Research Article

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Damage identification of wind turbine blades based on dynamic characteristics

Abstract: In this article, the Ansys Workbench was used to carry out the finite element analysis of 15 kW wind turbine blades with different damaged positions and different damaged degrees. The results show that the change rate of natural frequency, displacement modes, and strain modes of the blades increased with the increase in the damage degree; the change rate of the natural frequency and displacement modes of the blade decreased with the increase in the speed, while the change rate of the strain modes increased; the change allocation ratio of the displacement modes and strain modes after the damage was more obvious at the damage location than other positions, which can be used to locate the damage position of the blade; the change allocation ratio of strain modes is higher than the change allocation ratio of displacement modes when the damage degree is the same, which means that the recognition effect of the strain modes is more significant than that of the displacement modes.

Keywords: wind turbine, blade damage, natural frequency, strain mode, displacement mode

1 Introduction

In recent years, with the increasing depletion of fossil fuels and the increasingly prominent environmental problems, countries have begun to increase their investment in wind energy [1], and the wind power industry has developed rapidly and occupies an important position in renewable energy [2]. Once the blades of the wind turbine in operation were damaged, the damage would continue to develop under the action of alternating loads [3], and when the damage developed to a certain extent, the blades would break [4]. The fracture of the blade destroys the symmetry of the wind wheel, and the continuous rotation of the damaged wind wheel would produce a large unbalanced force and even cause the destruction of the wind turbine [5], which would not only affect the normal operation of the wind turbine but even cause damage to the whole machine [6]. This seriously affected the application and promotion of wind power generation [7]. If the initial damage of the blades could be found in time and maintenance measures could be taken, a series of losses caused by the damage of the blade could be avoided [8]. The initial stage of blade damage was difficult to observe with the naked eye, and the blades were installed on the top of the wind turbine tower above the ground, which brought a lot of inconvenience to the inspection work [9]. Therefore, effective detection of wind turbine blade damage has become a problem worthy of in-depth study [10].

Blade damage detection was to study the response of the blade structure under external excitation [11]. Through the analysis of the structure response, various characteristic parameters of the blade structure were obtained [12] and compared with the design data, which could judge the performance and state of the blade structure [13]. Scholars have done systematic research on the damage detection of wind turbine blades. Ghoshal et al. [14] put forward the idea of applying a piezoceramic actuator (PZT) sensor system for blade damage detection, detecting the blade damage through PZT excitation blade vibration. Sundaresan et al. [15] developed a new detection method that presets the PZT sensor system inside the wind turbine blade, which could monitor the blade in real-time and
send out early warning signals when the blade was damaged. Many universities and research centers carried out in-depth research on damage identification based on acoustic emission technology [16,17]. Joosse et al. [18] combined acoustic emission technology with wind turbine blade tests, installed sensors on the surface of the blade, and analyzed the data obtained in the static test and fatigue test, which could effectively detect the damaged part of the blade. It was proved that the combination of acoustic emission technology and experiment could detect the damage of the blade structure. Zhao [19] proposed a combination of acoustic emission technology and wavelet analysis to identify the damage of wind turbine blades and applied it for the damage identification of wind turbine blade materials, but this method was only limited to blades. The damage identification of materials has not been verified in the damage identification of real blades. Zhu et al. [20] developed a wind turbine blade damage detection method combining an acoustic emission sensor array and PZT sensor array. Smith et al. [21] used temperature changes as the basis to identify structural damage based on changes in the temperature of wind turbine blades. Beattie and Rumsey [22] developed a digital camera function to obtain the temperature change of the blade surface and then judged its damage. Xiao and Yan [23] combined infrared imaging technology with non-destructive inspection of wind turbine blades and used pulsed infrared imaging to detect possible damage to wind turbine blades, but this method was used to detect wind turbine blades in operation. Sometimes there are certain difficulties.

In recent years, many scholars have begun to study the dynamics of structures [24] and apply them to structural damage identification [25]. Some scholars also detect the damage of the blade through the change in the dynamic characteristics of the blade. Zeng [26] took rotating wind turbine blades as the research object, analyzed the changes in the dynamic characteristics caused by blade rotation and damage, and identified the damage of the rotating blades through changes in the modal parameters. Li [27] analyzed the dynamic characteristics of wind turbine blades before and after damage through finite element simulation, and found out the relationship between blade damage and dynamic characteristics changes, and developed a wind turbine blade damage detection based on this system. Li et al. [28] applied vibration detection technology to identify the damage of wind turbine blades and analyzed the changes in the dynamic characteristics of wind turbine blades before damage and when different crack damages occurred through experimental methods. The damage was judged by the change, and the damage location was identified by the change in the mode shape, which provided a basis for the damage identification of the wind turbine blade. Gu et al. [11] conducted damage experiments on blades under static and rotating conditions based on the change in the natural frequency. The results showed that the larger the damaged area of the blade, the more the drop in the natural frequency value. Zhang [29] analyzed the rotation softening effect and the stress stiffening effect caused by the blade rotation from both theoretical analysis and numerical simulation and used a vibration-based method to identify structural damage of wind turbine blades. Velazquez and Swartz [30] analyzed and estimated the load environment (including load effects) based on the dynamic behavior of the blade. Based on the dynamic characteristics, Su and Xue [31,32] identified wind turbine blade damage through finite element analysis.

At present, scholars have done a lot of research on the damage detection of wind turbine blades, and have made many research results. However, the existing research mostly focused on the research of blades in a stationary state [33], and there were few studies on blades in a working state, and the influence of rotation speed on damage identification was not considered. In this article, the finite element analysis software Ansys Workbench was used to analyze the dynamic characteristics of the blades at various speeds. Analyze the dynamic characteristics of wind turbine blades with different positions and different degrees of damage in the operating state, obtain the change law of the natural frequency, displacement mode, and strain mode before and after the damage, and carry out the influence of the speed on the damage identification, which can provide a theoretical basis for damage detection of wind turbine blades in operation.

2 Blade model establishment and damage unit setting

2.1 Finite element modeling of the blade

The blade length of a 15 kW horizontal axis wind turbine was 3.7 m, the skin thickness was 18 mm, and the material was glass fiber-reinforced plastic. The span modulus was 42.6 GPa, the radial modulus was 16.5 GPa, the shear modulus was 5.5 GPa, the density was 1,950 kg/m³, and the Poisson’s ratio was 0.22.

The shape of the blade was more complicated, and modeling through Ansys Workbench takes a lot of time. To simplify the modeling work of the blade, the 3D CAD modeling software Solidworks [34] and the finite element analysis software Ansys Workbench were used together for finite element modeling [35,36]. The solid model of the blade is shown in Figure 1, while the meshing of the blade finite element model is shown in Figure 2.
2.2 Damage unit setting

The elastic modulus of different elements was changed to simulate the damage at different positions, and the different degrees of damage were simulated by changing the elastic modulus [37]. The damage degree could be obtained as follows:

\[ \lambda = \frac{E - E'}{E} \quad (1) \]

where \( E \) is the elastic modulus of the element before the damage, and \( E' \) is the elastic modulus after the damage.

Take 5 damage units on the upper surface of the blade, and set the damage degree to 20, 40, 60, and 80\%, respectively. To facilitate the observation of the change in the blade mode shape, each damaged unit was equipped with an observation point of the mode shape, as shown in Figure 3. The damaged unit settings are shown in Table 1.

3 Blade damage recognition

3.1 Damage identification based on the natural frequency

The dynamic characteristics of blades running at different speeds (5 rad/s, 10 rad/s, 15 rad/s, 17 rad/s [rated speed], and 20 rad/s) before and after the damage were analyzed by Ansys Workbench [38]. To show more
intuitively the influence of damage on the natural frequency, the rate of change of the natural frequency was processed as follows [31]:

$$Q_f = \sqrt{\frac{f_i - f_i'}{f_i}},$$

(2)

where $f_i$ is the natural frequency before the damage, and $f_i'$ is the natural frequency after damage.

The natural frequency change rate after the square root processing was used as the parameter of damage identification ($Q_f$), and the damage of the $A_1$ unit was taken as an example for analysis. The change rate of

| Damage unit number | Distance from the blade end | Damage element size | Mode shape observation point number |
|--------------------|----------------------------|---------------------|-------------------------------------|
| $A_1$              | 1.3 m                      | 10 cm × 20 cm       | $G_1$                               |
| $A_2$              | 1.8 m                      | 10 cm × 20 cm       | $G_2$                               |
| $A_3$              | 2.3 m                      | 10 cm × 20 cm       | $G_3$                               |
| $A_4$              | 2.8 m                      | 10 cm × 20 cm       | $G_4$                               |
| $A_5$              | 3.3 m                      | 10 cm × 20 cm       | $G_5$                               |

**Figure 4:** First 3-order natural frequency change rate of the blade: (a) 1st order, (b) 2nd order, and (c) 3rd order.
the first 3-order natural frequency after square root processing at different speeds is shown in Figure 4. It can be seen that the change rate of the first 3-order natural frequency of the blades increased with the increase in the damage degree. Therefore, the change in the natural frequency of the blade could be used as the basis for judging the degree of blade damage in the operating state. When the blade damage degrees were the same, the change rate of the first 3-order natural frequency of the blade decreased with the increase in the speed. It showed that the sensitivity of damage identification based on natural frequency gradually decreased with the increase in speed. When the speed increases from 5 to 20 rad/s, the maximum change in the change rate of natural frequency was 4.51%.

3.2 Damage identification based on changes in mode shape

3.2.1 Damage identification based on displacement mode

3.2.1.1 Identification of damage degree

To show more intuitively the influence of damage on the displacement mode, the rate of change of the displacement mode was processed as follows [31]:

\[ Q_s = \sqrt{\frac{\varphi_{ig} - \varphi_{ig}^*}{\varphi_{ig}}} \]

Figure 5: First 3-order displacement modes change rate of the blade: (a) 1st order, (b) 2nd order, and (c) 3rd order.
Figure 6: Change trend of the displacement modes of each observation point: (a) $A_1$ unit damage, (b) $A_2$ unit damage, (c) $A_3$ unit damage, (d) $A_4$ unit damage, and (e) $A_5$ unit damage.
where $\varphi_{ig}$ is the displacement mode before the damage, and $\varphi_{ig}'$ is the displacement mode after the damage.

Taking the damage of the $A_1$ unit as an example, the change rate of the first 3-order displacement modes after the square root processing at the corresponding observation point ($Q_s$) is shown in Figure 5. It can be seen from Figure 5 that the change rate of the first 3-order displacement modes of the blades increased with the increase in the damage degree. Therefore, the change in the displacement modes of the blade could be used as the basis for judging the degree of blade damage in the operating state. When the blade damage degrees were the same, the change rate of the first 3-order displacement modes of the blade decreased with the increase in the speed. It showed that the sensitivity of damage identification based on displacement modes gradually decreased with the increase in speed. When the speed increases from 5 to 20 rad/s, the maximum change in the change rate of displacement modes was 1.80%.

### 3.2.1.2 Recognition of damage location

To show more intuitively the difference of the displacement mode at each observation point, the change

![Figure 7: First 3-order strain modes change rate of the blade: (a) 1st order, (b) 2nd order, and (c) 3rd order.](image-url)
Figure 8: Change trend of the strain modes at each observation point: (a) A1 unit damage, (b) A2 unit damage, (c) A3 unit damage, (d) A4 unit damage, and (e) A5 unit damage.
allocation ratio of the displacement mode was defined as follows [31]:

$$C_w = \frac{|\varphi_{ig} - \varphi'_{ig}|}{\sum_{i,j=1}^{n} |\varphi_{ij} - \varphi'_{ij}|} \times 100\%.$$  \hspace{1cm} (4)

Taking a blade with a unit damage degree of 60% and a speed of 17 rad/s as an example for analysis, the change allocation ratio of the first 3-order displacement modes at each observation point ($C_w$) is shown in Figure 6. It can be seen that the change allocation ratio of the first 3-order displacement modes before and after the damage was more obvious at the damage location than in other positions. Therefore, the change in displacement modes before and after damage could be used to locate the damage position of the blade in the running state.

### 3.2.2 Damage identification on strain mode

#### 3.2.2.1 Identification of damage degree

To show more intuitively the influence of damage on the displacement mode, the rate of change of the displacement mode was processed as follows:

$$Q_r = \frac{\psi_{ig} - \psi'_{ig}}{\psi_{ig}},$$  \hspace{1cm} (5)

where $\psi_{ig}$ is the displacement mode before the damage, and $\psi'_{ig}$ is the displacement mode after the damage.

Taking the damage of the $A_1$ unit as an example, the change rate of the first 3-order displacement modes after

![Figure 9: Comparison of $C_w$ and $C_f$: (a) 1st order, (b) 2nd order, and (c) 3rd order.](image-url)
the square root processing at the corresponding observation point \((Q_i)\) are shown in Figure 7. It can be seen that the change rate of the first 3-order strain modes of the blades increased with the increase in the damage degree. Therefore, the change in the strain modes of the blade could be used as the basis for judging the degree of blade damage in the operating state. When the blade damage degrees were the same, the change rate of the first 3-order strain modes of the blade increased with the increase in the speed. It showed that the sensitivity of damage identification based on strain modes gradually increased with the increase in speed. When the speed increases from 5 to 20 rad/s, the maximum change in the change rate of strain modes was 9.70%.

### 3.2.2.2 Recognition of damage location

To show more intuitively the difference of the strain mode at each observation point, the change allocation ratio of the strain mode was defined as follows [31]:

\[
C_y = \frac{\sum_{i=g=1}^{n} |\psi_{ig} - \psi'_{ig}|}{\sum_{i=g=1}^{n} |\psi_{ig}|} \times 100\%.
\] (6)

Taking a blade with a unit damage degree of 60% and a speed of 17 rad/s as an example for analysis, the change allocation ratio of the first 3-order strain modes at each observation point \((C_y)\) is shown in Figure 8. It can be seen that the change allocation ratio of the first 3-order strain modes before and after the damage was more obvious at the damage location than in other positions. Therefore, the change in strain modes before and after the damage could be used to locate the damage position of the blade in the running state.

### 3.2.3 Comparison of damage identification effect based on displacement mode and strain mode

Taking a blade with a unit damage degree of 80% and a speed of 17 rad/s as an example for analysis, the comparison of the change allocation ratio of displacement mode \((C_w)\) and the change allocation ratio of strain mode \((C_y)\) is shown in Figure 9. It can be seen that the change allocation ratio of strain mode \((C_y)\) was higher than the change allocation ratio of displacement mode \((C_w)\) when the damage degree was the same. Therefore, the recognition effect of the strain mode was more significant than that of the displacement mode when performing damage recognition of the blade in the running state.

### 4 Conclusion

1. The change rate of natural frequency, displacement modes, and strain modes of the blades increased with the increase in the damage degree;
2. The change rate of the natural frequency and displacement modes of the blade decreased with the increase in the speed, while the change rate of the strain modes increased;
3. The change allocation ratio of the displacement modes and strain modes after the damage was more obvious at the damage location than at other positions, which can be used to locate the damage position of the blade;
4. The change allocation ratio of strain modes is higher than the change allocation ratio of displacement modes when the damage degree is the same, which means that the recognition effect of the strain modes is more significant than that of the displacement modes.

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