Crack Location and Degree Identification of Wind Turbine Blades by Nature Frequency Analysis

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***Abstract*—Wind turbine (WT) blade cracks will affect the safe operation of the WT, and the diagnosis of blade cracks is of paramount importance. The cracks will influence in the natural frequency of the blade. Taking the ratio of the adjacent two-order natural frequency variation of crack blade, it is found that the ratio is only related to the crack position. Blade is fictitiously divided into multiple connected regions and implanted the crack at each joint point of regions to establish the database of the ratio parameters for crack locating. Combining the database, the crack position criteria are proposed and the region of the crack can be ascertained. Then, a position parameter in the region is proposed, and the mapping between this parameter and the specific position within the region is established. The crack can be located more accurately in the region. A parameter of crack degree is proposed, that is, the ratio of the variation of the natural frequency to the natural frequency itself. For the same position, the correspondence between the parameter and the degree of crack is established. After crack locating, the degree of crack can be ascertained by the correspondence. The numerical simulation analysis and experimental results show that the method is effective and accurate.**

Keywords- wind turbine blade, natural frequenc, crack position, crack degree

I. INTRODUCTION

In recent years, the massive use of fossil fuels has led to more and more serious damage to the global ecological environment. In order to protect it, countries have begun to vigorously promote the use of green and clean energy. Wind energy is a common and used one. At present, China has become the country with the largest installed capacity of wind power in the world. It is estimated that by 2020, the installed capacity of wind power in China will reach 100GW [1-2].

WT blades are key components of WT and expensive, and the cost can account for 15%-20% of the cost of WT assembly machines [3]. The blade is in a harsh environment and the operating conditions are complicated. The blade is subjected to long-term cyclic loading during operation, causing material is degraded and fatigued to germination crack. If the crack cannot be repaired in time, it will rapidly expand and cause a rotational unbalance, which may cause the tower to collapse and a major safety accident [4]. Therefore, the regular monitoring and continuous assessment of the blades structural health status are great significant [5].

In the past decades, many scholars have studied a variety of nondestructive testing (NDT) methods for structural damage detection, such as optical fiber, acoustic emission, ultrasound, X-ray and thermal imaging [6-9], etc. It is necessary to be near the crack position in the detection process, and it is difficult to accurately diagnose and qualitatively analyze the blade crack. Damage can also be identified by blade vibration response. It can save time and reduce costs without approaching the area near the crack position [10], it is suitable for online monitoring [11]. The generation of cracks will cause the blade structure to change, which will lead to the change of structural modal parameters. Therefore, the change of blade modal parameters can be regarded as the basis for the diagnosis of crack generation [12-17].

Modal parameters are structural physical properties that generally include natural frequencies, modal shape, and modal damping. Many scholars [12-14] also use modal shape parameters to detect the damage in the structure, and can detect the extent and position of the damage to a certain extent. In practical application, the difference curvature of modal mode shapes of blades caused by cracks is small (10^{-4}), and the test noise will lead to the measurement error of the modal mode is large, damage identification reliability is low. Structural damage detection by natural frequency parameters has been widely used in a variety of practical structures [15-17]. In the low damping structure, the natural frequency test accuracy reaches 99.9% or even higher [15], and it is simple to measure. Most scholars determine the structure's damage and the position of the damage by measuring the natural frequency variation of the structure. For example, Cawly and Adams [16] proposed a method for identifying damage using a ratio of nature frequency variation, and theoretically proved that when a structure is damaged, the ratio of any two-order natural frequency change is only related to the position of the damage. Zhang K et al. [17] proposed a high-precision cantilever natural frequency acquisition method, which can describe the natural frequency change rate and crack characteristics of the cantilever with variable section. Based on the above analyses, there is a problem that only the position of the unit in which the damage exists can be determined, resulting in a low positioning accuracy. The reliability of the damage is further reduced.

In this paper, multiple crack positions were taken on the blade, the variation of the natural frequency of the blade and the intact blade at different crack positions is studied, and the database of blade crack position parameters is established. Through the crack position parameters and crack region position method proposed in this paper, the position of the crack belongs to the region. The relationship between the crack

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position and the position parameters is studied to precisely locate the crack position. The relation between degree of crack and crack position was studied, and degree function model of the crack was established for different crack positions of WT blades. When the crack position is determined, the blade crack degree can be accurately ascertaind.

II. THEORY

A. Review of blade modal characteristics analysis

In this paper, the effect of blade structure damage on natural frequency is studied, ignoring the influence of environment and damping, then the vibration equation of the structure is as follows [18]

$$(\mathbf{K}-\omega^2\mathbf{M})\phi=0 \tag{1}$$

where **K** and **M** are the global stiffness and mass matrices of the structure, respectively; ϕ and ω are the natural frequencies and modal shape of the system, respectively. When the structure is damaged, small changes in stiffness or mass produce small changes in ω^2 and ϕ. The vibration eigenvalue equation of the structure is

$$\left[(\mathbf{K}+\Delta\mathbf{K})-(\omega^2+\Delta\omega^2)(\mathbf{M}+\Delta\mathbf{M})\right](\phi+\Delta\phi)=0 \tag{2}$$

Neglecting $\Delta\mathbf{M}$ and second-order terms, Eq. (2) leads to

$$\Delta\omega^2=\frac{\phi^T\Delta\mathbf{K}\phi}{\phi^T\mathbf{M}\phi} \tag{3}$$

Then the square of the natural frequency variation of the ith order is

$$\Delta\omega_i^2=\frac{\phi_i^T\Delta\mathbf{K}\phi_i}{\phi_i^T\mathbf{M}\phi_i} \tag{4}$$

In order to obtain the relationship between the unit damage and the change of the global vibration response, the global stiffness **K** is decomposed into the stiffness matrix k_N, and the natural modal shape ϕ is calculated by the deformation of a single component $\varepsilon_N(\phi)$.

$$\phi^T\Delta\mathbf{K}\phi=\sum_N\varepsilon_N^T(\phi)\Delta k_N\varepsilon_N(\phi) \tag{5}$$

where N is the damage unit number, ε_N and Δk_N are the unit deformation vector and the unit stiffness variation, respectively. When the structure has a single damage, and the damage position is N, Eq. (5) can be rewritten as

$$\Delta\omega^2=\frac{\varepsilon_N^T(\phi)\Delta k_N\varepsilon_N(\phi)}{\phi^T\mathbf{M}\phi} \tag{6}$$

The unit damage coefficient α_N was defined

$$\Delta k=\alpha_N k_N \tag{7}$$

For damage in a single member N, Eq. (6) can be rewritten as

$$\Delta\omega_i^2=\frac{\alpha_N\varepsilon_N^T(\phi_i)\Delta k_N\varepsilon_N(\phi_i)}{\phi_i^T\mathbf{M}\phi_i} \tag{8}$$

Similarly, the square of the natural frequency change of the jth order can be obtained, the two equations are divided

$$\frac{\Delta\omega_i^2}{\Delta\omega_j^2}=\frac{\dfrac{\alpha_N\varepsilon_N^T(\phi_i)\Delta k_N\varepsilon_N(\phi_i)}{\phi_i^T\mathbf{M}\phi_i}}{\dfrac{\alpha_N\varepsilon_N^T(\phi_j)\Delta k_N\varepsilon_N(\phi_j)}{\phi_j^T\mathbf{M}\phi_j}} \tag{9}$$

In the case of a single crack damage, it can be calculated by Eq. (9). When the right side of the equation is equal to the left side, the damage occurs in the unit. The ratio of any two-order natural frequency variation of the WT blade is equal when the blade cracks in the same position. The position of the crack can be identified by calculating the ratio of any two-order natural frequency variation of the blade at different crack positions.

B. Blade crack position parameters

According to the above analysis, most scholars can only locate the unit or component to which the structural damage belongs by using the natural frequency parameter. That it is difficult to accurately locate the damage position in the actual structure. In this paper, the blade crack position parameters are proposed to accurately locate the blade crack position.

In a single cracked blade, the distance between the crack and the blade root is denoted as

$$L_c(n)=\Delta d\cdot n\ (n=1、2、\ldots、N_M) \tag{10}$$

where n is the blade crack position number, and N_M is the number of blade crack position, and Δd is the distance between two adjacent cracks of the blade. For a blade with a crack at the $L_c(n)$ position, the ith crack natural frequency parameter was defined

$$C_i^n=\frac{\Delta\omega_i}{\Delta\omega_{i+1}}=\frac{\omega_i^*-\omega_i}{\omega_{i+1}^*-\omega_{i+1}} \tag{11}$$

That is, the ratio of adjacent two-order of natural frequency variation, where ω_i^* is the ith order natural frequency of the blade without cracks.

The single crack position parameter $\boldsymbol{H}_n$ of the blade is established

$$\boldsymbol{H}_n=\left(C_1^n\ \ C_2^n\ \ C_3^n\ \ C_4^n\right)^T \tag{12}$$

It can be known that the value of the parameter $\boldsymbol{H}_n$ will correspond one by one with the crack position $L_c(n)$. For blades of the same type of WT, the difference value of crack position parameters $\boldsymbol{H}_n$ with different damage degrees at the same position is equal to or close to 0. Therefore, the blade is fictitiously divided into multiple connected regions. Implant the crack at each joint point of regions to establish the database of the ratio parameters for crack locating through experiment or simulation analysis. The database is used to provide data support for crack position.

III. HIGH PRECISION LOCATIONING METHOD FOR BLADE CRACKS

According to the analysis in section II, this part will introduce a high precision crack position method based on $\boldsymbol{H}_n$. The proposed method also provides a necessary basis for the identification degree of crack subsequent blades.

A. Establishment of the blade crack position parameter database

According to the investigation, it was found that the position of 30-35% L and 70% L from the root of the blade is prone to cracks [19], and L is the total length of the blade. Therefore, when establishing the blade crack position parameter database, only the positions within 80%L are considered in the crack implantation.

In this paper, a type of WT blade is taken as the research object, and its blade structure diagram and 3-dimensional (3-D) model are shown in Figure 1.The blade root length L_1=0.5 m, the blade length L=19 m, the blade maximum width b=3 m, maximum height h=2 m, crack position distance from blade root is denoted as L_c, crack depth is denoted as d. The blade material is glass fiber composite material. Its elastic modulus is 73 GPa, Poisson's ratio is 0.23, and its density is 2540 kg/m^3.

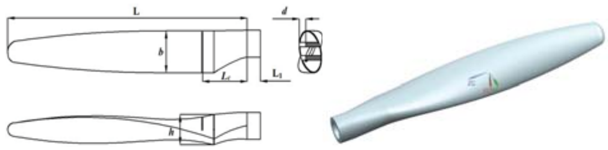

Figure 1 WT blade structure diagram and 3-D model

For this type of blade, a single crack position parameter $\boldsymbol{H}_n$ is established. The crack position region in the database is Δd = 0.5 m, and the number of crack position s is N_M=30, Eq. (10) can be rewritten as

$$L_c(n)= 0.5n \ \ (n=1、2、\ldots、30) \tag{13}$$

For the cracked blade at $L_c(n)$ position, FE software is used to calculate and simulate its natural frequency, and the crack position parameters and $\boldsymbol{H}_n$ are calculated. In order to prevent calculation errors, the average value of calculation results was taken to obtain the parameter database of blade crack position for this model. The partial data is shown in Tab. I.

TABLE I. PARTIAL BLADE CRACK POSITION NATURAL FREQUENCY DIFFERENCE RATIO DATABASE

$\bar{C}_i^n$		Crack position n				
		1	**2**	**3**	**4**	**5**
i	1	2.644	2.446	2.238	2.078	1.974
	2	0.178	0.169	0.171	0.173	0.172
	3	0.569	0.731	0.870	1.022	1.185
	4	2.714	2.606	2.536	2.498	2.484

B. Blade crack region locating method

Take the crack position of the blade as x away from the blade root, and define the crack position parameter $P_{n,x}$ was defined and

$$P_{n,x} = \left| \bar{\boldsymbol{H}}_n - \boldsymbol{H}_x \right| = \sum_{i=1}^{3} \left(\bar{C}_i^n - C_i^x \right)^2 \tag{14}$$

where $\boldsymbol{H}_x$ and C_i^x are position parameter and natural frequency parameter of the blade to be diagnosed, respectively.

In this paper, the crack region locating criteria are proposed as follows:

- For the blade with a crack at x, Eq. (14) is used to calculate the crack posoition parameter $P_{n,\,x}$ of the WT blade, and obtain the crack position r corresponding to the minimum value of $P_{n,\,x}$.
- According to the calculated r, the value of $P_{r\text{-}1,\,x}$ and $P_{r+1,\,x}$ is compared, and get the crack position t corresponding to the minimum value.

Based on the above crack locating parameters and region locating method, the position of crack region can be located.

C. Blade crack position method within the crack region

Considering that there are many types of WT blades, it is difficult to obtain the database of all crack positions of WT blades of each type. The identification of blade degree of crack depends on the accuracy of crack position. Therefore, based on the above mentioned blade crack region locating method, the accurate localization within the crack region is further studied to achieve the accurate localization of the crack position.

In this paper, the blade crack position region in the database is 0.5 m. According to the above crack region locating method, if the crack localization is within the region [r, r+1], and assuming that the crack moves within the region. The law of the crack localization parameters $P_{r,x}$ and $P_{r+1,x}$ changes with the crack position is studied, and the fitting curves of $P_{r,x}$ and $P_{r+1,x}$ are denoted as $P_r(x)$ and $P'_r(x)$, respectively. For the variation of the crack position in all the regions, the partial region fitting curve is shown in Figure 2.

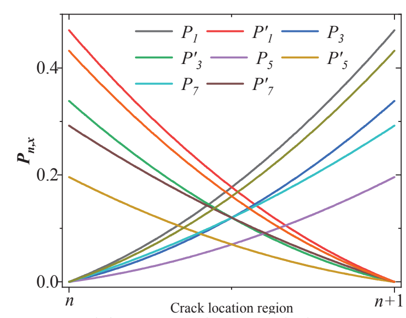

Figure 2 Natural frequency change ratio between r and r+1

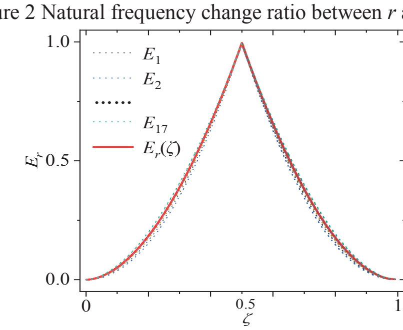

Figure 3 Curve ratio diagram

It can be seen from Figure 2, the fitting curve $P_r(x)$ of each region has the same trend as that of $P'_r(x)$, but there is no coincidence. In order to obtain the common characteristics of each region $P_{r,x}$ and $P_{r+1,x}$ varying with the crack position, the ratio of $P_r(x)$ to $P'_r(x)$ is taken in this paper, i.e

A new curve $E_r(x)$ is obtained from Eq. (15), and the region [r, r+1] is converted into the parameter space of [0, 1]. The shape of E_r curves of each region in the parameter space is shown in the dotted line in Figure 3. The curves are very close to each other and almost coincide, that is, E_r parameters are the common characteristics of crack positions in each region.

$$E_r=\begin{cases}\dfrac{P_r(x)}{P_r'(x)} & P_r(x)\le P_r'(x)\\ \dfrac{P_r'(x)}{P_r(x)} & P_r'(x)<P_r(x)\end{cases}\tag{15}$$

Each curve $E_r(x)$ obtained is fitted to a curve, denoted as $E_r(\zeta)$, ζ is the relative position of the crack. The results are shown in Figure 3, the red curve line indicates $E_r(\zeta)$, and the expression is as follows

$$\boldsymbol{E}_r(\zeta)=\begin{cases}4.70945\zeta^{2.26385} & 0\le\zeta\le 0.5\\ 4.70945(-\zeta+1)^{2.26385} & 0.5\le\zeta\le 1\end{cases}\tag{16}$$

By observing the curve $E_r(\zeta)$ in Figure 3, it can be seen that the curve $E_r(\zeta)$ is symmetric about ζ=0.5. When $E_r(0.5)$=1, the values of P_r and P'_r are equal, that is, the crack is located at the midpoint of the region.

The curve $E_r(\zeta)$ is used as the basis for judging the accurate locating in the crack region. That is, a correspondence between the crack position x and the function $E_r(\zeta)$ is established. For the crack position in the region $[r, r+1]$, it can be seen from the Eq. (16) that the relative position ζ function of the crack is determined as follows

$$\zeta=\begin{cases}\left(\dfrac{E_r(\zeta)}{4.70945}\right)^{\frac{1}{2.26385}} & , \ P_{r,x}\ge P_{r+1,x}\\ 1-\left(\dfrac{E_r(\zeta)}{4.70945}\right)^{\frac{1}{2.26385}} & , \ P_{r+1,x}>P_{r,x}\end{cases}\tag{17}$$

According to the corresponding relationship between region $[r, r+1]$ and parameter space, the crack position within the region can be further determined

$$x=L_c(n)+\zeta\cdot\Delta d\tag{18}$$

In order to better describe the accuracy of blade crack position, the following accuracy calculation formula is used.

$$\beta_1=1-\frac{|x-x^*|}{L}\times 100\%\tag{19}$$

where x and x^* are the diagnosed crack position and the actual crack position, respectively. The accuracy of crack position can be evaluated based on Eq. (19).

D. Accurate method for the crack locating of blade

Based on the above blade crack locating method, it can be known that the accurate crack position method proposed in this paper is as follows:

- The natural frequency parameters were obtained by means of experimental test or simulation analysis. Furthermore, the blade crack position parameter database is established. The corresponding relation between the crack position in the region and the locating parameter $E_r(x)$ was obtained.
- By monitoring the natural frequency information of the blade in real time, the crack locating parameters of the blade are obtained and the crack region is located.
- Calculate the locating parameters within the region based on Eq. (15), and obtain the exact position of the crack from the function of the crack position within the region.

IV. IDENTIFICATION METHOD OF BLADE DEGREE OF CRACK

A. Identification parameters of blade degree of crack

When the blade crack position is determined, the greater the degree of crack damage, the greater the amount of change in the natural frequency.

According to Eqs. (1) and (4)

$$\frac{\Delta\omega_i^2}{\omega_i^2}=\frac{\phi_i^T\mathbf{K}\phi_i}{\phi_i^T\Delta\mathbf{K}\phi_i}\tag{20}$$

Substitute Eqs. (6) and (7) into equation (13) to obtain

$$\delta=\frac{\Delta\omega_i^2}{\omega_i^2}=\frac{\varepsilon_N^T(\phi_i)\Delta k_N\varepsilon_N(\phi_i)}{\phi_i^T\Delta\mathbf{K}\phi_i}\tag{21}$$

It can be seen from the Eq. (21), δ is related to the crack position N and the degree of damage Δk_x. When the crack position is determined, there is a correspondence between δ and the degree of blade crack. Therefore, this relationship can be used to identify the degree of crack. On the contrary, when the blade crack locating error is large, it will affect the crack degree identification.

B. Study on parameters of degree of crack

In this paper, the ratio of crack depth to blade thickness is used to define the degree of crack damage, it can be written as

$$\alpha_x=\frac{d_x}{h_x}\times 100\%\tag{22}$$

where d_x and h_x are blade crack depth and the height of the section to which the blade crack belongs, respectively, and the subscript x represents the crack position. We can establish the relationship between the degree of crack α_x and the crack identification coefficient index parameter $\delta(x)$. Identify the different degrees of blade cracks through their correspondence.

In order to obtain the relationship between the damage degree and the position of the this type blade, n=4, 6, 8, 12, 16, 20, 24 are respectively taken according to Eq (13), and the degree of crack is taken as α=0, 10%, ... , 60%. The natural frequency of the corresponding cracked blade is obtained by numerical simulation, and the value of the degree of crack coefficient index parameter $\delta(x)$ is calculated by the Eq. (21).To study the relationship between $\delta(x)$ and the degree of crack, the obtained data is plotted as shown in Figure 4.

It can be seen from Figure 4 that when the crack position is determined, the value of $\delta(x)$ increases approximately as a power function as the degree of damage increases. Meanwhile, when the degree of crack damage is the same, the closer the crack position is to the root of the blade, the larger the value of $\delta(x)$ will be. According to the variation rule indicated by the icon in Figure 4, it will be fitted based on the following function

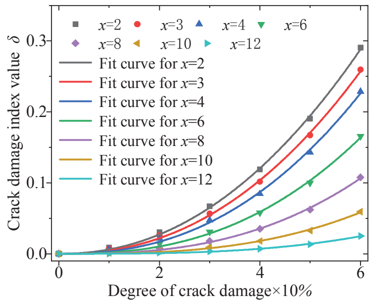

Figure 4 Diagram of damage position and extent

$$\delta(x)=p_x\,(0.1\alpha_x)^{q_x} \tag{23}$$

where p_x and q_x are the fitted power function coefficients and power function exponents, respectively.

Through the above fitted function, the relationship between $\delta(x)$ and α_x is obtained. By observing the function, it is found that both p_x and q_x are related to the crack position. According to the function of the above fitting, the values of 7 groups of p_x and q_x are obtained.

The functional relationship between p_x, q_x and crack position x in the above 7 groups was studied respectively. The relationship between p_x and q_x and the crack position x was drawn as a figure, as shown in Figure 5 and Figure 6. The vertical coordinates in Figure 5 is in *lg* ratio.

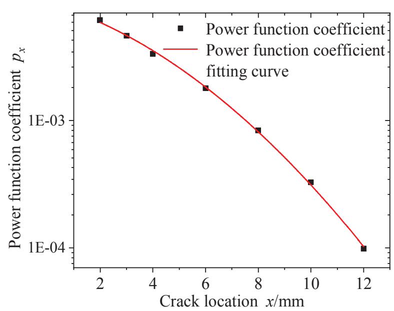

Figure 5 Power function coefficient and damage position map

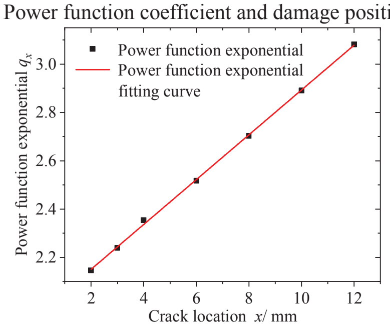

Figure 6 Power function index and damage position map

It can be seen from Figures 5 and 6 that lgp_x is approximately quadratic with the crack position, and the index q_x is approximately linear with the crack position. Its functional relationship can be fitted to

$$lgp_x=-2.07396-0.06133x-0.00819x^2 \tag{24}$$

$$q_x=1.9659+0.09271x \tag{25}$$

It can be seen from the above two equations that when the blade crack position x is determined, the relationship between $\delta(x)$ and α_x will also be determined, and then Eq. (23) is rewritten as

$$\delta(x)=10^{-2.07396-0.006133x-0.00819x^2}\left(\frac{\alpha_x}{0.1}\right)^{1.9659+0.09271x} \tag{26}$$

Eq. (26) can be used to identify the degree of crack at any position.

In order to describe the accuracy of blade crack identification, the absolute error of degree of crack identification is defined as

$$\beta_2=|\alpha_x-\alpha| \tag{27}$$

where α_x and α are the degree of crack diagnosed and the degree of actual damage, respectively. Based on the Eq. (26), the accuracy of the degree of blade crack can be ascertained.

C. Identification method of blade degree of crack

Through the study of the parameters of the damage degree coefficient of the cracked blade in Section IV-B. The method for identifying the degree of crack for any blade is as follows:

- Using experimental or simulation analysis methods, the relationship between the degree of crack α and the parameter δ at different crack positions is obtained. At the same time, the functional relation between crack position and damage degree is obtained.
- Based on the exact position x of the blade crack obtained in Section III, and the Eqs. (24, 25) of this Section, determine the relationship of the degree of crack position at x. By measuring the calculated natural frequency information of the blade, the crack degree coefficient parameter $\delta(x)$ is obtained, and the degree of crack is identified.

V. NUMERICAL EXAMPLE VERIFICATION

Based on the above mentioned WT blade crack diagnosis method, the model blade is also taken as an example. The crack is implanted at x^*=7.3 m, and the degree of crack α=53%. The natural frequency and natural frequency parameters of the cracked blade are calculated by simulation, as shown in Tab. II.

TABLE II. CRACK POSITION 7.3M BLADE FRONT 5TH NATURAL FREQUENCY

Natural frequency parameter	**Order *i***				
	1	**2**	**3**	**4**	**5**
$L_c(x)$ /Hz	3.94	7.02	23.81	24.57	38.06
C_i^n	0.623	0.057	0.061	0.241	

The natural frequency parameters of the cracked blade to be tested calculated from Table II. Eq. (12) can be written as

$$\boldsymbol{H}_x=\left(0.623\ 0.057\ 0.061\ 0.241\right)^T \tag{28}$$

The $P_{n,x}$ values can be obtained by the Eq. (14). The $P_{n,x}$ values is shown in Figure 7.

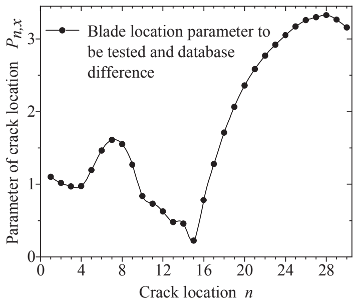

Figure 7 Sum of the difference between the blade crack position 7.3m and the database difference ratio

It can be seen from the Figure 7 that r=15 and t=14. It is shown that the blade crack position is located 7-7.5 m from the blade root and close to 7.5 m. In this case, x=7.3 m is indeed in this region, indicating that the crack region locating method is effective.

From the method of Section IV-D crack accurate position, it is known that $E_r(\zeta)$=0.84059 is obtained by the Eq. (15), and ζ=0.54456 is calculated by the Eq. (17). According to Eq. (18), x = 7.2728 m.

It can be known from Eq. (19) that the accuracy of crack blade locating is β_1=99.86%

The effectiveness of the proposed method for accurately locating cracks is verified by simulation examples.

The crack position of the crack blade mentioned above is accurately x=7.2728 m. Based on the identification of the degree of crack damage in Section IV, the power function coefficients and indices of the crack degree curve corresponding to x=7.2728 m are p_x=0.0011187896 and q_x=2.63912371, respectively. Then the degree of blade crack curve is

$$\delta_x=0.0011187896(\alpha_x/0.1)^{2.63912371} \tag{29}$$

Table II shows the natural frequency of the cracked blade. Calculated by Eq. (21), the blade damage degree parameter δ_x =0.087195567

The degree of blade crack is calculated by Eq. (29).

$$\alpha_x=5.209648\times10\%=52.09648\% \tag{30}$$

It can be seen from Eq. (27), the degree of crack identification error is β_2=0.90352%

Based on the above analysis and verification, the proposed crack diagnosis method using natural frequency can accurately diagnose crack damage.

VI. EXPERIMENTAL VERIFICATION

A. Test bench device layout

In order to verify the effectiveness of the proposed crack diagnosis method, the experiment takes a certain type of elliptical hollow PVC pipe as the research object. Because the hollow pipe and the WT blade structure are both cantilever beam structures. The structural diagram of the pipe is shown in Figure 8. The total length of the pipe is L'=1500 mm, the height is h' =28 mm, and the crack position distance from the root of the pipe is denoted as L'_c. The material is polyvinyl chloride. The material of the pipe is polyvinyl chloride, the modulus of elasticity was 1.1E+9Pa, the Poisson's ratio is 0.42, and the density is 950 kg/m^3.

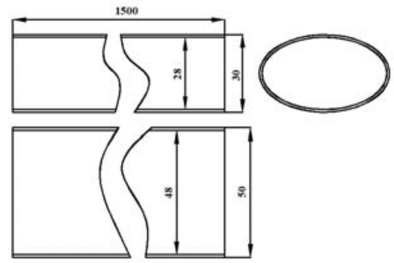

Figure 8 Pipe structure blade structure diagram

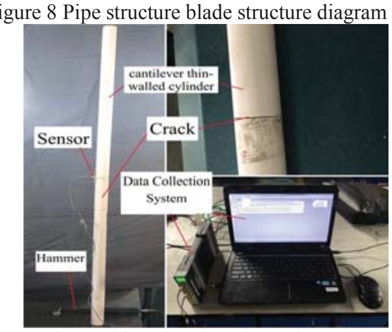

Figure 9 Experimental bench unit and Brüel & Kjær test system

The B&K Plus test system was used to measure the natural frequency of cracks at different positions of the pipe structure. The test bench device and test system are shown in Figure 9.

In the experiment, the region between two adjacent cracks is Δd=160 mm, and the Eq. (13) can be written as:

$$L'_c(n)= 160n\ (n=1, 2, ...8) \tag{31}$$

For each position of the above crack, 12 different degree crack levels were implanted, α=5%, 10%, ..., 60%, respectively. A database of different crack positions is established by measuring its natural frequency.

B. Experimental testing and analysis

Through multiple measurements, the first 5 order natural frequencies of the tube without cracks and different crack positions are taken to form a crack position database. Table III shows an example in which the degree of damage is 10%.

TABLE III. PARTIAL PIPE STRUCTURE CRACK POSITION NATURAL FREQUENCY DIFFERENCE RATIO DATABASE

$\overline{C}_i^n$		Crack position n				
		1	2	3	4	5
i	1	10.196	4.022	0.347	0.1649	4.2482
	2	0.0201	0.087	0.125	0.1503	0.2821
	3	1.7812	2.822	2.368	1.2961	0.2041
	4	0.1498	0.324	0.362	0.2287	0.5151

Based on the precise locating method of the blade crack in Section III-D. The relative position ζ of the crack is expressed as follows

$$\zeta=\begin{cases}\left(\dfrac{E_r(\zeta)}{3.49692}\right)^{\frac{1}{1.81896}}, & P_{r,x}\geq P_{r+4,x}\\ 1-\left(\dfrac{E_r(\zeta)}{3.49692}\right)^{\frac{1}{1.81896}}, & P_{r+4,x}>P_{r,x}\end{cases}\tag{32}$$

Based on the identification method of the blade degree of crack in Section IV-B, the δ values of the cracks of different degrees set by the experiment are calculated respectively. Observe the δ values and take the logarithm of the coordinate axis to fit the curve, as shown in Figure 10.

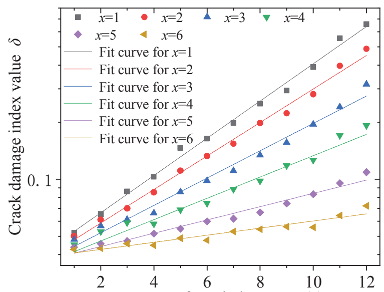

Figure10 Diagram of crack position and extent

It can be seen from Figure 10 that as the degree of crack increases, $lg\delta(x)$ and $lg\alpha_x$ are approximately linear, which is written as

$$lg\delta(x)=P_x+Q_x\,lg(\alpha_x/0.05)\tag{33}$$

where P_x and Q_x are the fitted linear function intercept and linear function coefficient, respectively.

Based on the damage degree function curves of the different crack position s described above, a function relationship between P_x, Q_x and the crack position x is obtained. The relationship between P_x and Q_x and the crack position x was drawn as a figure, as shown in Figure 11 and Figure 12, respectively. Its function relational expression is

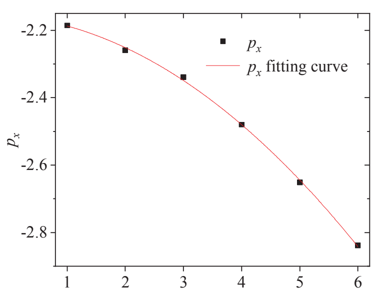

Figure 11 P_x and damage position map

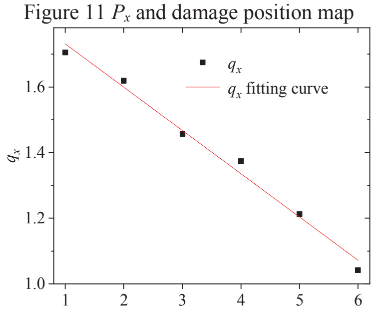

Figure 12 Q_x and damage position map

$$lgP_x=-2.15652-0.01412x-0.01669x^2\tag{34}$$

$$lgQ_x=1.86295-0.13184x\tag{35}$$

The relationship between $\delta(x)$ and α_x will also be determined, and then Eq. (23) is rewritten as

$$lg\delta(x)=(-2.15652-0.01412x-0.01669x^2)+(1.86295-0.13184x)\,lg(\alpha_x/0.05)\tag{36}$$

C. Experimental example verification

The experiment takes the crack position x^*=580 mm and the crack damage degree as 10% as an example. The natural frequency parameters of the cracked pipe measured by experiments. As shown in Table IV.

TABLE IV. CRACK POSITION 580 MM BLADE FRONT 5TH NATURAL FREQUENCY AND NATURAL FREQUENCY PARAMETERS

Natural frequency parameter	Order				
	1	2	3	4	5
$L_c(x)$/Hz	3.12	4.72	19.44	29.34	54.06
C_i^n	1.195	0.1179	1.3815	0.4032	

The Eq. (12) can be rewritten as

$$\boldsymbol{H}_x=(1.195\ \ 0.1179\ \ 1.3815\ \ 0.4032)^T\tag{37}$$

$P_{n,x}$ is calculated from Eq. (14), and the result is shown in Figure 13.

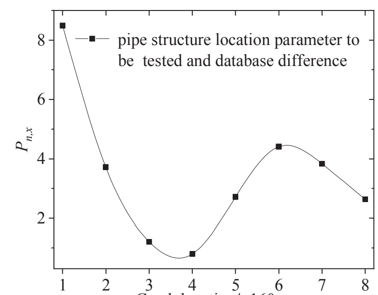

Figure 13 Sum of the difference between the blade crack position 580 mm and the database difference ratio

It can be seen from the Figure 13 that r=4, t=3. It is shown that the blade crack position is located 480-640 mm from the blade root and close to 640 mm. In this case, x=580 mm is indeed in this region, indicating that the crack region localization method is effective.

From the method of Section IV-D crack accurate position, it is known that $E_r(\zeta)$= 0.65957 is obtained by the Eq. (15) According to Eq. (22), x = 576.475 mm.

It can be known from Eq. (19) that the accuracy of crack blade locating is β_1=99.7365%

Based on the identification of the degree of crack in Section IV, the power function coefficients and indices of the degree of crack curve corresponding to x=576.475 mm are P_x=-2.4241 and Q_x=1.3879346, respectively. Then the degree of crack blade curve expression is

$$lg\delta(x)=-2.4241+1.3879346\,lg(\alpha_x/0.05)\tag{39}$$

Table IV shows the natural frequency of the cracked blade. Calculated by Eq. (21), the blade degree of crack parameter δ_x =0.010768149

The degree of crack damage of the blade is calculated by Eq. (37).

$$\alpha_x=2.1316\times5\%= 10.658\% \quad (40)$$

It can be seen from Eq. (27), the crack leaf crack identification error is β_2=0.658%

Based on the above experimental verification analysis, the identification method of crack damage degree proposed in this paper can accurately identify the degree of crack damage and the identification accuracy is high.

VII. CONCLUSION

In this paper, the diagnosis method of WT blade single crack is proposed based on blade natural frequency parameters.

- The ratio of the two-order natural frequency variation, which is between the cracked blade and the intact one, is only related to the crack position. According to this property and the parameter $\boldsymbol{H}_n$ crack position and database of crack position parameters are obtained. Through the crack locating parameters $P_{n,x}$ and crack locating criteria proposed in this paper, the position of the blade crack is located in region. Meanwhile, according to the variation law of the crack in the locating region, the crack precise locating parameter curve E_n corresponding to all the regions is proposed. And the crack can be accurately located in the region.
- The function relationship between δ and damage degree is established under different crack positions. When the crack position is determined by precise locating, the functional relationship between δ and the degree of crack is also determined. Finally, the degree of crack can be identified. Numerical simulation and experimental examples verify the effectiveness of the blade crack diagnosis method and accuracy is high.

The WT blade crack diagnosis method proposed in this paper can provide a diagnostic method for cracks of different types of blades and similar structures, and provide theoretical support for the actual blade on-line detection.

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