. Curves of lift coefficient.

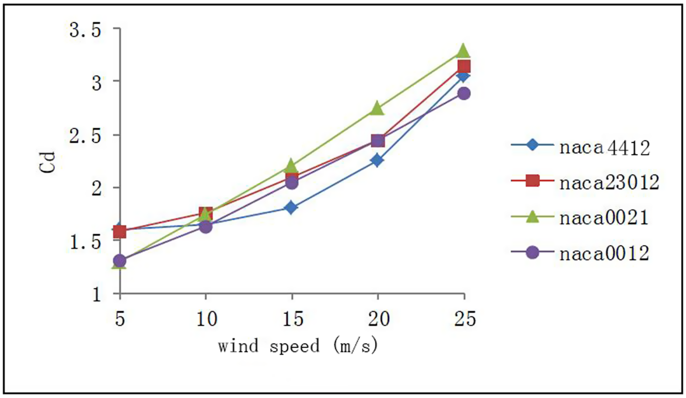

Fig. 3. Curves of drag coefficient.

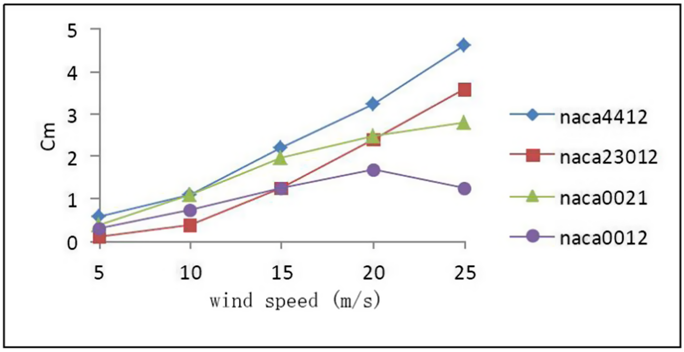

Fig. 4. Curves of moment coefficient.

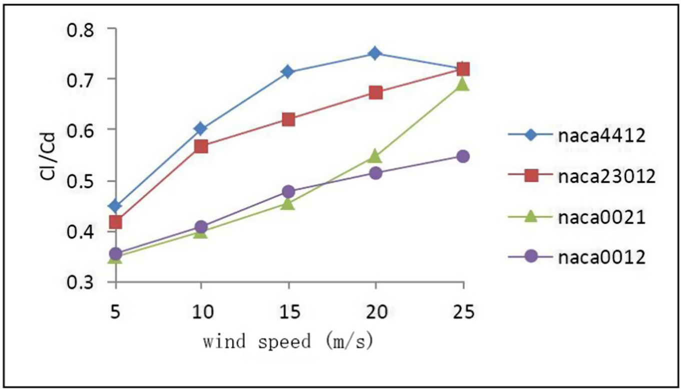

Fig. 5. Curves of lift-to-drag ratio.

Design Experimentation (UDE). Under the principle of UDE, a simulation test is performed according to the selected uniform table, then the response values corresponding to each simulation scheme in the uniform table are calculated. On the basis of each value factor and corresponding response value, a suitable model is established, and the optimal parameter value is theoretically derived. Thus, the number of simulation tests can be effectively reduced and the expected results can be obtained.

For the number of trials, factors and levels that need to be selected, it can find a suitable uniform table in the uniform design table series directly. According to the uniform table, the rule s/2 + 1 = 4 is used to obtain s = 6, and s can be 6 or 7. To enhance the reliability of the results, more test points can be selected. This design uses 4 factors and 12 levels. On the ground of test conditions, each factor is divided into 12 levels for simulation:

Radius (m): 0.25, 0.25, 0.3, 0.3, 0.35, 0.35, 0.4, 0.4, 0.45, 0.45, 0.5, 0.5;

Chord length (meters): 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19;

Number of blade (pieces): 2, 2, 2, 3, 3, 3, 4, 4, 4, 5, 5, 5;

Installation angle (degrees): −10, −8, −6, −4, −2, 0, 2, 4, 6, 8, 10, 12.

The test is arranged with uniform table U12 (1213), then the columns of 1, 6, 8 and 10 are selected to form U12 (124) according to the use table. The 12 levels of each factor are added to the test schedule, as shown in Table 1.

After 12 CFD numerical simulations, the corresponding response value of each analysis is obtained, which is the wind energy utilization rate of the wind turbine. According to the data in the table above, the optimal efficiency of the wind turbine is initially obtained as 36.2%. The wind turbine parameters are: the blade radius of the blade is 0.45 m, the chord length is 0.15 m, the installation angle α is 6°, and the number of blades is 2.

3.3 Data Processing

In order to test the validity of the data obtained by the uniform design, the data needs to be post-processed. Common processing methods include intuitive analysis, modeling, and

Table 1. Uniform design experiment results of wind turbine.

Radio (m)	Chord Length (m)	Number of blade(piece)	Installation angle (degree)	Wind efficiency (%)
0.25	0.13	4	8	20.1
0.25	0.19	2	−2	30.2
0.3	0.12	5	−4	18.2
0.3	0.18	3	−10	23.6
0.35	0.11	2	10	28.7
0.35	0.17	4	4	28.9
0.4	0.10	3	2	26.4
0.4	0.16	5	−8	21.2
0.45	0.09	4	12	24.3
0.45	0.15	2	6	36.2
0.5	0.08	5	0	21.7
0.5	0.14	3	−6	32.1

statistics. Generally, the relationship between the dependent variable and the independent variable is established, then each independent variable in the established relationship is tested for hypothesis. The relationship is established when it conforms to the law of the test, then the test method is valid. There is an error, which needs to increase the test to find the law.

Under the experimental situation, MATLAB calculates the stepwise regression equation of the quadratic model as:

$$E(y) = \beta_0 + \Sigma_{i=1}^{4}\beta_i x_i + \Sigma_{i\leq j}\beta_{ij}x_i x_j \tag{5}$$

Substitute the data analyzed above, then obtain the stepwise regression equation established by simulation after uniform optimization.

$$\begin{aligned} y = 0.0197 &+ 1.0047x_2 + 7.902x_1x_2 - 0.5883x_1x_3 - 2.6021\mathrm{x}_2^2 \\ &+ 0.0723x_2x_3 + 0.0032x_3^2 + 0.001x_3x_4 - 0.0002x_4^2 \end{aligned} \tag{6}$$

Shown in this equation, it is preliminarily judged that the chord length of the wind turbine blade airfoil has a great impact on the entire wind energy utilization rate, followed by the blade installation angle and the number of blades, and the change of the wind wheel radius has the least impact on the wind energy utilization rate.

In order to find the optimal value of each parameter of the wind wheel and the maximum point of simulation, the optimized range should be specified by each parameter of the wind wheel, so as to obtain a set of optimal wind energy utilization values of each parameter. After calculation, when $X_1 = 0.5$, $X_2 = 0.196$, $X_3 = 2.64$, $X_4 = -10$, the stepwise regression equation obtains the maximum value. The radius of the wind wheel is 0.5 m, the chord length of the blade is 0.196 m, the number of blades is about 3, the mounting angle is −10°, and the theoretical wind energy utilization rate is 39.3%.

4 Design of Vertical Axis Wind Turbine

4.1 Wind Turbine Structure

Using INVENTOR software to perform 3D modeling of wind turbines, the model mainly includes: wind turbines, generator and support. The key of structural design is the wind wheel. The overall height of the wind wheel is 0.8 m and the radius is 0.5 m. The wind wheel is designed in two layers, and the angle between the two wind wheels is 60° or 90° respectively, so the wind from any direction can make the wind wheel generate a larger torque, reducing the starting torque of the generator and the starting wind speed. The two-layer wind wheel can accept wind energy to a greater extent, which can improve the effect of wind energy utilization. The height of each layer of the wind wheel is 0.4 m. The wind wheel is composed of blades and the hub, which are bolted together. The axis of the wind wheel coincides with the axis of the generator so that the torque generated by the wind wheel is applied to the generator directly, reducing energy loss in the transmission system. The floor stand supports the wind wheel and overall height of the model is 1.5 m (Fig. 6).

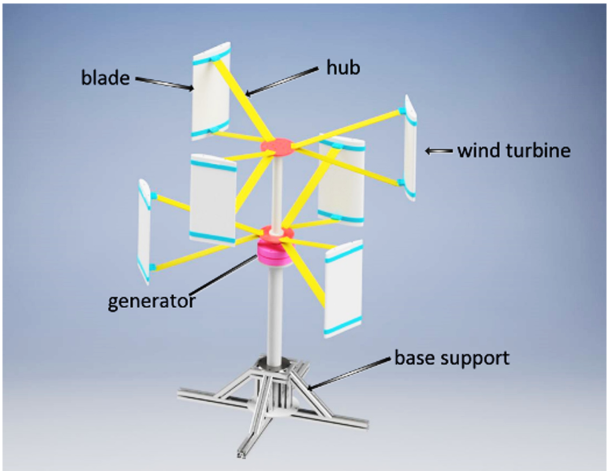

Fig. 6. 3D model of vertical axis wind turbine

4.2 Stress and Deformation Simulation

The static analysis of two-layer wind turbines with two installation angles are performed theoretically to the best wind turbine structure, and verified in the later experimental part. Inventor software is used to draw a 3D model of a 60° double-layer and a 90° double-layer wind turbine. The hub material is defined as structural steel with a density of 7.85, a Young's modulus of 2.0×10^{11} and a Poisson's ratio of 0.3. Applies corresponding loads and fixed constraints to the model.

According to relevant statistics, the average wind speed in Antarctica is 17 m/s and the wind pressure is 180 Pa. In addition to gravity, wind turbine is also affected by unstable aerodynamic forces and other inertial forces. In order to simplify the calculation process, the wind force is vertically loaded on a certain blade [14–17]. After static analysis in ANSYS, the consequences of maximum equivalent stress simulation and deformation simulation cloud diagram are shown in Fig. 7, 8, 9 and 10.

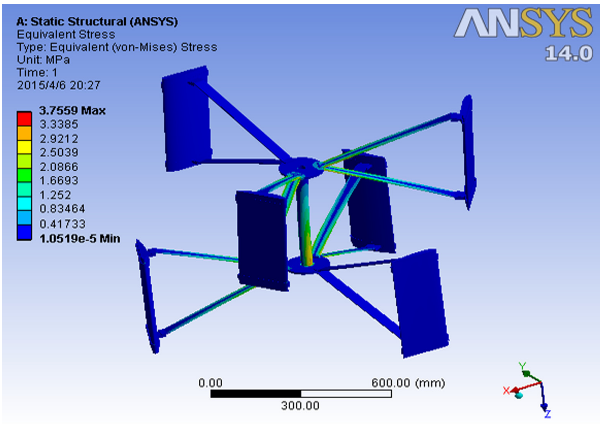

Fig. 7. Equivalent stress simulation at 60° installation

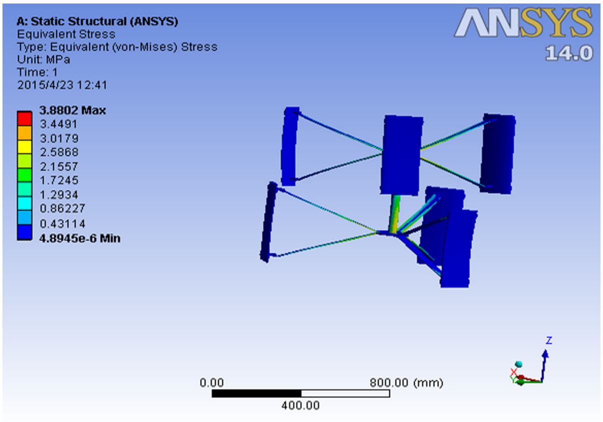

Fig. 8. Equivalent stress simulation at 90° installation

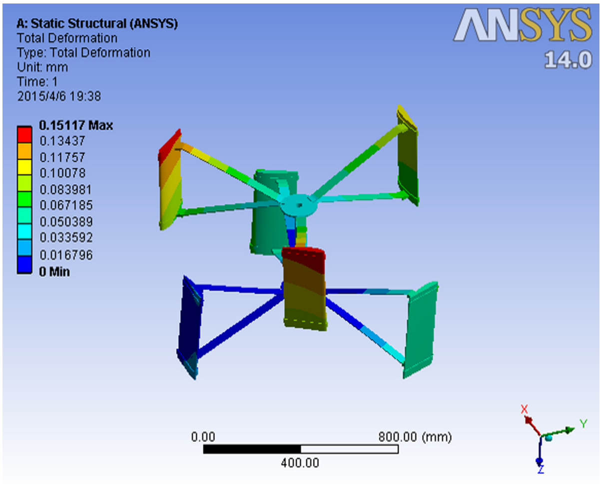

Fig. 9. Deformation simulation at 60° installation

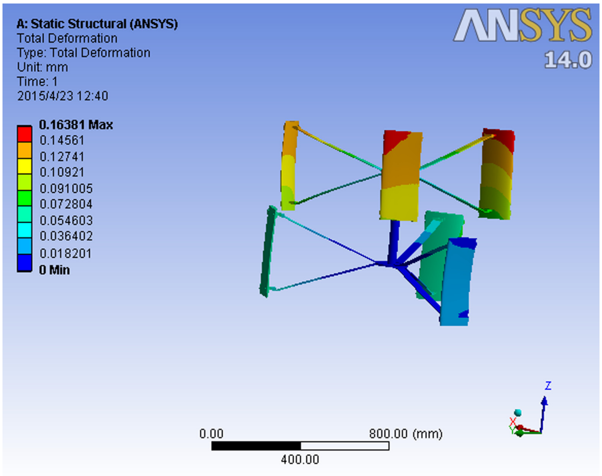

Fig. 10. Deformation simulation at 90° installation

It can be seen from the simulation results that the maximum equivalent stress of the triangular structure hub is 4.4093 MPa and the maximum deformation is 0.1511 mm when installed at 90°, the maximum equivalent stress of the triangular structure hub is 3.7559 MPa and the maximum deformation is 0.1495 mm when installed at 60°. The maximum stress of the two installation methods is far less than the respective yield strength, and neither exceeds the allowable stress, so it meets the strength requirements of the material, which cause no damage when the wind turbine is running.

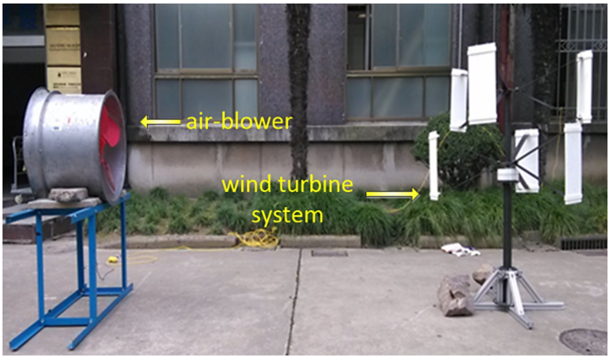

Fig. 11. Experimental platform of vertical axis wind turbine system

5 Prototype Experiment

5.1 Experimental Platform Construction

The experimental platform of vertical axis wind turbine system is mainly composed of wind turbine system and air-blower. A data acquisition platform is also necessary in the experiment. The data acquisition platform mainly includes ammeter, voltmeter, anemometer and speed detection system. The ammeter and voltmeter are used to detect the electrical output of wind turbines. The anemometer can measure wind speed of blower. And the speed detection system measures rotational speed of wind turbine.

5.2 Experiment of Optimal Installation Angle of Blade

A single-layer wind turbine is chosen as an example to verify the CFD numerical simulation and analysis results of blades at different installation angles with changing the different installation angles of the blades to test the experimental data at a constant wind speed, then changing the wind speed to perform an experimental test on the installation angle.

Limited by the experimental conditions, the wind speed in the Antarctic of 17 m/s cannot be simulated. It is intended to test the power and wind efficiency at a test blade installation angle of 0°, 4°,6°, 8°, 10° under a wind speed of 10 m/s. The blade installation angle is adjusted as shown in Fig. 12, the experiment result is shown in Table 2. As can be seen that the optimum installation angle of the blade is 6°.

5.3 Performance Test When the Installation Angle of Double Layer Wind Turbine Is 60° or 90°

Performance of 90° double-layer wind turbine at 1.5 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, 10 m/s wind speed are tested under the 6° blade installation angle to verify the performance of double-layer wind turbines with different installation angles.

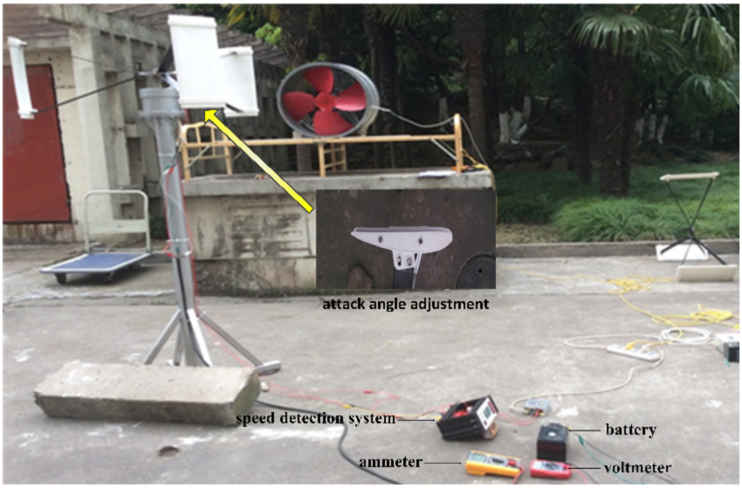

Fig. 12. Experiment of optimal installation angle of blade

Table 2. Experiment result of optimal installation angle of blade

Installation angle (degree)	Rotate speed (r/min)	Output power (w)	Conversion efficiency (%)
0	200	38.4	14.85
4	221	43.2	16.70
6	240	46.5	18.75
8	232	44.1	17.05
10	215	17.05	16.51

Then the Performance of 60° double-layer wind turbine at the same condition are tested to verify the previous theory. The scene of the experiment is shown in Fig. 11. The double-layer 90° installation angle and double-layer 60° installation angle wind turbine are shown in Fig. 13. The performance of the wind turbine is shown in Table 3 and Table 4.

As can be seen from the tables above, performance of the wind turbine at 60° installation angle is better than 90° installation angle, and the maximum conversion efficiency of wind energy is 24.66% at the wind speed of 7 m/s.

Fig. 13. Wind turbines at 90° and 60° double-layer installation angle

Table 3. Performance of the wind turbine at 90° installation angle

Wind speed (m/s)	Rotate speed (r/min)	Output power (w)	Conversion efficiency (%)
1.5	0	0	0
3	87	0.020	0.15
4	121	0.153	0.48
5	170	8.496	13.61
6	229	20.879	19.36
7	274	41.829	24.43
8	321	55.391	21.67
9	370	66.257	18.20
10	423	94.483	18.93

Table 4. Performance of the wind turbine at 60° installation angle

Wind speed (m/s)	Rotate speed (r/min)	Output power (w)	Conversion efficiency (%)
1.5	0	0	0
3	90	0.022	0.16
4	125	0.158	0.49
5	176	8.765	14.05
6	235	21.243	19.70
7	278	42.228	24.66
8	326	55.740	21.81
9	374	66.550	18.29
10	427	94.690	18.97

6 Conclusion

This paper presented a vertical axis wind turbine for Antarctic. Firstly, the aerodynamic performance of the wind turbine structural parameters was numerically simulated using CFD software combined with the Uniform Design Experimentation method. The wind turbine parameters were determined: the wind turbine radius was 0.5 m, the blade chord length was 0.196 m, the number of blades was about 3, and the installation angle of blade was 6°. Then the wind turbine structure model was established and the static strength analysis was performed using ANSYS software. The maximum stress obtained by simulation was much smaller than the allowable stress of the structural steel, and the maximum deformation relative to the overall size of the wind turbine was negligible. Finally, a prototype was fabricated to verify its performance. The prototype experiment results showed that performance of the wind turbine at 60° installation angle was better than 90° installation angle, and the maximum conversion efficiency of wind energy was 24.66% at the wind speed of 7 m/s.

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