HYBRID TEXTILE COMPOSITE FAN WITH SMART AND FRACTAL STRUCTURE

by

Xiao Dong CHEN [a], ***Li QIU*** [a*], ***Yanmin NAN*** [a], ***Ze Lin CHEN*** [b], ***and Jing LI*** [b]

[a] College of Textile and Light Industry, Inner Mongolia University of Technology, Hohhot, Inner Mongolia, China
[b] Inner Mongolia Dazhi Energy Technology Co., Ltd. Hohhot, Inner Mongolia, China

Original scientific paper
https://doi.org/10.2298/TSCI200410030C

It is a key issue to embed sensing components in a smart material. A fractal-like distribution of sensing components is considered in this paper to collect data for smart-type fan test blades with hybrid textile composite, which is proved to have self-monitoring property. A fluid-solid coupling model is proposed to analyze the functional relationship among the hybrid fiber arrangement and morphology and the mechanical properties of blade in each force point. It is concluded that the deformation and the self-adaptability of flexible fan blades are two main factors affecting power efficiency.

Key words: *fan test blade, hybrid textile composite, smart type, self-adaption, deformation-power, fractal distribution*

Introduction

Wind energy as a renewable energy has been caught worldwide attention, and the wind energy technology focuses mainly on the efficiency of the wind power generation. Among all factors, the fan blade is the core component of the wind-driven generator, and its operation and performance strongly depend upon its structure and material properties. Due to the characteristics of low weight, high specific strength and strong environmental resistance, textile composite materials are widely applied to optimal design of fan blades. However, fan test blades with smart hybrid textile composite were rarely studied, and the theory for the design was preliminary.

Now the carbon nanowire sensor has been widely used for 3-D braided composite materials [1], and all the peaks in the spectra can be identified [2], however, the mechanism of the sensor, which is embedded in the structure, requires further study to monitor dynamically the external environment of the blade and the change of its own state in real-time.

The smart composite with an embedding sensor has a matrix structure and can monitor the structural integrity. Optical fiber sensing is commonly used in sensitive materials. Through smart structural integration and implantation in hybrid textile composites, the whole process of blade operation can be dynamically monitored online, and the deformation degree of the blade running in the wind field can be described. The research on fan test blades with smart hybrid

[*] Corresponding author, e-mail: 540601336@qq.com

textile composite is both the research priority of the field of intelligent materials and the necessary means for quantitative testing and calculating the blade stress during the operations of wind turbine. The automatic fusion of multi-sensor information allows an increasing accuracy of the health status of the blades and even the overall operation of the fan [3].

The micro-structure plays an important role in optical fibers, when combined with functionally sensitive materials, the structural design and material integration can be physically fused on the optical fiber, and the sensing mechanism can be improved [4]. By embedding the data sensing structure into the blade, the fan blade with smart hybrid textile material can collect directly the deformation data in the wind field, as a result, feasibility and reliability of the homogenization method in the dynamic calculation and experimental development process of the blade with hybrid textile composite material are verified.

Theory and research framework

Among the different types of sensors, the optical fiber owns the features of high sensitivity, little influence on the performance of the material itself, strong anti-interference, and can sense a variety of parameters [5]. Besides the aforementioned properties, the fiber Bragg grating (FBG) sensor is highly sensitive to external physical quantities such as temperature and strain, therefore, it is widely used in structural health monitoring [6].

The reasonable lay-out of FBG sensor network is key to realize the on-line monitoring of intelligent composite materials [7]. In this experiment, FBG sensor system is embedded in a fractal-like distribution in the weaving process of hybrid composite fan blades to sense the shape variables of key points of the blades. When the optical fiber materials with the same state as the blade are subjected to mechanical stress, the optical fiber sensing system will send back the changed data of each point.

Optical coupler FBG sensor array is embedded in a blade in a fractal-like distribution braided by a hybrid textile composite material. To demonstrate the selection and the structure distribution of smart materials for the finite element analysis, the following constraint condition is considered for single cell perimeter:

$$p = \sum_{k=1}^{m} l_k \left[\sqrt{(p_i - p_j)^2 + \varepsilon^2} - \varepsilon \right] \le \bar{p}$$

where p is the boundary perimeter of the discrete structure, m – the total number of cell interfaces, l_k – the interface length between adjacent cells i and j, p_i and p_j are the density of cells i and j, and ε is the small positive number, which is introduced to ensure the differentiability of the perimeter. The upper limit $\bar{p}$ controls the total change of density of all connecting elements and gets the hexaprism model, the mesh division and stress cloud diagram of each single crystal cell are shown in figs. 1 and 2.

Each regular hexagonal prism includes two parts, epoxy resin and yarn. The fiber with 0.52 of volume fraction is analyzed from the arrangement method of the microscopic, and selects a segment that cuts a height of 0.5275 mm along the direction of the fiber for numerical simulation analysis. The length of the regular hexagon on the bottom surface of the single cell model is 0.163 mm, and the radius of the fiber is 0.107 mm. After the calculation, the stress cloud diagram of the cell is obtained, and the feasibility of the six-prism single cell model is preliminarily verified through analysis.

Currently, the self-healing nature of data transmission network is mainly improved by the optical switch and optocoupler. Constrained by the cost of network construction and the difficulty of central control, the signal transmission link provided by optocoupler can improve

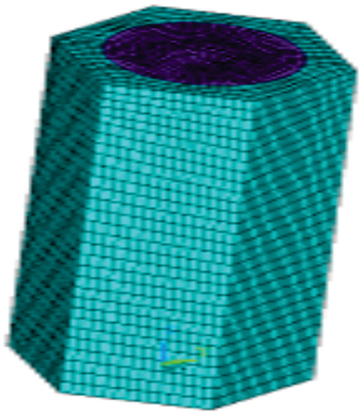

Figure 1. Single cell finite element model

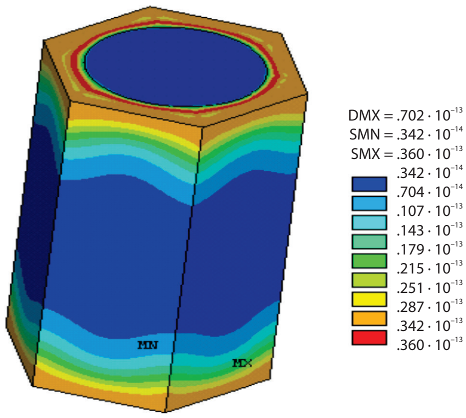

Figure 2. Stress cloud of single crystal structure where; DMX – displacement max, SMX – solution max, and SMN – solution min

the stability of transmission link [8]. Under the condition of the same coverage area of the network, the use of hexagonal network structure, the use of fiber link length is the minimum and the cost is minimal.

The wind energy design code requires to determine the first and second natural frequencies of the blade swing and swing direction at rest, and consider the influence of hub and blade bear, with more than 20% of the excitation frequency and the inherent frequency of the wind turbine, and more than 105 of the difference with the natural frequency of the blade. Considering the complexity of stall prediction of fan blades, the method of simplifying variables can anchor the research focus of this experiment on the performance description of non-stall type blades. The equation of motion of the element of the blade in the outer direction per unit length is attached to the radius of the time-varying load $q(r, t)$:

$$m(r)\ddot{x}+\hat{c}(r)\dot{x}+\frac{\partial^2}{\partial r^2}\left[EI(r)\frac{\partial^2 x}{\partial r^2}\right]=q(r,t) \tag{1}$$

The item on the left side of eq. (1) is the load on the element, caused by inertia, damping and bending moment, respectively. The $I(r)$ is the second moment on the blade cross-section of the weak principal axis (for this purpose, it is assumed that it is on the rotating plane), and x – the out plane displacement. The expressions $m(r)$ and $c(r)$ is the mass damping per unit length, respectively. The dynamic response of suspended blades to fluctuating aerodynamic loads can be easily investigated by the model analysis method, in which the excitation caused by different natural frequencies of vibration can be calculated separately and the results can be superposed:

$$x(r,t)=\sum_{j=1}^{\infty} f_j(t)\mu_j(r) \tag{2}$$

where $\mu_j(r)$ is the shape of the j^{th} mode, and is forced to assume a uniform value at the blade tip, and $f_j(t)$ – the change of blade tip displacement with time. The equation is replaced:

$$\sum_{j=1}^{\infty}\left\{m(r,t)\mu_j(r)\ddot{f}_j(t)+\hat{c}(r)\mu_j(r)\dot{f}_j(t)+\frac{\mathrm{d}^2}{\mathrm{d}r^2}\left[EI(r)\frac{\mathrm{d}^2\mu_j(r)}{\mathrm{d}r^2}\right]f_j(t)\right\}=q(r,t) \tag{3}$$

For ground-level damping, the natural frequency is solved:

$$m(r)\omega_j^2\mu_j(r)=\frac{\mathrm{d}^2}{\mathrm{d}r^2}\left[EI(r)\frac{\mathrm{d}^2\mu_j(r)}{\mathrm{d}r^2}\right] \tag{4}$$

Multiply both sides by $\mu_j(r)$, integrate on the blade length, and derive the following:

$$\sum_{j=1}^{\infty}\left\{\int_0^R m(r,t)\mu_j(r)\ddot{f}_j(t)\mathrm{d}r+\int_0^R \hat{c}(r)\mu_j(r)\dot{f}_j(t)\mathrm{d}r+\int_0^R m(r)\omega_j^2\mu_j(r)f_j(t)\mathrm{d}r\right\}=$$

$$=\int_0^R \mu_j(r)q(r,t)\mathrm{d}r \tag{5}$$

According to Betti's law, the shape of the undamped mode is a rectangle, and satisfies the orthogonality condition

$$\int_0^R m(r)\mu_i(r)\mu_j(r)\mathrm{d}r=0 \tag{6}$$

If the blade assumes that the damping change $c(r)$ along the blade unit length is direct ratio to the mass change $m(r)$ of per unit length. Generally, the free vibration frequencies of single blade are close, therefore, the dynamic analysis of single blade is of great significance.

The distribution structure of the FBG sensor network, the meshing mode of the blade and the analysis of the dynamic of the non-stall blade illustrate the possibility of the development of the smart blade. Through the embedded sensor for data transmission and parameter correction of performance design and material ratio, the complete design data set of power adaptive fan blade is obtained. Through the classical laminated plate theory, the stiffness equation of composite material includes three stiffness matrices: tensile stiffness matrix [A], coupling stiffness matrix [B], bending stiffness matrix [D]. The closed-loop constructed by the physical test and the postback of smart data forms a complete data stream of characteristic parameter comparison and data correction, in order to provide mapping conditions for deformation state of deformable power adaptive blade and full power curve. The research framework is constructed as shown in fig. 3.

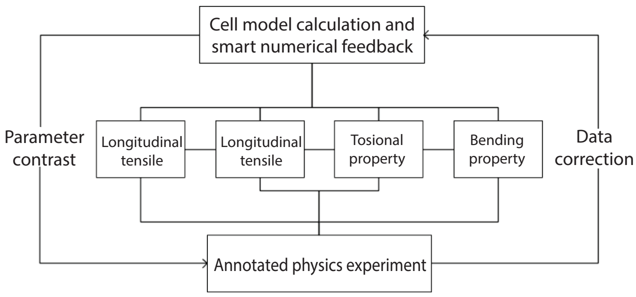

Figure 3. Expression and realization of mechanical property data of machine blade

The analysis method applied in dynamic analysis of blade structure, modal analysis, is the main method of dynamic analysis of blade structure. The results of the structure field and flow field exchange the information by constructing the intermediate data exchange platform, in order to achieve the coupling of the two fields. On the basis of zone continuity, this paper studies on whether the smart hybrid textile meets the stress performance of various points of the fan blade and the fiber arrangement. Combined with the Taylor expansion and the functional theory based on Hilbert space, the accurate error, convergence and uniqueness are analyzed. The cell arrangement of the honeycomb structure just has the property of macro periodic distribution.

The mapping relationship between blade performance and low wind speed quick cut and high wind speed self-braking to maintain power of distributed fan is constructed. Based on the study of the multi-dimensional design model of fan blade engineering performance, structural performance and material performance, the fiber optic sensing system is added to form the data feedback, as a result, it can both reveal the relationship between fiber type arrangement and blade mechanical properties, the relationship between blade deformation and power, and the influence of environmental parameters on relevant design values, and form a closed-loop data flow of environmental variables – blade performance variables – simulation parameters – process model – finite element algorithm.

Data analysis and discussion

The mechanical properties of a single cell are summed by distribution. The smart hybrid textile composite fan blade can achieve fast cut in at low wind speed and self brake at high wind speed to maintain the overall performance of power, because of the adaptive change of physical state in the wind field. The whole process of shape change requires that both FBG sensor system feedback data master the process data change, and the critical value of the blade is measured and confirmed. Table 1 shows the relevant data during the blade bending test.

Table 1. Bending test data

Modulus of elasticity in static bending	Deflection	Bending fracture energy	Bending strength	Total bending energy	Fracture deflection	Max. bending force
E_b	f	U	σ_{bb}	W_t	f_{bb}	F_{bb}
28.77 GPa	11.402 mm	54.281 Nm	763.904 MPa	54.28 Nm	11.402 mm	9.327 kN

Figure 4 shows the stress-strain curve of blade bending. As shown from the data change of blade sample failure, the bending strength is the stress on the surface of the sample at the time of failure, which it is fracture with the fiber instead of interlayer shear failure. As seen from the force-displacement curve, under the bending stress, the material shows the characteristics of line elasticity. This property fully demonstrates the correctness of the linear elastic material hypothesis. The flexural elastic modulus differs from the longitudinal elastic modulus of the material by 10 Gpa, indicating the large bending strength of the textile composite used for the weaving blades.

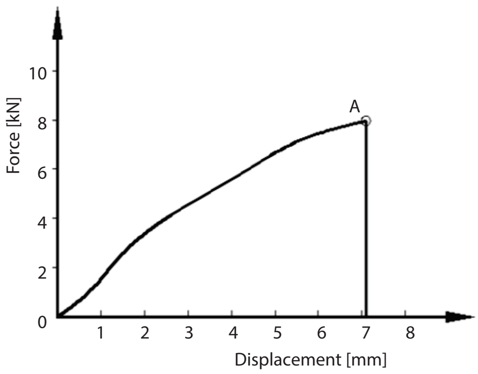

Figure 4. Bending stress-strain curves

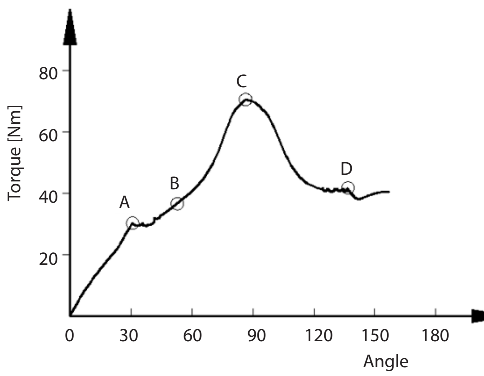

Figure 5. Torque corner curve

As shown from the torque angle curve in fig. 5, the secondary strengthening phenomenon (section A-B) occurs during the torsion of the material, due to the first failure of the interface between fiberglass and resin during the torsional process, which this fully explains that when the blade is subjected to strong torque, the failure process starts from the failure of the interface, and when the distortion limit of reinforced glass fiber is reached C, the overall failure occurs.

The first-order to fifth-order vibration modes of the blade of smart hybrid textile composite fan are expressed as bending vibration modes, so bending vibration is the main vibration of the blade. The bending vibration is usually a compound bending mode of swing vibration and swing vibration, but the swing vibration mode is the main component. During the vibration, the energy is mainly concentrated in the first and second order, and is shown as wave bending vibration, small torsional vibration, and the relevant data are shown in tab. 2.

Table 2. Model characteristics parameters of blades

Degree	Frequency [Hz]	Period [s]	Flapping bending	Lag motions bending
1	3.573	0.27988	1 order	1 order (less)
2	23.875	0.04188	2 order	None
3	24.949	0.04008	None	2 order
4	68.347	0.01463	3 order	None
5	79.889	0.01252	None	3 order

The blade has the characteristics of long spanwise, short chord and good flexibility, which determines that all kinds of vibration of wind turbine first occur on the blade. According to the five order bending data of the fan blade, it can be seen that the smart hybrid textile composite fan blade is a typical aerodynamic component, which not only bears mechanical vibration but also bears aerodynamic force during rotation. This characteristic will play an important role in the development of the blade and the description of the stress and deformation of the fan blade. When the external variable condition is within the normal threshold value of blade deformation, the flapping, shimmy, torsion and aerodynamic interweaving forces act on each point of the blade .This result is due to the formation of aeroelastic composite force.

Blade bending order and shape measurement affect the sensor mechanism embedded in the blade structure. If the data returned by the internal sensing mechanism indicates that the aeroelastic interaction is mutual weakening, it means that the fan is running smoothly, otherwise, flutter and divergence will occur. The smart structure formed by integrating the sensing mechanism in the blade of hybrid textile composite materials to form the monitoring of this unstable signal must be considered and avoided in the safety design of wind turbine.Cascaded multiple resonators can not only realize the whole measurement of multi-point twist but also realize the positioning and quantitative description of blade twist point under deformation by measuring the beat frequency curve period of different resonators.

Conclusions and expectation

Based on the previous analysis, it is feasible to embed the smart structure into the weaving in a fractal-like structure and performance data of the textile composite fan blade. The embedding geometry and its properties can be studied by a way similar to the fractal harmonic law [9]. Under the support of smart materials and structures, the deformation state and deformation process of smart hybrid textile composite fans with deformation-power adaptive performance in the wind field own relatively complete and observable data flow.

This paper analyzes and develops the theory of the test blade of the smart hybrid textile composite fan, the smart hybrid textile composite based on the test blade will realize the quantitative analysis of the deformation power change of the fan blade, and finally realize the multi-dimensional monitoring of the blade health. The running state of the fan is always affected by the dynamic and irregular external environmental factors, which is a long-term challenge to the performance control and structure development of the blade. Therefore, the improvement of the fan blade and the improvement of the overall system need to be development.

Acknowledgment

This work was financially supported by National Natural Science Foundation (11962023).

References

[1] Alexopoulos, N. D., et al., Improved Strain Sensing Performance of Glass Fiber Polymer Composites with Embedded Pre-Stretched Polyvinyl Alcohol-Carbon Nanotube Fibers, *Carbon*, *59* (2013), Aug., pp. 65-75
[2] Artigao, E., *et al*., Current Signature Analysis to Monitor DFIG Wind Turbine Generators: SA Case Study, *Renewable Energy*, *116* (2018), Feb., pp. 5-14
[3] Luyang, J., *et al.*, An Adaptive Multi-Sensor Data Fusion Method Based on Deep Convolutional Neural Networks for Fault Diagnosis of Planetary Gearbox, *Sensors*, *17* (2017), 2, 414
[4] Ming, W., *et al*., Optical Fiber Sensing Technologies Based on Femtosecond Laser Micromachining and Sensitive Films, *Acta Physica Sinica*, *66* (2017), 7, pp. 29-37
[5] Kun, C., *et al*., Experimental Research on Damage Detection of Glass-fiber Composite Materials with FBG Sensing Network, *Journal of Experimental Mechanics*, *31* (2016), 4, pp. 476-482
[6] Yiwen, O., *et al*., Large WDM FBG Sensor Network Based on Frequency-Shifted Interferometry, *IEEE Photonics Technology Letters*, *29* (2017), 6, pp. 535-538
[7] Dagong, J., *et al*., A Self-Healing Passive Fiber Bragg Grating Sensor Network, *Journal of Lightwave Technology*, *33* (2015), 10, pp. 2062-2067
[8] Zefan, W., *et al*., Research on Reliability of Honeycomb Fiber Grating Sensor Network, *Optical Communication Technology*, *42* (2018), 6, pp. 18-20
[9] Kong, H.-Y., He, J.-H., The Fractal Harmonic Law and Its Application Swimming Suit, *Thermal Science, 16* (2012), 5, pp. 1467-1471

Paper submitted: April 10, 2020
Paper revised: May 30, 2020
Paper accepted: May 30, 2020