Research on the defect types judgment in wind turbine blades using ultrasonic NDT

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Abstract. Because of the complex internal structure of wind turbine blades, there are many types of defects. There will be important significance to determine the type of defects to assess the blade residual life and feedback on the design and production process. At present the type of defects found by ultrasonic nondestructive testing (NDT) can't be determined. Physical models of several typical defects are constructed. The sound intensity reflection coefficients of different physical models are calculated separately, and the calculation method of the sound intensity reflection coefficient of actual defect is presented. Combined the calculated coefficients with the defect information tested, a method of recognize the type of defects is presented. Actual specimen testing is used to verify the effectiveness of the method.

1. Introduction
Wind energy is an important renewable energy. It is still a period of rapid development of wind power for China. Life and safety of wind power generator affects the pace of the utilization and development of wind power, and is the important factor for rapid and healthy development. Wind turbine blades as one of the wind turbine’s foundation and key components, its service life and safety directly affects the life of the wind turbine and its security situation. In the process of the blades’ production and operation, there will be structural and composite materials damages because of the production process and operation conditions. The damages will expansion under the effect of complex alternating load during operation, and then weak parts will appear. Eventually the life and operation safety of the blade will be reduced [1].

In order to guarantee the life and the safety of wind turbine blades, it is necessary to carry out the defect diagnosis. These defects in the blades can not be found out using conventional quality inspection. Nondestructive testing (NDT) is a kind of testing method that can find internal defects without destroying the structure of objects. Ultrasonic NDT technology has the advantage of larger penetration, greater sensitivity for plane type defects, more accurate judgments for depth and size, more safety operation, and so on. We can try to use the NDT method to search for defects in wind turbine blades.

There are many types of defects in wind turbine blades. Firstly, the defect types judgment in finished wind turbine blades can feedback on the design and production process to improve the quality of the product. Secondly, the defect type judgment can help to assess the blade residual life, because
different defect types will have different effects on the blade in the process of operation. So the defect type judgment in wind turbine blades is very important. The judgment can also be carried out with ultrasonic NDT method. According to the literature study, the present applications of ultrasonic NDT in wind turbine blades or glass fiber reinforced plastics are if the the defects can be found [2], or how to find defects [3]. No research on the defect type judgment is published yet. Different types of defects may have similar ultrasonic signals in the process of NDT on wind turbine blades. How to use the echo signal of defect to determine the defect type is the article research content. Physical models of several typical defects are constructed. The sound intensity reflection coefficients of different physical models are calculated separately, and the calculation method of the sound intensity reflection coefficient of actual defect is presented. Combined the calculated coefficients with the defect information tested, a method of recognize the type of defects is presented. Actual specimen testing is used to verify the effectiveness of the method.

2. Analysis of several typical defects in blade
Defects are often generated due to production process in wind turbine blade manufacturing process. Inclusions, lack of structural adhesive glue and other defects are generated due to the randomness of human action. Delamination, gas holes and other defects are generated in the infusion process. With the comprehensive effect of load, vibration and environmental factors like sheat, acid and alkali, the initial defects will be extended, and new defects or damages like delamination and fracture will be generated.

Delamination defects are generated between the fiber laminates. It’s generated in the interlayer by the low energy impact in the production process and operation conditions. When composite material containing delamination defect is under external load, local buckling will occur, causing delamination growth, resulting early damage of laminates, and the bearing capacity is greatly reduced [4]. There is gap between laminates containing delamination defect [2].

Gas holes are generated by the bubbles in resin in the production process, causing local fiber not saturated. Gas holes include the pores in glass fiber cloth layer bundle, the pores between bundles, and the pores between the glass fiber clothes. The presence of gas hole will reduce the fatigue performance of wind turbine blades [5].

Inclusion defects are generated because of the foreign body in layer or perfusion resin. The presence of inclusion will reduce the mechanical properties of wind turbine blades [5].

Structural adhesive lacked defects are generated when the structural adhesive does not fill between the girder and shell or between the two shells of the trailing/front edge. The scope of contact between two structures can not be completely filled with structural adhesive. The defects directly affect the internal force transfer between the bearing force structures in the blades, reducing the load bearing ability of blades [6].

Through analysis of the typical defects above, there are two kinds of interface with different properties in the damage surface.

3. Judgment Method

3.1. Analysis of the principle of ultrasonic nondestructive testing
The frequency range of ultrasonic used in NDT is generally between 0.25 MHz~15 MHz. The ultrasonic wave can spread in a certain speed and direction in the material, when it meet heterointerface with different acoustic impedance, such as defect or the bottom surface of the measured object, a reflection will be produced. The common method for detection is pulse echo testing at present. Pulse oscillator sends out voltage to the probe, while ultrasonic pulse generated by the probe propagates through the coupling agent into the material. When the ultrasonic wave meets the defects, partial reflection wave transfers along the original way and returns to the probe. The probe transforms the wave into electric pulse, and the pulse is amplified and displayed on the screen by the instrument. The principle of ultrasonic NDT is shown in figure 1. According to the location and
amplitude of the reflected wave of defect showed on the screen, the position and the approximate size of defects can be determined [7].

![Figure 1. Principle of ultrasonic NDT.](image1)

Through analysis of typical defects of blades, in the delamination, gas hole, inclusion and Structural adhesive lacked defects, there are different acoustic impedance interfaces, such as interfaces between the composite material and air or composite materials and impurities. This interface can reflect ultrasonic wave.

Combined with the principle of ultrasonic and the generalization of blade defects, the blade defects above can be simplified to two physical models, glass fiber reinforced plastics-air (GFRP-Air) and glass fiber reinforced plastic-impurity (GFRP-Impurity), shown in figures 2 and 3, respectively. The delamination, gas hole, Structural adhesive lacked defects are simplified to GFRP-Air physical model, and the inclusion defect is simplified to GFRP-impurity physical model.

![Figure 2. GFRP-Air physical model.](image2)

![Figure 3. GFRP-Impurity physical model.](image3)
Ultrasonic NDT relies on the identification of reflection wave from the defect interface. The intensity of the sound wave reflection and transmission related to material on either side of the interface. The intensity can be reflected by the sound intensity reflection coefficient and transmission coefficient. Sound intensity reflection coefficient $R$ and the transmission coefficient $T$ can be expressed by equations (1) and (2).

\[
R = \frac{I_r}{I_o} = \left( \frac{P_r}{P_o} \right)^2 = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2
\]  

\[
T = \frac{I_t}{I_o} = \left( \frac{P_r^2}{2Z_2} \right) \left( \frac{P_o^2}{2Z_1} \right) = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2}
\]  

$I_o$ refers to the sound intensity of incident wave, $I_r$ refers to the sound intensity of reflection wave, $I_t$ refers to the sound intensity of transmission wave, $Z_1$ refers to the acoustic impedance of acoustic outgoing materials, $Z_2$ refers to the acoustic impedance of acoustic incoming materials, $P_o$ refers to the sound pressure of incident wave, $P_r$ refers to the sound pressure of reflection wave, $P_t$ refers to the sound pressure of transmission wave. Acoustic impedance $Z$ can be expressed by equation (3).

\[
Z = \rho V_L
\]  

$\rho$ refers to the density of the material, $V_L$ refers to the longitudinal wave velocity.

From the equations (1) and (3) it can be seen that there will be different material interface in different physical models, and different material interface will produce different sound intensity reflection coefficient. When a material is fixed as the premise of GFRP, the sound intensity reflection coefficient of each defect interface is unique. So we can determine the corresponding physical model of defect according to the sound intensity reflection coefficient.

In order to determine the physical model corresponding to the actual defects, the two sound intensity reflection coefficients of physical model interface and actual defect interface, and compare the two coefficients with each other.

3.2. The sound intensity reflection coefficient of physical model interface

The structure of GFRP with actual defects can be shown in figure 4. The material around the defect is made by glass cloth layer and resin layer alternately. The GFRP in physical models in figures 2 and 3 will be simplified to homogeneous material.

![Figure 4. Structure of GFRP with actual defect.](image)
\[ Z_1 = \rho_1 V_{L1} \]  \hspace{1cm} (4)  

\[ Z_2 = \overline{\rho_2} V_{L2} \]  \hspace{1cm} (5)

\( \rho_1 \) refers to the density of defect material, \( V_{L1} \) refers to the longitudinal wave velocity of defect material, \( \overline{\rho_2} \) refers to the average density of GFRP, \( V_{L2} \) refers to the average longitudinal wave velocity.

3.3. The sound intensity reflection coefficient of actual defect interface

Similar to the simplification of the physical model of GFRP, in the actual defects detection process, each layer echoes before the defect echo will be seen as attenuation of acoustic waves as shown in figure 5.

![Figure 5. Actual defect detection echo sketch.](image)

It’s still need to rely on equation (1) to calculate the sound intensity reflection coefficient of actual defect interface. When using ultrasonic testing, sound pressure is directly proportional to the screen wave height.

\[ \frac{P_1}{P_2} = \frac{H_1}{H_2} \]  \hspace{1cm} (6)

\( P_1 \) refers to the sound pressure of position 1, \( P_2 \) refers to the sound pressure of position 2, \( H_1 \) refers to the screen wave height of position 1, \( H_2 \) refers to the screen wave height of position 2.

By the relationship between sound pressure and the screen wave height from equation (6), the sound intensity reflection coefficient of actual defect interface can be expressed through the screen wave height.

\[ R_1 = \frac{I_{r-1}}{I_{o-1}} = \left( \frac{P_{r-1}}{P_{o-1}} \right)^2 = \left( \frac{H_{r-1}}{H_{o-1}} \right)^2 \]  \hspace{1cm} (7)

\( I_{o-1} \) refers to the defect sound intensity of incident wave, \( I_{r-1} \) refers to the defect sound intensity of reflection wave, \( P_{o-1} \) refers to the defect sound pressure of incident wave, \( P_{r-1} \) refers to the defect sound pressure of reflection wave, \( H_{o-1} \) refers to the defect screen wave height of incident wave, \( H_{r-1} \) refers to the defect screen wave height of reflection wave.

Reflecting type ultrasonic NDT carries out detection by seeing the echo of target on the screen. If it meets the defect, there will be the reflection wave echo in the defect position on the screen. The defect screen wave height of reflection wave \( H_{r-1} \) can be read directly from the screen. But the
defect screen wave height of incident wave $H_{o-1}$ is virtual, which is unable to read from the screen, needing conversion with other parameters.

![Non-Defect location Defect location](image)

**Figure 6.** Schematic diagram of defect testing.

The schematic diagram of defect testing is shown in figure 6. In the location of defect testing, o-1 is the incident wave, in the GFRP - defect interface, part of the incident wave reflects back as reflection wave r-1, and the other part transmit into the defect as transmission wave t-1. In the location of non-defect testing, o-2 is the incident wave, in the GFRP-air interface, part of the incident wave reflects back reflection wave r-2, and the other part transmits into air transmission wave t-2. The incident wave height $H_{o-1}$ in defect position needs conversion with the incident wave height $H_{o-2}$ in non-defect position by considering as material attenuation from defect to bottom surface. And then $H_{o-2}$ can be got by the reflection wave height $H_{r-2}$ in non-defect position with the help of sound intensity reflection coefficient of GFRP-air interface $R_2$. And the reflection wave height $H_{r-2}$ in non-defect position can be got from the ultrasonic instrument’s screen when scanning non-defect position.

Basing on the derivation above, incident wave height $H_{o-2}$ can be got by equation (7), showing as equation (8).

$$H_{o-2} = \frac{H_{r-2}}{\sqrt{R_2}}$$  \hspace{1cm} (8)

The relationship among sound pressure, wave height and decibel is known as follows.

$$\text{decibel} = 20\log \frac{P_1}{P_2} = 20\log \frac{H_1}{H_2}$$  \hspace{1cm} (9)

The incident wave height of defect interface can be got by equation (9), shown as equation (10):

$$H_{o-1} = H_{o-2} \times 10^{\frac{\text{decibel}}{20}}$$  \hspace{1cm} (10)

The sound intensity reflection coefficient of actual defect interface can be got combined with equations (7), (8) and (10).
\[ R_i = \left( \frac{H_{r-1}}{H_{n-1}} \right)^2 = \left( \frac{H_{r-1} \times \sqrt{\frac{R_2}{\text{deci}}} \times 10^{-20}}{H_{r-2} \times 10^{-20}} \right)^2 \] (11)

3.4. Judgment of the defect types

By comparing the sound reflection coefficient of actual defect interface and physical model interface, the type of physical model of the defect can be determined. If it’s corresponding to the GFRP-Impurity model, the defect type is inclusion. If it’s corresponding to the GFRP-air model, the type of defect will be determined according to the position and size. If defect appears in the GFRP layer, with continuous and large size, it’s delamination defect. If defect appears in the GFRP layer, with discontinuous and small size, it’s bubble defect. If defect appears out of the GFRP layer, it is judged as structural adhesive lacked defect.

4. Experiment and analysis of ultrasonic NDT

In order to verify this method, a specimen with pre-setting defect is prepared to carry out actual test. Thickness of the GFRP specimen as shown in figure 7 is 20 mm.

**Figure 7.** GFRP specimen being tested.

Firstly the sound intensity reflection coefficients of both GFRP-Air and GFRP-Impurity physical model interface will be calculated.

In the GFRP-Air physical model, ultrasonic transmits into air from GFRP. The average density of GFRP is 1.8×10³ Kg/m³, the average longitudinal velocity of GFRP is 3000 m/s, the density of the air is 1.29 Kg/m³, and the longitudinal velocity of air is 340 m/s. Using equations (1) and (3), the sound intensity reflection coefficient from GFRP to air is 0.998.

Teflon is used as the inclusion in GFRP-Inclusion physical model in this test, because in the process of wind turbine, teflon is most likely as the mixed material. The density of teflon is 2.2×10³ Kg/m³, longitudinal velocity of teflon is 1350 m/s. By calculating, we can get the sound intensity reflection coefficient from GFRP to teflon is 0.084.

Next step is to calculate the interface sound interface reflection coefficient of actual defect. Ultrasonic NDT on the specimen is needed.

In the defect location, echo image is shown in figure 8, showing there is a defect in 15 mm in depth. The defect reflection wave height \( H_{r-15} \) is 86% of the screen height in 51.5 dB gain conditions.

In the non-defect location, echo image is shown in figure 9, showing the bottom surface is in 15 mm in depth. The bottom surface reflection wave height \( H_{r-20} \) is 58% of the screen height in 51.5 dB gain conditions.
The incident wave in 20 mm depth is attenuated from the incident wave in 15 mm depth. In order to determine the attenuation of GFRP materials, another GFRP specimen is prepared to measure ultrasonic decibel values in different depth. And the curve shown in figure 10 is fitted by the decibel values.

Though the image in figure 10, we can get the decibel in 15 mm depth is 41 dB, the decibel in 20 mm depth is 37.5 dB, and the attention decibel is 3.5 dB.

Using the bottom surface reflection wave height $H_{r-20}$, the defect reflection wave height $H_{r-15}$, the attention decibel, and the equation (11), we get the sound interface reflection coefficient of defect in 15 mm is 0.982. By comparison with the sound interface reflection coefficient of
physical models, considering the influence of error, physical model of the actual defect can be determined as the GFRP-Air model.

Though testing range of the defect is about 30 mm*30 mm, and 15 mm in depth. The defect appears in the GFRP layer, with continuous and large size, so it’s delamination defect belonging to the GFRP-Air model.

The selected specimen has a flat bottom hold in 15mm depth, used to simulate the delamination defect. Through the analysis above and comparison with practical specimen, this method is proved to be effective.

Using this method, through actual specimens of delamination, gas hole, inclusion and structural adhesive lacked defects can also be determined the types of defects.

5. Conclusion

- Due to the complexity of the design, production and operation of wind turbine blades, there may lead to many defects. It has good application prospect to use ultrasonic NDT on the flaw detection of blades.
- By establishing and analyzing physical models of typical defects, comparing with actual test of defect specimen, it is proved judgment of type of the typical defects can be realized, using the analysis of sound intensity reflection coefficient in ultrasonic flaw detection of wind turbine blades.
- In actual detection, we can calculate the actual sound intensity reflection coefficient, compare it with physical models of typical defects, confirm the type of models and determine the type of defect combining the information such as location and size.
- Through the calculation of sound intensity reflection coefficient, we can also guide the manufacture of defect simulating specimen, getting specimens as close as possible to the physical model and actual defects.

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