Acoustic Simulation of Hydraulic Turbine Top Bolt Fatigue Crack Detection Based on DG-FEM

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Abstract. The top bolt is one of the important parts of turbine, and its health condition affects the stable operation of the pumping and storage unit. In this paper, the DG-FEM method was used to simulate ultrasonic waves to detect bolt crack defects. In the experiment, the ultrasonic propagation of single thread side and double thread side was simulated respectively under the condition of center excitation and bias excitation, and the feasibility of ultrasonic detection of bolt crack was explored. In addition, the reflection wave shapes of the two days under different excites of the center and the offset were compared, and the conclusion was drawn that the offset excites were more sensitive to the detection of bolt cracks than the center excites, and the reflected wave peaks were higher, which was conducive to improving the success rate of defect detection. It is prepared for the practical application of engineering and has certain reference value.

Keywords: Bolt; Crack; Finite Element Method, Ultrasonic detection; Discontinuous Galerkin.

1.Introduction

The safety of the top bolt is the key to the stable operation of the pumping and storage unit. In recent years, with the development and maturity of ultrasonic technology, the use of ultrasonic technology for defect detection has attracted the focus of scholars and enterprises [1]. This technology is beneficial to greatly advance the early warning time of fatigue fracture of high-strength bolts, so as to eliminate the accidental fatigue fracture of bolts and the accidents caused by the unit operation, and realize the full cycle safety state detection in a true sense.

Lu Mingge [2] proposed a method to obtain the preload by measuring the radial strain of the head to solve the problem of bolt loosening by using the finite element method, which provided a new idea for the health detection of bolt structures. Wu Guannan [3] from Northwestern Polytechnical University numerically simulated the propagation behavior of elastic waves in bolts and found that the propagation path, waveform and amplitude of elastic waves changed greatly when they passed through the connection surface of bolts. Wu Zunhong [4] used COMSOL software to model ultrasonic guided wave bolt detection technology and simulated the running status of in-service bolts, providing reference experience for online bolt detection. Sun Chaoming [5] carried out finite element model calculation on bolts to solve the numerical calculation difficulties of the acoustic-elastic effect, and found that the finite element calculation results were basically consistent with the experimental demonstration results, which provided a new idea on the detection method.

The Discontinuous Galerkin method (DG-FEM) has the features of both Finite Element Method (FEM) and Finite Volume Method (FVM) , and it is increasingly widely used. [6-9]. Just like the general finite element method, the DG method uses the element polynomial space as the approximate solution and test function space. However, different from the traditional finite element method, the basis function of the finite element function space is completely discontinuous fragment polynomial, and the communication between each element also needs to be realized by constructing appropriate numerical flux on the element boundary like the finite volume method. The appearance of DG method expands the application range of traditional finite element method and improves people's understanding of traditional finite element method. Aiming at the ultrasonic detection of fatigue crack of turbine top bolt, the DG-FEM method was used in the simulation in this study, and the effectiveness of the method was verified by several simulations under different conditions.

2.Theory

2.1 A. FEM

Finite Element Method (FEM) divides a continuous solving domain into many tiny elements of appropriate shape arbitrarily, constructs interpolation functions for each small element fragment, and then converts the governing equation of the problem into finite element equations for all elements according to the extreme value principle. The extremum of the population is taken as the sum of extremum of each element, that is, the local element population is synthesized, and the algebraic equations embedded with the specified boundary conditions are formed, and the function values to be solved at each node are obtained by solving the equations. The governing equation of FEM is as follows:

$$\rho\frac{\partial^2\varepsilon}{\partial t^2}-\nabla\cdot S=F_v \tag{1}$$

Where ρ is the density, ε is the strain tensor, ∇ is the gradient operator, S is the stress tensor, and F_v is the volume force vector.

2.2 B. DG-FEM

The DG method is very similar to the traditional finite element (FEM) method, but with several essential differences. The mass matrix of DG is local rather than global, which is easier to invert, resulting in the dominance of the semi-separated scheme. Moreover, Numerical Flux, which is carefully defined to reflect the characteristics of the problem, would provide better flexibility than the traditional finite element, thus ensuring the stability of the wave-dominant problem. Its governing equation is as follows:

$$\rho\frac{\partial v}{\partial t}-\nabla\cdot S=F_v \tag{2}$$

$$\rho\frac{\partial E}{\partial t}-\frac{1}{2}[\nabla v-(\nabla v)^T]=0 \tag{3}$$

$$S=C:E \tag{4}$$

Where, v is velocity, ρ is density, S is stress tensor, E is strain tensor, C is stiffness tensor, F_v means volume force vector.

The DG method uses local element base, which overcomes the limitation of high precision in general grid, and maintains local conservation and flexibility in selecting numerical flux.

3.Model

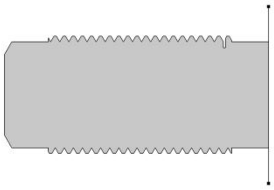
COMSOL Multiphysics software has been used to simulate the propagation process of ultrasonic waves in the bolts for the acoustic simulation of fatigue crack detection of the turbine top bolt, so as to visually understand the ultrasonic detection. Due to the need to analyze the ultrasonic track in a period of time, the time domain transient research is selected.

3.1 Geometric Structure and Material Mroperties

It can be seen from literature [10] that two-dimensional plane element can simulate the actual operating condition and reduce the calculation amount at the same time. Therefore, this study uses the two-dimensional model with defective bolt to replace the three-dimensional model for simulation.

The total length of the bolt is 704mm, and the nominal diameter of the three threads is 79.50mm, 72mm and 79.50mm respectively. In order to simplify the single calculation time, the bolts were divided into single-threaded side and double-threaded side, as shown in Figure 1 below. The notched defect is artificially set on the last thread with a width of 1mm and a depth of 2mm. The ultrasonic probe can be placed in the middle and placed on the edge.

(a) Double threaded side



(b) Single threaded side

Two-dimensional geometric diagram of bolt model with defects

The bolt is made of Steel AISI 4340, which is a linear material. Table 1 shows the specific parameters.

TABLE I. Mechanical Parameters of Material

Density (kg/m3)	Young’s modulus (GPa)	Poisson’s ratio	P-wave speed (m/s)	S-wave speed (m/s)
7850	205	0.28	5900	1000

3.2 Excitation Signals and Boundary Conditions

$$y(t) = \frac{1}{2}\left(1 - \cos\left(\frac{2\pi ft}{n}\right)\right)\sin(2\pi ft) \tag{5}$$

The frequency of 2.5MHz is a low frequency among common 6mm wide ultrasonic inclined probes. The three-period sinusoidal pulse signal modulated by Hanning window is a common excitation signal for ultrasonic flaw detection, as shown in Figure 2. Figure 3 shows the frequency domain spectrum of the excitation signal.

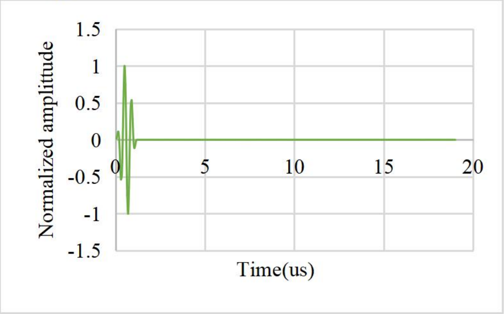


Figure 2. Normalized input signal

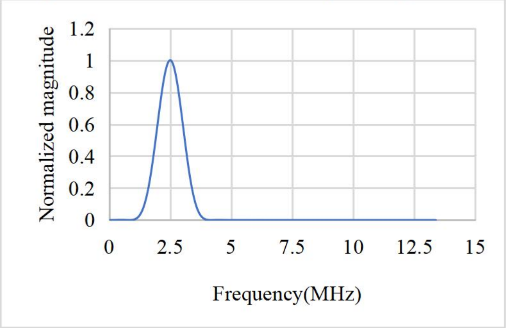


Figure 3. Frequency spectrum of input signal

Besides the excitation surface of ultrasonic wave, the other boundary conditions are mainly low reflection boundary and continuity setting. For the ultrasonic probe, in addition to the excitation generated signal, other clutter is needed to absorb, such as the reflection wave at the interface of two materials, because the sensor in addition to the excitation surface and the contact surface with the bolt, other surfaces need to be set as a low reflection boundary. The effect of the low reflection boundary is to provide a boundary impedance matching that absorbs part of the S-wave and P-wave reaching the boundary.

3.3 Mesh and Time Step

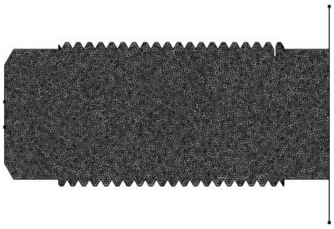
In order to control the accuracy of detection, special requirements are made for grid division. According to ultrasonic detection requirements, the size of the grid should not be larger than the wavelength, and if the grid is much lower than the wavelength, the calculation time will be greatly increased, which will greatly deepen the complexity of detection, increase the calculation time, and reduce the experimental efficiency.

In general, for planar elastic wave simulation using DG-FEM, the mesh is set as a free triangle mesh. The recommended maximum mesh size is as follows

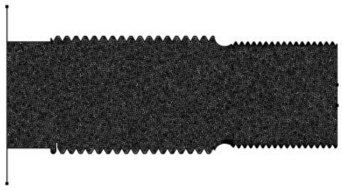
$$h_{\max} = \frac{c_{\min}}{1.5 \cdot f_{\max}} \text{ to } \frac{c_{\min}}{2 \cdot f_{\max}} \tag{6}$$

Where, $h_{\max}$ refers to the value of maximum mesh size, $c_{\min}$ represents the lowest wave speed, $f_{\max}$ represents the highest frequency.

In terms of numerical stability, whether to obtain a good stiffness matrix depends largely on the quality of grid elements, such as mesh size and type, and the divided grid should be as regular and uniform as possible. The triangular mesh has good adaptability, so the triangular mesh is freely divided. In order to ensure the accuracy of finite element simulation of ultrasonic propagation, the grid was set as 1/1.5 of the wavelength, that is, at least 1.5 grids should be divided within a single ultrasonic wavelength range. The overall grid division of bolts with defects is shown in Figure 4.



(a) Double threaded side



(b) Single threaded side

Figure 4 Grid division of bolts

In terms of solver, DG-FEM uses Runge-Kutta method as the explicit time solver. Its time step depends on the size of the minimum cell length, so it has good performance.

For DG-FEM using the elastic wave interface, the step size used by the default solver Rungekutta is calculated from the size of the minimum grid and the speed of sound in the material. Therefore, as far as possible in the grid Settings to ensure that there is no too small grid, and to use as much as possible uniform network.

The step size of the output solution is set as 0.1μs considering the limitation of storage and simulation accuracy. Probe step size I choose according to the time step of the solver to ensure the accuracy of the probe output.

The simulation time is set to 80μs to obtain the whole process of transmitting and receiving.

The main steps of finite element analysis in COMSOL include pre-processing, pre-processing, solver solution and post-processing. The specific operation process is shown in Figure 5 below.

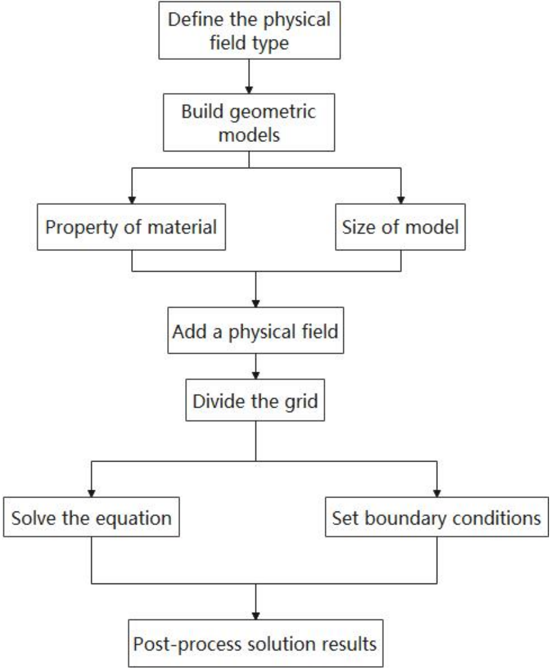


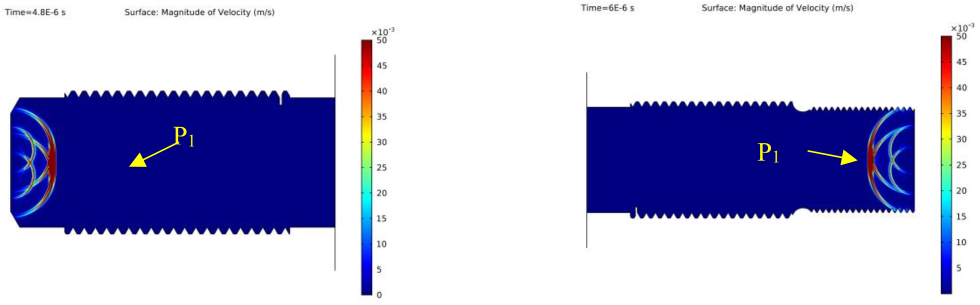
Figure 5 Flow chart of sound field simulation

4.Result

In order to study the feasibility of ultrasonic detection of bolt crack and the influence of probe position on ultrasonic detection effect, and to provide reference suggestions for subsequent practical engineering applications, two different positions of probe in the center and offset have been simulated in this paper. Two types of results have been recorded in this study. One is the distribution of ultrasonic sound field in the crack defect bolt under different excitation positions. The second is the acoustic pressure emission and receiving waveforms of bolts under different positions of excitation. The results are as follows.

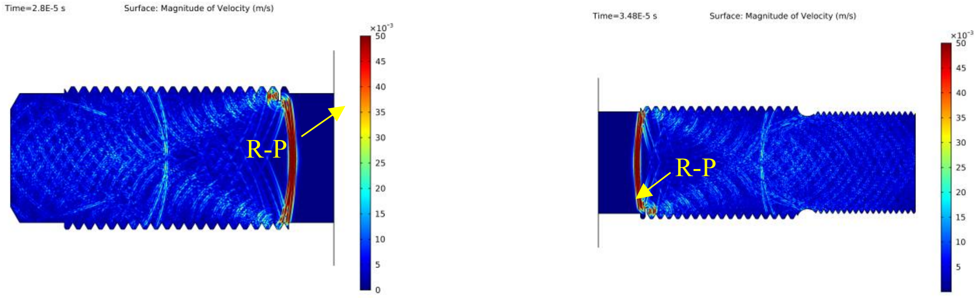
4.1 Process of transmission

Firstly, the ultrasonic transmission process is described in detail with the probe transmitting and receiving ultrasonic wave at the central position of both sides of the bolt. In order to realize the visualization of ultrasonic propagation process, DG-FEM can be used to directly observe the distribution of sound field in the material, which is convenient for further analysis of waveform and propagation mode. Figure 6-Figure 8 show the distribution of sound fields of important nodes in the process of ultrasonic propagation of the single thread side and the double thread side with the defective bolt under central excitation respectively. Figure 6 shows the initial stage of acoustic excitation. The acoustic wave propagates downward along the incidence direction, and the P-wave P1 propagates along the loading direction with the increase of propagation time, and the energy is concentrated and clear. As shown in Figure 7, when the incident P-wave P1 reaches the flaw crack, it generates a backward-reflecting P-wave R-P. Since the acoustic impedance of the air is much smaller than that of the steel, the sound wave is completely reflected on the defective surface. Figure 8 shows the reflected P-wave reaching the probe and being received. The whole process completely expresses the process of ultrasonic from excitation to reflection acceptance. It can be intuitively found that ultrasonic P-wave propagation speed is the fastest, and the signal is the strongest. The sound velocity of S-wave is slow and gradually diverges from that of P-wave. Surface waves have the slowest sound speed and travel only along the surface. According to the simulation process, it can be clearly found that the obvious reflection occurs when the ultrasonic wave propagates to the thread defect, which provides the simulation basis for the ultrasonic detection of bolt defects.



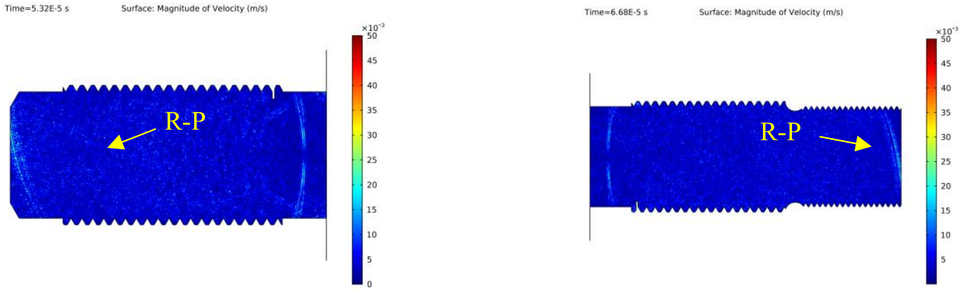
(a) 4.8 μ s (b) 6 μ s

Figure 6 Initial stimulation stage



(a) 28 μ s (b) 34.8 μ s

Figure 7 Reflected wave generation stage



(a) 53.2 μ s (b) 66.8 μ s

Figure 8 Reflected wave reception stage

4.2 Contrast of wave forms

The main basis of ultrasonic detection of bolt crack is the difference between the echo at the defect and without the defect, which can be intuitively felt through the waveform. In this study, the double-threaded side of the bolt was selected as an example. In order to fully express the difference of defect echoes under central excitation and bias excitation, the acoustic wave waveform received by the probe in the time range of 65.7μs~68.2μs was intercepted. As shown in Figure 9, the offset excitation arrangement of the ultrasonic piezoelectric probe can obviously obtain a larger amplitude of sound pressure than the central excitation arrangement, the peak difference is nearly four times, and the information is more abundant. According to the results of sound field simulation, for the fatigue crack detection at the bolt thread, better reflection signal and signal-to-noise ratio can be obtained by placing the ultrasonic piezoelectric probe in the way of bias excitation, and more information about the flaw crack can be obtained, so as to improve the success rate of crack detection and make the detection more sensitive.

Figure 9 Defect echo waveform under two excitation arrangements

5.Conclusion

Through the finite element simulation of the ultrasonic sound field of bolt crack detection, it is found that the ultrasonic wave propagates to the thread defect will have obvious reflection, and is received by the transducer and reflected in the waveform. It shows that ultrasonic wave can effectively detect the fine crack of the bolt of the turbine top cover, and give timely warning before the fault damage expands In addition, under two different conditions of central excitation and bias excitation, we found that the bias excitation is more sensitive to bolt crack detection than the central excitation, and the reflected peak value is higher, which is conducive to improving the success rate of defect detection. However, this study did not determine the location of the probe more accurately, which needs further research. In addition, how to deal with ultrasonic signals to better distinguish reflected waves caused by defects from reflected waves is also worth further exploration, which has profound significance.

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