Study on Crack Propagation Characteristics of Pitch Bearing Based on Sub-model

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Abstract. The pitch bearing is one of the key components of the wind turbine. The complex stress state, manufacturing process and harsh environment can all produce cracks that will lead to the final failure of the pitch bearing. Since there are few papers on cracked pitch bearings, the paper uses ANSYS and Franc3D co-simulation, and innovatively proposes a sub-model method to study the stress intensity factor and crack growth characteristics of the bolt hole defects of pitch bearings. From two aspects of crack length-depth ratio c/a and its propagation, the distribution of the stress intensity factor at the crack tip is explored. It is found that as the length-to-depth ratio c/a increases, the crack propagation trend gradually changes from extending along the crack length to the crack depth direction; as the crack propagation length increases, the intensity factor at the end of the crack surface is greater than that at the tip of the crack depth. The intensity factor indicates that when the crack expands to a certain size, the trend of crack growth along the surface is greater than the trend along the depth direction, and the propagation path is similar to the actual crack propagation path, which verifies the accuracy of the numerical simulation.

1. Introduction

The pitch bearing is a key component of the wind power pitch device. The performance and life of the pitch bearing are related to the normal operation and power generation efficiency of the wind turbine [1-3]. Due to the complex force of the pitch bearing, the impact and vibration of the bearing are relatively large, and there are working conditions such as low-speed operation or swing, condensate or salt erosion, so it is prone to failure problems [4]. In addition, in the long-term use of the bearing outer ring, the inner wall of the bolt hole is prone to oxidation and corrosion, and there may even be micro-cracks at the bottom of the corrosion pit, which will eventually lead to the fracture of the pitch bearing [5]. Moreover, due to the large size of the pitch bearing, there is no systematic research and analysis on the defected pitch bearing from the perspective of fracture mechanics.

In view of this situation, this paper proposes a crack propagation analysis method for pitch bearing with initial cracks, establishes a three-dimensional finite element model, and assumes that there are surface defects in the bolt holes of the pitch bearing. Based on the theory of fracture mechanics, the defects are equivalent to a semi-elliptical surface crack. The sub-model technology is used to improve calculation efficiency and accuracy. FRANC3D and The ANSYS co-simulation method was used to study the crack propagation characteristics of pitch bearings with defects in the bolt holes.
2. Fracture Mechanics Theory

According to the deformation types of the crack front area, cracks can be divided into open cracks (type I cracks), sliding cracks (type II cracks), and tear-open cracks (type III cracks). Among them, type I cracks are frequently produced in engineering practice [6], which is the most important reason for low-stress fractures. According to the linear elastic theory, the stress intensity factor is a parameter that characterizes the strength of the singular field at the crack tip, reflecting the strength of the elastic stress field at the crack tip, and it has nothing to do with the coordinates (x, y). Ignoring the plastic deformation of the material, the calculation formulas for the stress distribution and displacement of the crack tip of the isotropic linear elastic material are shown in equations (1) and (2):

\[
\sigma_{ij} = \frac{1}{2\pi r} \left[ K_{I,ij} f_{ij}(\theta) + K_{II,ij} f_{ij}^{II}(\theta) + K_{III,ij} f_{ij}^{III}(\theta) \right] \quad (1)
\]

\[
u = \frac{1}{G} \sqrt{\frac{r}{2\pi}} \left[ K_{I,ij} g_{ij}(\theta) + K_{II,ij} g_{ij}^{II}(\theta) + K_{III,ij} g_{ij}^{III}(\theta) \right] \quad (2)
\]

Where \(\sigma_{ij}\) is the stress tensor; \(\nu\) is the displacement; \(r\) and \(\theta\) is the position of the coordinate system; \(K_{I,ij}\), \(K_{II,ij}\), \(K_{III,ij}\) are the stress intensity factors of the three crack forms; \(G\) are the shear modulus; \(f_{ij}^{I}\), \(f_{ij}^{II}\), \(f_{ij}^{III}\), \(g_{ij}^{I}\), \(g_{ij}^{II}\), \(g_{ij}^{III}\) are the polar angle functions of the three crack tips, respectively.

According to the crack tip finite element model (Figure 1) and formula (2), the displacement expression of the stress intensity factor can be obtained as:

\[
K_{I} = \frac{G}{k + 1} \left[ \frac{2\pi}{L} \left( 4v_{b}v_{c} + v_{c} - v_{d} \right) \right] \quad (3)
\]

\[
K_{II} = \frac{G}{k + 1} \left[ \frac{2\pi}{L} \left( 4u_{b}u_{d} + u_{d} - u_{e} \right) \right] \quad (4)
\]

\[
G = \frac{E}{2(1 + \nu)} \quad (5)
\]

\[
k = \left\{ \begin{array}{ll}
\frac{3 - 4\nu}{1 + \nu} & \text{if } K_{II} \text{ is the main fracture parameter.} \\
\end{array} \right.
\]

Where \(k\) is the shear coefficient; \(\nu\) is the Poisson's ratio; \(L\) is the element length; \(u\) and \(v\) are the nodal coordinates in the coordinate direction.

Since most of the crack surfaces in engineering practice are semi-elliptical and structural failures with cracks are mainly caused by open cracks, this paper takes \(K_{I}\) as the main fracture parameter to study the crack fracture.
3. Finite element modeling and crack simulation

The pitch bearing uses a hexahedral mesh dominant form for meshing. In order to simplify the calculation and improve the convergence, five groups of only compression LINK10 elements are used to simulate the form of bearing force transmission and the nonlinear stiffness of the ball. According to the bolt engineering calculation criterion VDI2230 criterion, the equivalent beam element [7-8] is used to simplify the bolt connection, that is, the rod and beam elements are used to simplify the bolt connection, and the pre-tightening force element Prets179 is used to simulate the pre-tightening force. The hub is modelled by a tetrahedral mesh, and only one segment of the blade is taken as a prosthesis. The finite element model is shown in Figure 2.

![Figure 2. Finite element model of pitch bearing](image)

Next, quasi-static analysis is performed for the full model and the results for each step are stored. The imposed limit conditions are shown in Table 1, and then the area with the largest stress in the bolt hole of the outer ring bearing is cut out to create the sub-model shown in Figure 3. In the maximum stress area, the sub-model is divided into elements of the same type as the elements in the complete model analysis, and the sub-model grid is encrypted to improve the calculation accuracy. The result of the complete model is interpolated to the forefront of the sub-model, and the interpolation result is used as the boundary. The condition is applied to the sub-model.

![Figure 3. Maximum stress sub-model of bolt hole](image)

| Table 1. \( M_{xy, \text{max}} \) load condition |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( M_x \) \((KN\cdot mm)\) | \( M_y \) \((KN\cdot mm)\) | \( M_z \) \((KN\cdot mm)\) | \( F_x \) \((KN)\) | \( F_z \) \((KN)\) | \( F_{xz} \) \((KN)\) |
| 7308.55          | 14943.86        | -57.43          | 398.04          | -281.12         | 675.47          |
The sub-model method is also called the cutting boundary displacement method or the specific boundary displacement method [9]. The sub-model is based on Saint-Venant's principle, that is, if the actual distributed load is replaced by an equivalent load, the stress and strain will only change near the load. The results in the sub-model are obtained using dense meshes. They do not have to be completely consistent with the results of the coarse-mesh full model. As long as the difference between the calculation results is small enough, the results can be input into the sub-model for crack stress intensity factor calculation and cracks Extended simulation. The calculation results of the complete model and the sub-model are shown in Figure 4. From the calculation results, it can be seen that the calculation results of the sub-model and the complete model have relatively small errors, and the crack growth analysis can be performed.

An elliptical crack is built into the maximum stress point of the bolt hole of the sub-model through the Franc3d software. The crack depth $a$ is 1mm and the length radius $c$ is 1mm. The volume mesh in the crack tip template is predefined, and it will be in the template when dividing the mesh. Three regular rings are formed around the crack tip inside. Among them, the innermost part is a wedge-shaped element with 1/4 node, and the outer two circles are second-order hexahedral element rings, which can eliminate the singularity of stress at the crack. This paper takes the crack as an example to analyse the stress and stress intensity factors of the finite element results. The sub-model crack grid is shown in Figure 5.

Under extreme conditions, the cracked sub-model is solved by finite element method, and the finite element results of crack surface stress and tip stress intensity factor $K_I$ are obtained (Figure 6). There is stress concentration at the crack tip, and the maximum stress in the stress concentration zone is
3478.25MPa, which is dozens of times higher than the maximum stress value of 296.26MPa in the non-crack model, so the existence of cracks will greatly affect the safety of the pitch bearing.

4. Crack stress intensity factor analysis
Considering the diversity of crack sizes, four types of semi-elliptical surface cracks with depth \(a=1\)mm and length-depth ratio \(c/a=1, 1.5, 2, 2.5\) are established. The curve distribution of the crack tip with different length-to-depth ratios is shown in Figure 7. The abscissa in the figure is the ratio of the calculated arc length at each point of the crack tip to the total arc length. It can be seen from Figure 7 that under different aspect ratios \(c/a\), the stress intensity factor \(K_i\) at the tip of the crack surface is almost symmetrically distributed in the direction of the crack long axis \(c\), and its size changes on the crack front edge are as follows: When \(c/a=1\), \(K_i\) decreases from the crack endpoints A and B along the crack depth direction, and its minimum value is located at the farthest end of the crack from the bolt hole surface, and the crack is easy to grow along the length direction; as \(c/a\) increases , The crack end point \(K_i\) gradually decreases, and \(K_i\) gradually increases along the crack depth direction, even exceeding the value of the crack end point, which means that the crack propagation trend gradually changes to the direction of depth \(a\), and the continuous increase of \(K_i\) indicates the crack propagation it becomes easier, and in severe cases it will directly cause the pitch bearing to break. When \(c/a=1.5\), the change of \(K_i\) at the crack tip is small, indicating that the crack propagation is relatively stable at this time, and the crack may expand in all directions. In summary, \(c/a=1.5\) can be approximated as the critical state of crack propagation direction change. In engineering practice, the length-to-depth ratio \(c/a\) of the detected elliptical surface cracks can be used to determine the initial crack propagation direction and crack propagation difficulty, so as to take corresponding preventive measures.
5. Simulation and analysis of crack propagation path

Although the length-to-depth ratio $c/a$ of the crack can be used to determine the direction of crack propagation, how the cracks on the surface of the bolt hole propagate needs further verification. For this reason, the above-mentioned length-to-depth ratio crack propagation analysis is carried out. The growth increment of each crack is 0.15mm, and the $K_I$ and propagation paths of cracks with different length-to-depth ratios $c/a$ at different stages are obtained. The results are shown in Figure 8 (Where $K_{I-0}$ represents the stress intensity factor of the initial crack front edge, $K_{I-1}$ represents the crack front edge intensity factor after the first expansion, and so on). After crack propagation, it is necessary to explore the rate of change of the stress intensity factor $K_I$ under different crack angles during the crack propagation process to confirm that the crack propagates fastest in that direction. The division of crack angles is shown in Figure 10. The change of $K_I$ with crack growth under different crack angles is shown in Figure 9. It can be seen from the figure that as the crack grows, the stress intensity factor at the crack surface endpoint gradually increases, and gradually approaches or exceeds the crack depth direction. The stress intensity factor, and the stress intensity factor $K_I$ at the tip of the crack depth changes relatively smoothly during the crack propagation process, indicating that after the crack size expands to a certain extent, the crack grows faster along the length of the surface. In actual engineering, the port morphology of a certain type of pitch bearing with a defect in the bolt hole is shown in Figure 11 [10]. It can be seen from the figure that the crack propagates along the axial surface of the inner wall of the bolt hole, which eventually causes the pitch bearing to fracture in the radial direction. In summary, the actual crack propagation path of the pitch bearing is similar to the simulated crack propagation path.
Figure 8. Stress intensity factor distribution chart

Figure 9. Change of stress intensity factor with crack growth

Figure 10. Crack angle division

Figure 11. Macro morphology of fracture of pitch bearing
6. Conclusions
This paper comprehensively analyses the relevant characteristics of the stress intensity factor $K_I$ from two aspects of crack length-depth ratio $(c/a)$ and crack propagation. The results show that with the increase of the aspect ratio $(c/a)$, the crack propagation trend in the bolt hole gradually expands from along the bolt hole surface to along the crack depth direction. However with the increase of crack propagation length, the stress intensity factor at the end of the crack surface is greater than the stress intensity factor at the tip of the crack depth, and the stress intensity factor changes in the depth direction of the crack are relatively small. It shows that the crack propagation speed along the surface of the bolt hole is faster than the propagation speed in the depth direction. In addition, this paper proposes a method of using sub-model technology to establish a finite element model of a pitch bearing with three-dimensional cracks, thereby improving the calculation accuracy and efficiency of the crack front stress intensity factor. At the same time, this method is also a brand-new method for crack propagation analysis of defective parts of wind turbines, which has certain engineering value.

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