Finite element numerical simulation analysis based on ultrasonic phased array

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Abstract. In this paper, the ultrasonic phased array technology is used to detect the defects in the welded seam test specimens. Using pulse echo method to detect a specimen with defects and establishing the corresponding numerical model. At the same time, the finite element is used to simulate the propagation of ultrasonic waves in the defective test specimens, and figures of the sound pressure amplitude are obtained. Compared with the theoretical values, the experimental values and the simulated values show good agreement, and the errors are only 1.37% and 4.11%, respectively. The results show that the ultrasonic phased array with finite element simulation is effective.

1. Introduction

Ultrasonic non-destructive testing (NDT) techniques have been remarkably used in test and evaluation of critical components of defence, space and in industrial applications [1]. NDT is a method of detecting and testing the size, quantity, position, type and other characteristics of defects on the surface or inside the material without affecting the performance of the object to be inspected and the internal organization of the material [2]. Ultrasonic testing is one of the most commonly nondestructive testing methods, its main principle is based on the characteristic of ultrasonic wave propagation in the specimen. Using the ultrasonic propagation characteristics in order to evaluating the specimen itself or its internal defects and the features of defect [3].

In the past 30 years, acoustic emission has been widely used for the non-destructive evaluation of damage and the study of fracture behavior of materials [4]. Ultrasonic phased array detection is widely used as an important acoustic emission detection technology. The transducer array of this technology is designed based on the Huygens principle. The transducer element has a small area and can be regarded as an ultrasonic emission source to emit an ultrasonic beam to the inside of the detected work-piece. When the sound beam is emitted, the excitation delay sequence of each array of wafers in the transducer is controlled by computer software, so that the sound beams emitted by the array elements generate phase superposition, constructive interference and form a focused sound field at a set depth position, thereby controlling the shape and direction of the transmitted ultrasonic beam, and control the angle, focus position and focus size of the generated beam to achieve focusing and deflection of the ultrasonic beam. Subsequently, the ultrasonic transducer echo signal containing the internal defect or tissue structure information of the detected work-piece is received by the array transducer, and then the signal processing is performed to evaluate and image the internal defect or structure of the detected work-piece. It has the advantages of high detection efficiency, high signal-to-
noise ratio, convenience and flexibility, and easy detection of complex shaped work-pieces [5].

With the rapid development of electronic technology, the ultrasonic phased array has also developed rapidly. In 2000, A Erhard [6] of BAM College in Germany used a phased array system to detect austenite welds with coarse grain structure and severe ultrasonic attenuation, and enhanced the intensity of the sound beam in the detection area by dynamic focusing. Further, the IZFP non-destructive testing institute in Germany [7] successfully realized the miniaturization of the piezoelectric ultrasonic phased array, which could complete the axial and radial high-quality imaging of the pipeline. There are a lot of experimental studies on the sound field numerical simulation technology of ultrasonic phased array. Zhao et al [8] proposed an approximate multi-Gaussian beam model, and used this to show the distribution of the sound field of the phased array when focusing on the axis of the array element. Satyanarayan [9] used 2-D time domain finite difference method to model and simulate the pipeline structure with artificial defects. The simulation error was large and the results were not intuitive enough. Zhu et al [10] proposed a finite element reconstruction algorithm based on the frequency domain Helmholtz equation for ultrasonic tomography, which was used to monitor grouting defects in reinforced concrete structures. The numerical simulation results were compared with the experimental results to verify the reliable and effective phased array ultrasonic testing. The finite element method has rich material elements and flexible meshing, and it is close to the exact solution by approximation calculation, which has unique advantages for the calculation of complex structures.

2. Experimental research

2.1. The experimental system composition and model establishment

The equipment used in this experiment includes a computer, a Muti 12000 portable ultrasonic phased array device, a 64-wafer phased array linear array transducer with center frequency of 5 MHz(array element spacing of 0.6 mm), a phased array control system, and a 54.7° wedge, an artificial defect test specimens. As shown in figure 1.

Modeling plays an important role in the understanding of any physical process. This is particularly true of non-destructive testing and evaluation where a variety of energy forms are used to inspect engineering components. In the process of establishing a two-dimensional model of a defect test block according to the purpose of the experiment, for the defect test piece of the crack hole defect type, we directly perform such a hole defect by performing a Boolean operation on the defect test block by ANSYS software. For irregular weld defects such as unfused at the sidewall and root, model the Auto-CAD software and import it into ANSYS software.

This experiment uses a natural weld defect with a length, width and height of 300 mm*300 mm*16
mm made of Q235. As shown in figure 2, the phased array probe is placed above the work-piece under test during the experiment, and then the wave-forms are transmitted by the computer to observe the A-scan and S-scan. The A-scan is a graph of the amplitude and propagation time of an ultrasonic signal during propagation. The abscissa represents the propagation time of the wave, and the ordinate represents the signal amplitude. S-scan, also known as fan-shaped scan, is two-dimensional images of the probe's delay and refraction angles that have been corrected and superimposed on all A-scans in a particular channel. The S-scan reflects the actual coordinate position of the reflector and is very helpful for intuitive display of the test results and figures comparison. As shown in figure 2.

2.2. Experimental methods and results
The phased array probe is placed on the surface of the work-piece to be tested, and the excitation sequence of the array element is adjusted by the computer to control the shape and direction of the emitted ultrasonic beam, so that the ultrasonic beam is focused and deflected to detect the defect without moving the probe.

When the work-piece is tested by adjusting the excitation rules, when there is no defect, there will be no defect echo as shown in figure 3(a), and no defect display on the right S-scan. When a defect is detected, the situation shown in figure 3(b) will appear. Both the A-scan and the S-scan have defects. By pulling the coordinate pointer, you can clearly see the amplitude and geometric position of the coordinate position.

![Figure 3.](image)

(a) Defect-free situation and (b) defective situation.

3. Simulation section

3.1. Ultrasonic detection model establishment

![Figure 4.](image)

Figure 4. Conventional ultrasonic detection by phased array technique.

The ultrasonic testing model generally includes the following three parts about the phased array transducers, probe shoes and a defective test specimen as shown in figure 4. The role of the phased
array transducer is to transmit and receive ultrasound signals. The probe shoe is used that the ultrasonic wave is obliquely incident on the detecting surface. The function of the probe shoe is to control the beam angle to form a strict angle between the wafer of the probe and the surface of the work-piece. The defective test specimen is detected by the object.

The role and effects of the coupling layer and the wedge are ignored during the simulation. The processing technique for this point is that the simulation does not change. In the experiment, it is discriminated that the ultrasonic wave is injected into the work-piece, and then the ultrasonic wave is framed by the gate and finally collected. The simulation process is equivalent to simulating different pulse signals emitted by the ultrasonic probe according to the focus rules.

3.2. Ultrasonic detection model establishment

In this paper, the ultrasonic finite element analysis model by ANSYS software is established to investigate the ultrasonic propagation process mechanism and the effects of the weld slag on the ultrasonic diffraction. In the experimental part, the selected transducer probe contains 64 crystals. A part of the crystal can be selected to apply a time pulse containing a corresponding delay to control the emission direction of the ultrasonic wave. In the ultrasonic simulation of the model, the loading of the ultrasonic signal is mainly to introduce a waveform function similar to the experimental ultrasonic function, and then apply the waveform function as a load to the nodes on the surface. Therefore, in the simulation, the ultrasonic wave source can be regarded as excited directly at the node of the model surface. However, in the experimental process, the ultrasonic wave is excited at the probe, passes through the coupling layer, wedge, and finally enters the work-piece. According to the formula of the delay rules, the mathematical relationship between the angle ($\theta$) of the sound beam, the velocity (V), the time delay ($\Delta t$) of the adjacent wafer, and the distance (d) between adjacent wafers are:

$$\sin \theta = \frac{V \Delta t}{d}$$  \hspace{1cm} (1)

In the ultrasonic inspection model, the simulation of the ultrasonic wave source is the most important. The ultrasonic waves from the phased array transducer are modeled by applying appropriate transient excitation pulses to different nodes on the surface of the specimen model. The transient excitation pulse function equation commonly used for ultrasonic simulation is shown in the equation (2):

$$Y(t) = \begin{cases} \cos(2\pi ft)[1 - \cos(\frac{2\pi f}{N} t)], & 0 \leq t \leq \frac{N}{f} \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (2)

Which $f$ represents the pulse excitation frequency and $N$ represents the number of waves in the excitation pulse waveform. The probe frequency is defined by the pulse width and the number of the cycles of the pulse. The frequency in the model is 5 MHz and $N = 3$.

Figure 5 is a comparison of the experimental ultrasonic source and the simulated wave source in the simulation. Part (a) is the load waveform of equation (2), taken in ANSYS software. Part (b) is the waveform of the wave source in the experiment, which is extracted from the configuration section of the experimental software. Comparing the wave source diagrams of the experimental and simulation models, it can be seen that the phase of the simulated wave source is exactly opposite to the experiment, and the rest show a good consistency.
3.3. Finite element simulation of ultrasonic propagation in defective specimens

As described in Section 2.2, a specimen with groove is used for the model of the conventional ultrasonic detection for the defect by phased array technique. The geometric size and material parameters in simulation models are the same as the experiments. A two-dimensional flat specimen modeling is developed to simulate the ultrasonic wave propagation. The longitudinal wave is used for the detection of the defect because the wave propagation propagates in the vertical direction, which coincides with the position of the defect.

According to the various parts of the ultrasonic detection in equation (2), a 2-D numerical simulation model is established to simulate the ultrasonic B-scan of the specimen and the A-scan is obtained by the displacement of the special nodes. The four ultrasonic pulse snapshots shown in figure 6 are all generated according to the specific parameters. These figures are obtained at different time points when the ultrasonic pulse passes through the defective test specimen, and the degree of the color indicates the value of the displacement. The letters L, S, H and R represent the longitudinal, transverse, head and Rayleigh waves, respectively. L-L represents a longitudinal wave generated by waveform conversion of a longitudinal wave, and S-L represents a transverse wave generated by waveform conversion of a longitudinal wave. These color images clearly show that the longitudinal, shear, head and Rayleigh waves are generated from the nodes excited by the source and propagate through the model. They can be easily distinguished based on the difference in wave velocities.

![Figure 6](image)

**Figure 6.** Snapshot results of four different moments in the defect test simulation: (a) 2.1 us; (b) 2.4 us; (c) 2.8 us; (d) 3.8 us.

Figure 6 shows the snapshot diagrams extracted at the four different times of 2.1 us, 2.4 us, 3.1 us,
and 3.8 us in the numerical simulation results of the defect test. The figure 6(a) below shows the simulation results, and the blue cuboid part shows the test block. The central black cuboid represents the stomata defect. The grayish white ripple indicates the propagation of ultrasound in the test block. In figure 6(b), the longitudinal wave propagates to the defect at 2.4 us, which will reflect in the opposite direction and produce a reflected wave (R-Wave). In figure 6(c), at 2.8 us, the defect reflection wave propagates in the opposite direction of the incident direction. Since the waveform conversion occurs, the entire reflected wave contains the reflected longitudinal wave and the reflected transverse wave. Since the longitudinal wave velocity is twice the transverse wave, it is also possible to distinguish them by the wave speed (or the time of wave propagation). In figure 6(d), it is observed that the longitudinal wave in the reflected wave is about to reach the incident point at 3.8 us, and the transverse wave propagates along the longitudinal wave but has a certain distance from the incident point.

4. Comparative analysis and results

The node to which the load is applied in the specimen model is taken as a special node, and the time displacement data of the node is derived as a simulated A-scan view. Extract the A-scan data of the test results in the experiment, and compare the simulation results with the experimental results. The amplitude map corresponding to the two methods is shown in figure 7. The abscissa is the time of ultrasonic propagation, and the ordinate is the defect echo percentage of amplitude.

![Figure 7](image)

**Figure 7.** A-scan simulation and experimental results for defect detection: (a) Simulated signals; (b) Experimental signals.

Figure 7 compares the finite element analog signal with the A-scan experimental signal for a clear comparison of the defect echo amplitude and time. Figure 7(a) represents the simulation signal and figure 7(b) represents the experiment signal. Figure 7(a) shows that the pulse node receives the reflect wave when the time is 3.9 us and the amplitude of the flaw echo signal is observed clearly. Figure 7(b) shows the probe received the flaw echo when the time 3.7 us and the amplitude of flaw echo is large enough to be observed. The echo time by the defect in the simulation wave is the same as that in the experimental signal. With the theoretical value as the reference standard, it can be found that in the column of the defect in the echo time, the theoretically calculated receiving probe should receive the defect echo at 3.65 us, and the experimental value and the simulated value both show a relatively good consistency.

Table 1 compares the defect echo time and the echo amplitude in the A-scan data of the defect test piece simulation and experimental results. The errors are only -1.37% and 4.11%, respectively. In the case of echo amplitude, the experimental value is 50.1%, and the simulation value is only 15.6%, which is far lower than the experimental value. The distortion of the experimental result is more serious. The reasons for this phenomenon are as follows: (1) Error exists. As an approximate calculation method, the finite element method itself has a certain error range. (2) Calculation accuracy. Although the finite element method has constant error, it can greatly improve the accuracy by increasing the calculation conditions (such as reducing the mesh size and shortening the time step). In
theory, as the calculation conditions improve, the simulation results will become closer to the actual situation.

| Theory value     | Echo Time (us) | Error(%) | Echo Amplitude(%) |
|------------------|----------------|----------|-------------------|
| Experimental value| 3.6            | -1.37    | 50.1              |
| Simulation value  | 3.8            | 4.11     | 15.6              |

5. Conclusion
The finite element numerical simulation of ultrasonic phased array is the main part of this paper. It is very effective and novel to simulate the propagation of ultrasonic waves through load loading, and it has certain accuracy. Compared with the theoretical values, the experimental values and the simulated values show good agreement, and the errors are only -1.37% and 4.11%, respectively. The results show that the ultrasonic phased array with finite element simulation is effective.

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