WIND TURBINE BLADES WITH HYBRID FIBER COMPOSITE
Tensile Properties and Numerical Verification

by

Tianyu LONG, Xiaodong CHEN*, Li QIU, Jia HAN, and Qi Jing DONG

College of Textile and Light Industry, Inner Mongolia University of Technology, Hohhot, Inner Mongolia, China

Original scientific paper
https://doi.org/10.2298/TSCI2403109L

Wind turbine blades are the main component of wind turbines to capture effective wind energy, and require good quality and reliable performance. Therefore, the manufacturing cost of wind turbine blades is much higher than that of other components of wind turbines. The blade is a slender elastomer prone to vibration. The wind turbine vibration always arises in the blade instability. At the same time, the blade is also a typical aerodynamic component. In the process of rotation, it will not only produce mechanical vibration but also bear aerodynamic force. In this paper, the mechanical properties and modal numerical simulation analysis of composite blades with different hybrid ratios of carbon fiber and glass fiber are analyzed, it is found that with the increase of carbon fiber content, the mechanical properties of the blade gradually increase, and the torsional vibration resistance of the blade become stronger. Therefore, the wind turbine blades of hybrid fiber composites have a longer service life, which can reduce material wastage and help protect the environment.

Key words: *small wind turbine, composite materials, modal simulation, hybrid fiber, pultrusion process*

Introduction

In recent years, under the influence of the energy crisis, the demand for new energy equipment has soared extremely. Due to its high wind energy harvesting efficiency, wide application range, unlimited application sites, and low cost, the small wind turbine has seen a great market, it can be used by families and factories [1-3]. Compared with other energy harvesting devices, *e.g.*, the spring-pendulum system [4-7], the carbon nanotube-embedded boundary layer technology [8], MEMS-based energy harvesting technology [9-14], the small wind turbine is portable, it can be used at extreme environment, for examples, in desolate deserts and isolated islands.

At present, there were much literature on large wind turbines, however, the research on the structure of small wind turbines was rare and very preliminary. Wen *et al*. [15] studied the influence of the number of small wind turbine blades with a diameter of 0.18 m on the wake, and designed an airfoil with high lift coefficient for the wind turbine model. Lan and Wang [16] used the self-designed wind turbine general airfoil to design the shape of small wind turbine blades, and established a 3-D model to analyze the stress value of the blades un-

* Corresponding author, e-mail: qiuli@imut.edu.cn

der the condition of wind speed of 20 m/s using ANSYS software. Chaudhary and Prakash [17] designed and optimized a small horizontal axis wind turbine at low wind speed. Through numerical and experimental research, the influence of wind turbine solidity and blade number on wind turbine power was investigated.

The modal analysis was the main method to analysis of the dynamic properties of the blade structure [18], the blade is always subject to the following three vibration forms: flapping, shimmy, and torsion, which will interact with aerodynamic force, causing an aeroelastic problem [19]. Chen *et al*. [20] conducted a comprehensive experimental and numerical study on the complex curvature modal shape and modal coupling dynamics of three-blade wind turbine.

In this paper, carbon fibers and glass fibers are used as reinforcing fibers, and the epoxy resin is used as the matrix, and unidirectional fiber composites with different hybrid ratios are made to study the tensile properties of the composites. The ANSYS software is used to analyze the first six modes and vibration modes of wind turbine blades. According to the simulation results of composite blades with different hybrid ratios, the appropriate hybrid ratio composite blades are finally determined.

Principle of modal analysis

The modal analysis of the wind turbine is mainly to obtain the natural frequencies and corresponding vibration modes of the main components of the wind turbine. The main purpose is to enable the wind turbine designer to make the wind turbine run in the non-resonant region by various means, so as to avoid the wind turbine damage due to structural resonance, to reduce the maintenance cost and to improve the service life. The modal analysis is one of the main methods to study the dynamic characteristics of structures. Through the modal analysis, the natural frequency and vibration mode of the structure can be obtained. The motion equation is:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \tag{1}$$

where $[M]$ is the mass matrix, $[C]$ – the damping matrix, $[K]$ – the stiffness matrix, $\{u\}$ – the displacement matrix, and $\{F(t)\}$ – the force matrix. When the structural system is excited by external excitation, it will vibrate naturally at a specific frequency, which is called the natural frequency of the structure. A structure usually has many natural frequencies. Natural frequency is an inherent attribute of the structure and has nothing to do with external excitation. For undamped single degree of freedom systems, the natural frequency calculation formula is:

$$\omega_\mathrm{n}=\sqrt{\frac{k}{m}} \tag{2}$$

where ω_n is the undamped, natural frequency, k – the elastic coefficient, and m – the mass. Generally, the structural system is damped, so its natural frequency is damped natural frequency. The relationship between undamped natural frequency and damped natural frequency is:

$$\omega_\mathrm{d}=\omega_\mathrm{n}\sqrt{1-\xi^2} \tag{3}$$

where ω_d is the damping natural frequency and ξ – the damping ratio. It can be seen from the above formula that the natural frequency of the structure is mainly affected by the stiffness distribution and mass distribution.

Experiments

Mechanical properties test of carbon fiber/glass fiber hybrid composites

The 300Tex e-glass fiber glass fiber bundles and 3K carbon fiber bundles were selected as reinforcements, and epoxy resin was used as matrix to make unidirectional hybrid fiber composites. The tensile properties of hybrid fiber composites with different volume fractions of carbon fiber and glass fiber were tested, respectively.

The ASTM D3039/3039M-14 is the reference standard for the preparation of composite samples. The length of the specimens was 250 mm, the width was 25 mm, and the thickness was 2 mm. The strengthening plates were added at both ends of each specimen. The length of the strengthening plate was 50 mm, the width was 25 mm, and the thickness was 2 mm. The tensile test was carried out under the following conditions. The static tensile load was applied uniformly along the axial direction of the specimen until the specimen broke or reached the predetermined elongation. The load applied to the specimen and the elongation of the specimen were measured throughout the process to determine the tensile stress, tensile elastic modulus, Poisson's ratio, and drew stress-strain curve.

Tensile performance test instrument: Shimadzu AGS-X universal testing machine Loading speed the gripper: 2 mm per minute. Standard environmental conditions: temperature 23 ±2 °C; relative humidity 50 ±10 %, see fig. 1.

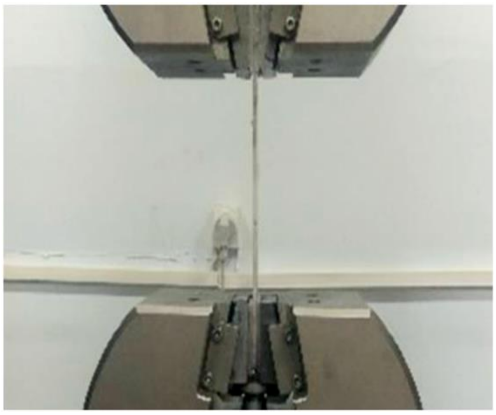

Figure 1. Shimadzu AGS-X universal testing machine

Prestressed modal simulation analysis of hybrid fiber wind turbine

In this paper, a small wind turbine with a rated power of 300 W is designed for modal numerical simulation analysis. The wind turbine is a NACA6412 airfoil with equal section of pultrusion process, and the rated wind speed is designed to be 4 m/s. The surface pressure of the wind turbine is obtained by fluid-solid coupling method, and then modal numerical simulation analysis is carried out.

Results and discussion

Mechanical properties of hybrid fiber composites

The stress-strain curves of hybrid fiber composites with different volume fractions are shown in fig. 2. According to the curve, the maximum stress of the composite material is reduced when 5% carbon fiber is added. This is due to the less carbon fiber content. The interface between carbon fiber and glass fiber is prone to separation. When the carbon fiber content increases to 15%, the maximum stress is much larger than that of glass fiber composites.

From the curve in the graph, it can be seen that the fracture of the composite material occurs suddenly, and the slope of the curve changes obviously before the fracture. The force of the composite in the initial stage is mainly the resin matrix to bear the load. As the applied stress increases, the main body of the force gradually changes from the matrix to the reinforcement. At this time, the growth rate of the stress-strain curve increases. When the load reaches the critical value, the reinforcement and the matrix are peeled off, the material is damaged, the fiber begins to break, de-bond, pull out, and finally fail.

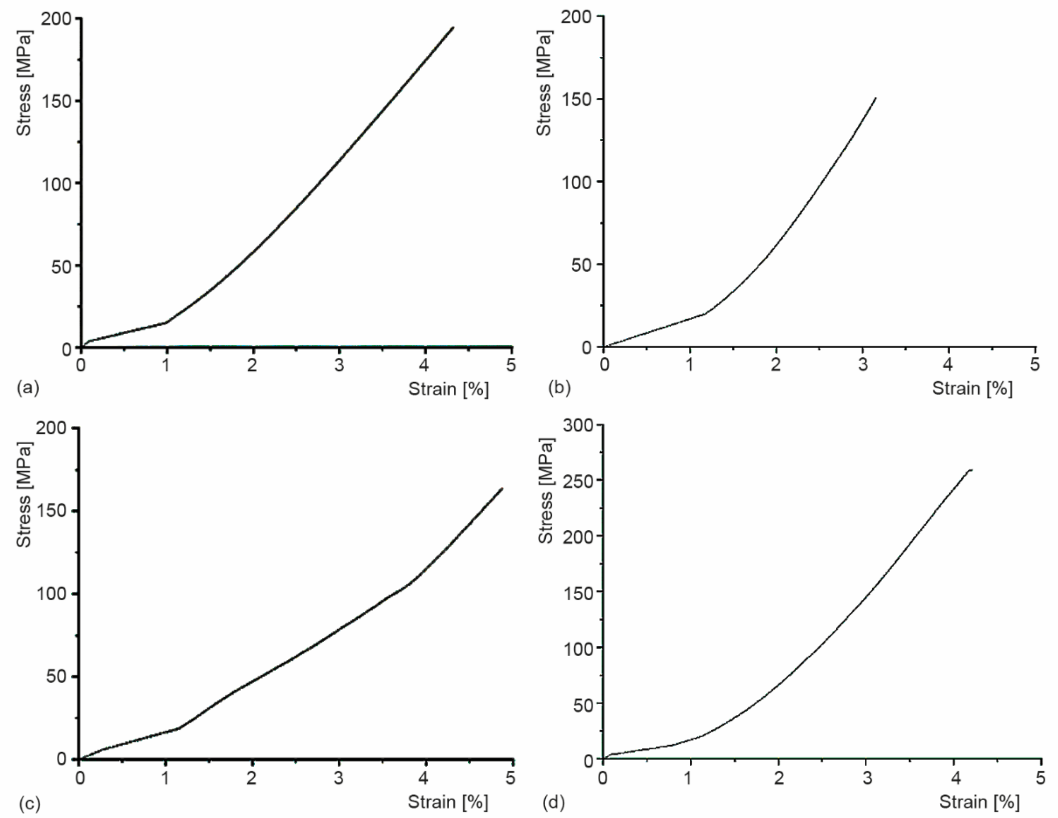

Figure 2. Tensile stress-strain curve of composite material; (a) glass fiber with volume content of 15%, (b) 15% glass fiber + 5% carbon fiber, (c) 15% glass fiber + 10% carbon fiber, and (d) 15% glass fiber + 15% carbon fiber

Modal simulation results

The first six-order modal simulation results of the wind turbine are shown in fig. 3. According to the vibration mode diagram, the fiber volume content has no effect on the vibration mode in the low-order modal analysis. The first-order is the flapping vibration, and the deformation gradually increases from the blade root to the blade tip. The second-order vibration mode is flapping motion, which has obvious deformation compared with the first-order. The tail end of the blade is the maximum deformation, and the middle of the blade also has a large deformation. The third-order is the shimmy motion, but the shimmy deformation is not large. The fourth-order is torsional vibration, which is torsional with the leading edge of the blade as the axis, and the trailing edge has a large torsion because the structure is relatively thin. The fifth-order is flapping vibration. The trailing edge of the blade and the leading edge of the blade tip are greatly deformed at one third and two thirds of the blade root, and the maximum deformation is the leading edge of the blade tip. The sixth-order is mainly flapping vibration. The trailing edge, half of the blade root and the end of the blade are greatly deformed, and the maximum deformation is at the end of the blade. As a slender elastic body, wind turbine blades are prone to flapping vibration and shimmy motion. Due to the addition of a certain amount of carbon fiber blades, the torsional vibration resistance of the blades in this paper is stronger than that of glass fiber blades.

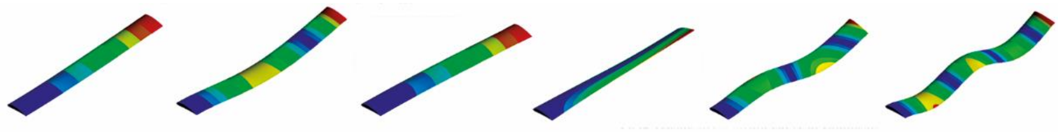

Figure 3. Vibration mode of wind turbine with different fiber volume fraction

The vibration frequencies of wind turbine blades with different fiber volume fractions are shown in fig. 4. According to the frequency line chart, it can be seen that the natural frequency of wind turbine blades increases gradually with the increase of order. With the increase of the carbon fiber content of the wind turbine blade, the natural frequency of the blade gradually increases. This is because the increase of the carbon fiber content makes the blade mass increase, so the natural frequency also increases. When the content of carbon fiber increases from 10% to 15%, the natural frequency of the blade increases significantly. These indicating that when the volume fraction of carbon fiber reaches 15%, the stiffness of the composites wind turbine blade increases significantly.

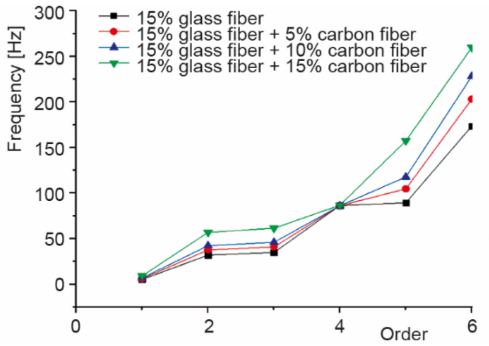

Figure 4. Frequency of wind turbine blades with different fiber volume fractions

Conclusion

In this paper, the hybrid fiber composite wind turbine blade made of glass fiber/carbon fiber has better mechanical properties than the composite wind turbine blade made of pure glass fiber. The increase of carbon fiber content further enhances the stiffness of the blade and has strong torsional vibration resistance. Therefore, adding a certain amount of carbon fiber to specific parts of the blade can greatly improve the mechanical properties of wind turbine blades, prolong its service life, and furthermore it is environmentally friendly, and a fractal-like distribution [18] of the carbon fiber can further improvement of the blade mechanical property as that discussed for porous concretes [21, 22].

Acknowledgment

This work was financially by National Natural Science Foundation of China (11962023) and Inner Mongolia Natural Science Foundation (2021LHMS05011)

References

[1] Gurbuz, M. T., *et al*., Investigation of Radial Turbines for Wind Energy Harvesting, *Proceedings of the Institution of Mechanical Engineers Part A-Journal of Power and Energy, 233* (2019), 5, pp. 659-672
[2] Kishore, R. A., *et al*., Small-Scale Wind Energy Portable Turbine (SWEPT), *Journal of Wind Engineering and Industrial Aerodynamics, 116* (2013), May, pp. 21-31
[3] Liu, K., *et al*., Enhancing Wind Energy Harvesting Performance of Vertical Axis Wind Turbines with a New Hybrid Design: A Fluid-Structure Interaction Study, *Renewable Energy, 140* (2019), Sept., pp. 912-927
[4] He, C. H., *et al*., Hybrid Rayleigh-Van der Pol-Duffing Oscillator (HRVD): Stability Analysis and Controller, *Journal of Low Frequency Noise, Vibration and Active Control, 41* (2022), 1, pp. 244-268
[5] He, C. H., *et al*., Controlling the Kinematics of a Spring-Pendulum System Using an Energy Harvesting Device, *Journal of Low Frequency Noise, Vibration and Active Control, 41* (2022), 3, pp. 1234-1257
[6] He, J.-H., *et al*., Periodic Property and Instability of a Rotating Pendulum System, *Axioms, 10* (2021), 3, 191
[7] He, C. H., El-Dib, Y. O., A Heuristic Review on the Homotopy Perturbation Method for Non-Conservative Oscillators, *Journal of Low Frequency Noise Vibration and Active Control, 41*(2022), 2, pp. 572-603
[8] He, J. H., Abd-Elazem, N. Y., The Carbon Nanotube-Embedded Boundary Layer Theory for Energy Harvesting, *Facta Universitatis Series: Mechanical Engineering*, *20* (2022), 2, pp. 211-235
[9] Mahmud, M. A. P., *et al*., Advances in MEMS and Microfluidics-Based Energy Harvesting Technologies, *Advanced Materials Technologies, 7* (2022), 7, 2101347
[10] Tian, D., *et al*., Fractal N/MEMS: from Pull-in Instability to Pull-in Stability, *Fractals*, *29* (2021), 2, 2150030
[11] Tian, D., He, C. H., A Fractal Micro-Electromechanical System and Its Pull-in Stability, *Journal of Low Frequency Noise Vibration and Active Control, 40* (2021), 3, pp. 1380-1386
[12] He, C. H., A Variational Principle for a Fractal Nano/Microelectromechanical (N/MEMS) System, *International Journal of Numerical Methods for Heat and Fluid Flow, 33* (2023), 1, pp. 351-359
[13] He, J. H., Fast Identification of the Pull-in Voltage of a Nano/Micro-Electromechanical System, *Journal of Low Frequency Noise Vibration and Active Control, 41* (2022), 2, pp. 566-571
[14] He, J. H., *et al*., Pull-in Stability of a Fractal System and Its Pull-in Plateau, *Fractals*, *30* (2022), 9, 2250185
[15] Wen, J., *et al.*, Mode Interpretation of Blade Number Effects on Wake Dynamics of Small-Scale Horizontal Axis Wind Turbine, *Energy*, *263A* (2023), 125692
[16] Lan, P., Wang, X. D., Structure Design and Performance Analysis of Small Wind Turbine Blade Based on General Airfoil (in Chinese), *Mechanical Research and Application*, *35* (2022), 1, pp. 20-22
[17] Chaudhary, M. K., Prakash, S., Experimental Investigations and Aerodynamic Shape Optimization of Small Horizontal-Axis Wind Turbine Blades, *Transactions of the Canadian Society for Mechanical Engineering*, *45* (2021), 4, pp. 594-603
[18] Chen, X. D., *et al.*, Hybrid Textile Composite Fan with Smart and Fractal Structure, *Thermal Science*, *25* (2021), 2B, pp. 1329-1335
[19] Chen, C., *et al.*, Simplified Complex-Valued Modal Model for Operating Wind Turbines Through Aerodynamic Decoupling and Multi-Blade Coordinate Transformation, *Journal of Sound and Vibration*, *547* (2023), 117512
[20] Chen, Y. C., *et al*., Experimental and Numerical Study of High-Order Complex Curvature Mode Shape and Mode Coupling on a Three-Bladed Wind Turbine Assembly, *Mechanical Systems and Signal Processing*, *160* (2021), 107873
[21] He, C. H., Liu, C., Fractal Dimensions of a Porous Concrete and Its Effect on the Concrete's Strength, *Facta Universitatis Series: Mechanical Engineering, 21* (2023), 1, pp. 137-150
[22] He, C. H., *et al*., A Novel Bond Stress-Slip Model for 3-D Printed Concretes, *Discrete and Continuous Dynamical Systems-Series S*, *15* (2022), 7, pp. 1669-1683

Paper submitted: October 14, 2022
Paper revised: May 16, 2023
Paper accepted: May 24, 2023