DEFORMATION PROPERTIES OF SELF-ADAPTING WIND TURBINE BLADES
Numerical Approach and Optimization

by

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All wind-driven generators need to be equipped with brakes to ensure operational control and safety. Many methods are available to avoid over-speed of the blower. This paper establishes a mechanics model to investigate each point on turbine blades, which are such designed that they would change shape in high winds to reduce the frontal area through adaptive and flexible deformation. In this way, high wind speeds will cause deformation of the blades and decrease of the rotational speed, as a result the turbine slows down. A numerical analysis of the fluid in the fan housing and a force analysis of the blades are performed, and numerical results are used to design the non-uniform arrangement of the hybrid glass/carbon fiber. A wind tunnel experiment is performed on the new blade design. The experimental results show that the new blade achieves an improvement in its mechanical properties and is able to adaptively adjust the torque. During the operation of the wind-driven generator, the new blade could effectively broaden the operational range of wind speeds, thereby improving the power generation when the wind speed is low. A generator without a brake stalls when the wind speed exceeds 13 m/s. After the adoption of the self-adaptive blade made up of the uniform-section complex textile material, the power set shows reduction of noise, avoidance of blade runaway, improvement of the efficiency of the power generation, decrease of cost and enhancement of blade consistency.

Key words: *composite, wind turbine, blade, self-adaptive, air suction*

Introduction

The wind power generation is the chief method for wind energy utilization. It is also one of the RES which are the most developed and have the greatest potential [1] for large-scale development and commercialization. Stand-alone wind-driven generators have been widely used in practice [2]. Safety is an essential aspect of the blower design, as a mechanical failure always causes great disaster. The blower is always equipped with a brake to prevent the blower from burning out due to the over-speed of the blades in the generator, thereby ensuring safe and reliable operation of the wind-driven generator. The brake can operate based on either mechanical, electrical or air retardation force.

Currently, the problems of the stand-alone blower include the high cost of power generation, a poor safety record and the loud noise [3]. A new blower has been designed in

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this paper in order to address these problems. The results of a fluid mechanics simulation and a wind tunnel experiment were combined to design a blade using a hybrid one-way composite material, which has provided an effective solution to the bottlenecks which have impeded wide-spread adoption of the stand-alone blower.

Finite element model

In order to quantify the steady power output of a flexible blade under high wind speed conditions using the finite element analysis method, it is necessary to systematically perform a fluid-solid coupling analysis on the flexible blade of the blower [4]. It is also necessary to perform an in depth study on the aeroelasticity of the blade. The fluid-solid coupling mechanisms could be used to fully understand the variation in wind speed and the rotational speed of the blade constructed from a hybrid textile formed by pultrusion for the three zones of the blower (*i. e.* entry zone, working zone, and exit zone). The work in this paper has laid a theoretical foundation for the design of the pultruded power-adaptive blade within the budget.

As shown in fig. 1, the flow field within the blower housing was analyzed through simulation of the flow of the fluid. The structural mechanical parameters required during flow-solid coupling analysis can be determined by performing a modal analysis of the pultruded blade. A flow-solid coupling analysis of the induced air blower was performed to ascertain the deformation of the blade in the air flow as well as the stress at each point.

Figure 2 has shown the force acting on the 12 blades inside the fan housing in the wind field. The transfer of force to the blade's root, tail, side and back was obtained from the analysis. The parameters were determined for the deformation design of the flexible blade and the arrangement of the pultruded textile. Furthermore, the design could be customized for different wind speeds and the demands acting on the blade based on the relevant parameters.

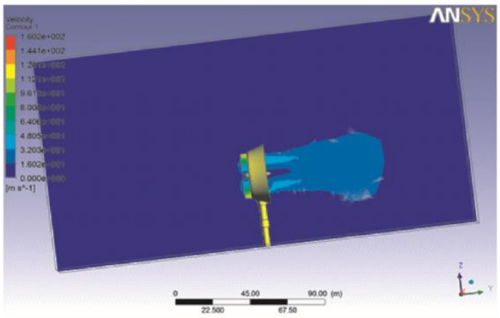

Figure 1. Illustration of the fluid-flow within the blower housing (*for color image see journal web site*)

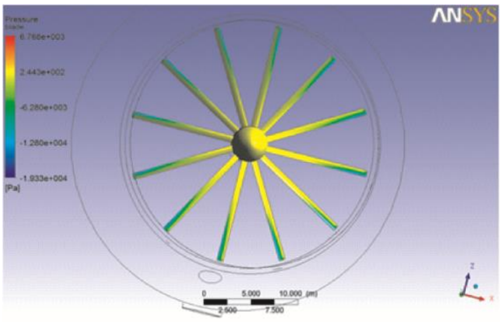

Figure 2. Force analysis of the blade in the air-flow (*for color image see journal web site*)

Modal analysis was the main method of analyzing the dynamics of the blades. It can be classified into two categories; calculation-based or test-based [5]. In the former type, the finite element method is used to simplify the blade's structure and constraints. Valid computational results can be achieved by establishing an appropriate mechanical model. The results of a five-order modal analysis of the blade under five forces have been presented in fig. 3.

The flow-fluid coupling theory was used to analyze the deformation-force relationships and mapping conditions of the force-adaptive blade. Based on the results of the analysis, the blade was then designed in the manner in which it can meet the performance requirements. Finally, a static mechanical and modal analysis of the overall blade was performed.

The method adopted in this study was CFD/CSD, a nonlinear aero elastic calculation method, as shown in fig. 4.

The static mechanical experiment performed on the blade was based on the designed load value. During the experiment, particular attention was paid to the maximal-load region obtained from the analysis, and neither local instability nor deformation was acceptable. The deformation threshold of the blade under 50% and 100% load needed to be determined for the blade experiment and then compared with the computed values from the simulation [6]. Meanwhile, the core parameters of the blade along the waving direction (*e. g.*, first-order natural frequency, mass, and center of gravity) were also measured.

The material characteristics of the blade have been shown in tab. 1. The root constraints and loading forces were applied sequentially to the uniform-sectioned blade. The computation results have been shown further in the text.

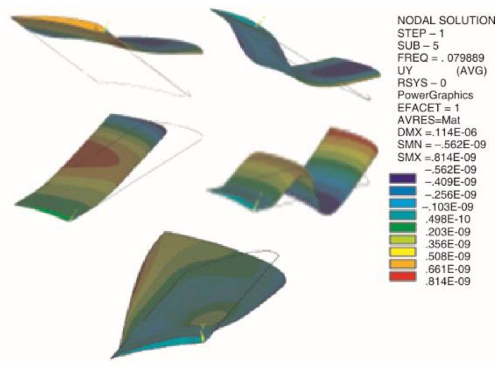

Figure 3. Five-order modal analysis of the blade (*for color image see journal web site*)

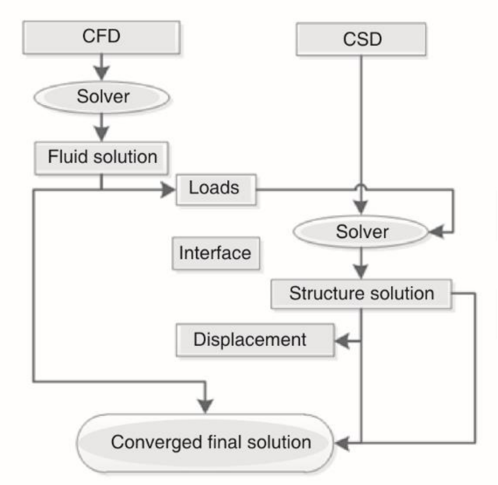

Figure 4. The algorithm for partitioning the numerical simulation for air operated flexibility

Table 1. Material characteristics of the blades

Density	Elasticity modulus [Gpa]	Shear modulus [Gpa]	Poisson's ratio
1450 kg/m^3 Length L = 1.5 m	E_1 = 19.2 E_2 = 4.3 E_2 = 4.3	G_{12} = 3.34 G_{23} = 3.34 G_{13} = 3.12	V_{12} = 0.35 V_{13} = 0.35 V_{23} = 0.312

Figure 5 has shown the deformation of the blade under the constraints and the load. It can be seen from the calculation and the analysis that under the root constraint, the blade deformed and bent in the direction of the flow.

The distribution of overall blade displacement has been shown in fig. 6. The results of the calculation and analysis have shown that in the Z-direction, the red tip of the blade had the largest displacement of 56.704 mm, accounting for a small proportion of the size of the entire blade. Therefore, this has shown that the blade will not crack even under the maximum wind force load.

The stress distribution for the blade has been shown in fig. 7. The results of the calculation and analysis have shown that the root of the blade was subject to tensile stress, and that the largest tensile stress of 2.91 MPa was acting on the part of the blade near the root. This value was less than the maximum stress allowed for the material under the working temperature. This indicates that it was within the range of safety and fulfilled the strength requirement.

The combination and arrangement of the fibers in the textile were designed as shown in the following figure, based on the results of the simulation and previous analysis.

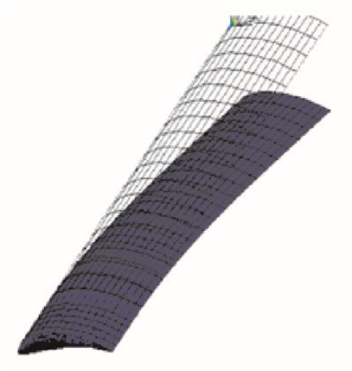

Figure 5. Illustration of the deformation of the blade

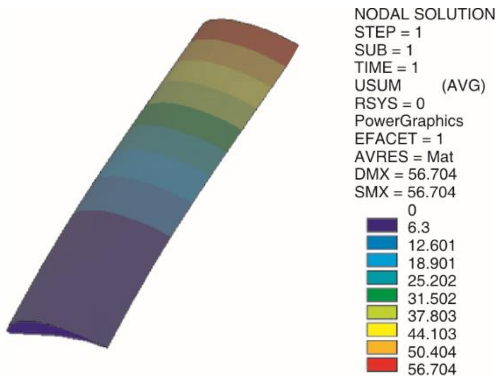

Figure 6. Cloud image for the distribution of blade displacement (*for color image see journal web site*)

The joint between the blade and the bolt is the point where failure most commonly occurs. Accordingly to address this, the carbon fiber can be blended and regularly arranged in the blade, as shown in fig. 8. The load being absorbed in the central longitudinal section of the blade is relatively large, so the density of the glass fibers in the center of the blade can be increased to account for this, as shown in fig. 8. Consequently, blending fibers that have a high strength and changing the distribution density of the fabric could enhance the strength of the blade.

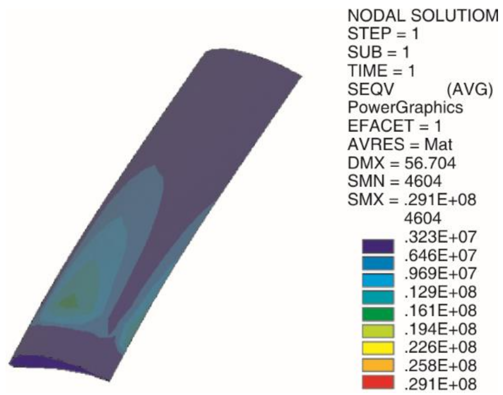

Figure 7. Cloud image for the distribution of the overall blade stress (*for color image see journal web site*)

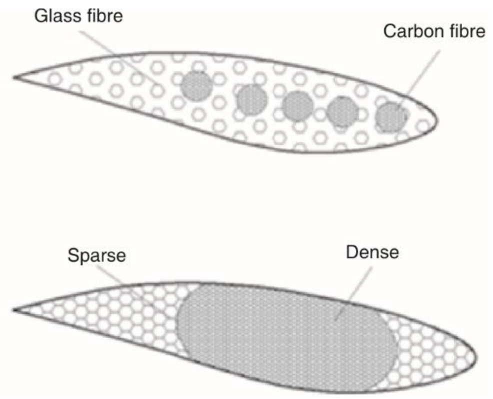

Figure 8. Arrangement and combination of the densities of the fibers

Experiments

The wind tunnel experiment was carried out to test the aerodynamic characteristics of the distributed flexible turbine blade. In the test section of the wind tunnel, the minimum wind speed was less than 2 m/s, and the maximum wind speed was greater than 15 m/s. The difference between the maximum and minimum wind speed over the course of one minute was less than 0.2 m/s. For 80% of the cross section in the center of the test section, the difference between the maximum and minimum wind speed was less than 0.2 m/s and the deflection angle of the local stream was less than 0.5 degrees. The variation in the flow temperature did not exceed 15 °C. The turbulence intensity was less than 0.5% in the center of the test section. The power generation performance of the prototype was tested, as shown in fig. 9.

Results and discussion

Under the experimental conditions previously described, the blower with the uniform-section flexible blades was compared with the traditional blower with inflexible blades. The results of the comparison have been shown in fig. 10.

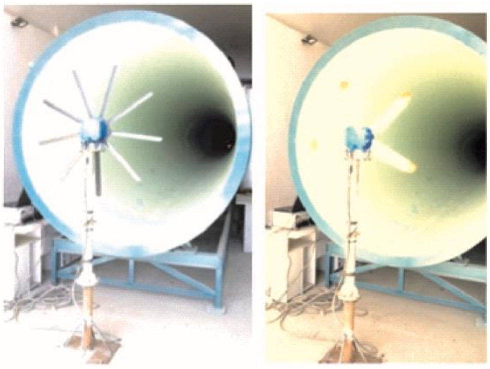

Figure 9. Wind tunnel experiment of both blowers

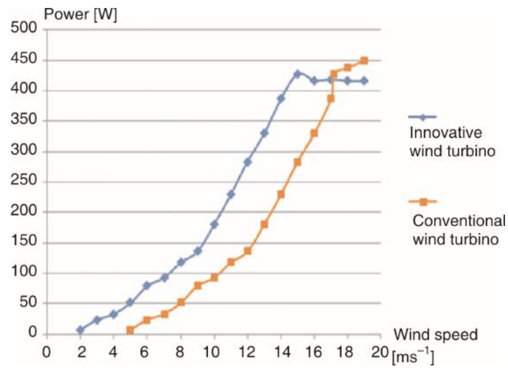

Figure 10. Performance comparison diagram for the new wind generator and the traditional unit

As can be seen from fig. 10, in the area where the turbines cut in, the innovative wind turbine was able to turn to face the wind automatically when the natural wind speed was 2 m/s and it was able to establish a voltage to charge a battery when the natural wind speed was 3 m/s. In contrast the conventional wind turbine was able to turn to face the wind automatically when the natural wind speed was 3 m/s and both wind turbines did not generate any noise. In the area of work, the rotational speed of the impeller of the innovative wind turbine was 400 n/min at which point the rotation was difficult to ascertain with the naked-eye. The output power, which was 1.6 times that of the power output of the ordinary turbine, was steady with an operating noise of 35-40 dB. The rotational speed of the conventional wind turbine impeller varied from 600 to 700 n/min, at which point the rotation was difficult to distinguish with the naked-eye, and the noise of the turbine was between 50 to 60 dB during operation. In the area where the turbine cuts out (danger area), the self-adaptive blade of the innovative wind turbine displayed its speed limitation properties, which maintained the rotation status and eliminated the rise in power. The noise produced by the innovative wind turbine was between 40-50 dB. In terms of the conventional wind turbine, the rotational speed of the impeller gradually increased and the machine apparently trembled when the speed rose above 700 n/min. In this situation, the noise rose to 80 dB and the friction between the blades and the air produced a harsh sound. In addition, the risk the blade may fracture and the probability of turbine runaway increased.

From the curves in fig. 10, it can be seen that the proposed blower could operate at a low wind speed of 2 m/s and adaptively act as a brake to slow the rotation of the turbine at a high wind speed of 14 m/s. In addition, the operating region has been enlarged. In the case of a low wind speed, deformation of the blade was small, enabling it to achieve the maximum wind loads at the optimal windward angle and the maximum windward area. In the case of a moderate wind speed, the deformation of the blade increased with the wind speed. Therefore, the windward angle and the windward area gradually decreased to ensure the relative stability of the wind load and the steady output of power generation. In the case of high wind speeds, the blade self-adaptively deformed with the wind speed. The windward area substantially decreased to reduce the wind load. In this way, the rotational speed of the blade was stabilized to guarantee normal power generation and avoid overloading the blower. In this carbon fibers are used in this paper, and nanoscale fibers [7, 8] will greatly improve the mechanical property of the blade.

Conclusion

This paper was focused on the design of the blades for a stand-alone blower. Finite element simulation was combined with physical experiments to design a flexible blade which could fulfill the performance requirements. An analysis of the fluid within the housing and a mechanical analysis of the blade were performed to lay the foundation for the arrangement and combination of the textiles needed for the construction of the blade. A wind tunnel experiment was conducted to demonstrate the performance of the proposed flexible blade. A high-strength textile was used for the construction of the proposed blade. The molded surface of the flexible part of the blade was able to adapt to the wind speed. In addition to increasing the quantity of wind energy obtained and converting it to electricity, the work has improved the stressed state of the blade and alleviated the threat of turbine overspeed, providing the benefit of the safe and stable operation of the windmill in the case of high wind speeds. Moreover, the working region has been enlarged. Due to its excellent power generation performance and self-control ability of the material, the proposed blade has great potential for success in the market.

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