Research on 3D Defect Reconstruction in Plate with Phased Array Ultrasonic Test (PAUT)

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Abstract. In order to clarify the distribution and shape information of the defects inside the workpiece, it has become a new industrial testing requirement to display the defects more intuitively in three dimensions (3D). In this paper, by introducing 3D volume rendering method, the expansion of PAUT from 2D to 3D is realized. The method is used to reconstruct specific "gu-shaped" ("Gu" is the Pinyin in Chinese characters, and at the same time, "Gu" is the shape of the defect in the plate discussed in the paper.) defects, and the results of reconstruction are compared with actual defects. By using ultrasonic phased array focusing to detect defect C-scan images of different depths, the collected C-scan images were preprocessed and reconstructed according to the defect contour by volume rendering. The results show that the defect morphology with different depths can be well obtained by focused detection, and the reconstruction effect is good, which is consistent with the actual defect.

1. Introduction
Although there are many nondestructive testing technologies for industrial purpose, none of them is accepted omnipotent. In fact, every technique has some intrinsic limitations[1-2]. Generally, structural damages have to be evaluated while keeping intact structure. It is suggested to choose the most appropriate technology in accordance to practical situations. Generally speaking, one effective way is to use one or more methods in line with the data fusion technology. It’s worth noting that ultrasonic test (UT)[3] is a standardized technique which is applied mostly in the aviation industry. As an important branch of ultrasonic nondestructive test, the phased array ultrasonic test (PAUT)[4-5] is appreciated more and more because of the fast test, multichip probe, real-time color imaging, intuitive testing results and convenient identification of defects. PAUT technology was originally used in the medical field and was transferred to the industrial field by the mid-1980s. Since then, the technology has been applied in many industry-related applications and has shown unique imaging results. At present, PAUT is widely used in metal component inspection in aerospace, oil pipeline, bridge and other industries[6-7]. However, at present, the non-destructive testing using phased array is mainly limited to the two-dimensional slice of single-array imaging component, and only shapes with a certain depth can be observed, but the defect that can not be intuitively reflected is the three-dimensional shape. Distinguishing defect types is critical for thorough and accurate inspection, because the severity of defects depends on their size, orientation, and shape. For example, it is well known that planar discontinuity defects are generally more dangerous than volume defects (such as voids) because their sharp edges have the potential to grow and cause fracture. Therefore, it is an ideal method to accurately obtain 3D images of defects.
The purpose of this paper is to propose a defect three-dimensional reconstruction method. By reconstructing the three-dimensional model, we preliminarily identified the defects and obtained a more accurate defect shape. To verify the feasibility of this method, complex defects are machined on the surface of the sheet metal. A series of C-scan images with different focus depths are obtained by combining ultrasonic phased array device with computer software. These images are then used to reconstruct the three-dimensional image of the defect. Finally, by comparing with the actual defects, the validity and feasibility of the method are verified, which provides a feasible method for the ultrasonic inspection and 3D imaging research of defects.

2. Experimental study
A "gu-shaped" complex artificial defect was reconstructed by PAUT. By setting different focus depths to scan the specimens, preprocessing the C-scan image of defects and then carrying out three-dimensional reconstruction, a more intuitive quantitative analysis of defects can be achieved.

2.1. Specimen with an artificial defect
A piece of 160mm (length)×130mm (width)×12mm (thickness) steel plate made of Q275 common straight carbon steel was used as the experimental specimen. A "gu-shaped" artificial defect was produced at the back of the plate (Fig.1) by using a portable metal cutter to simulate local damages at the non-visible side of the steel plate of a closed container in service.

2.2. Nondestructive test
Experimental device for PAUT was composed of a specimen with an artificial defect and OmniScan MX2 phased array ultrasonic detector (Olympus). The 5L64-A12 linear phased array probe (Olympus) was applied. It had a frequency of 5MHz and 64 array elements (Fig.2). The near-field effect was relieved, while the relatively ideal imaging effect of defect was achieved by matching SA12-0L wedge block with the probe. Moreover, the wedge block can protect the phased array probe. In the ultrasonic test, the special CG-98 couplant joint was employed between the probe and wedge block to reduce attenuation of acoustic beam in air. Water was used as the couplant between the wedge block and the specimen.

![Fig. 1 Specimen with an artificial defect](image-url)
2.2.1. **Working process.** Huygens-Fresnel principle and Helmholtz sound pressure integral theorem are the theoretical foundations of PAUT technique described by Anandika[8]. Phased array transducer is composed of several independent array elements. Each array element is equipped with an independent emission and receiving circuit. Deflection and focus of the acoustic beam could be realized by controlling the launch delay of each array element. Thus, the ultrasonic scanning images were acquired.

Phase control is the core of PAUT described by Lopez et al.[9]. The phased array contains transmission part and receiving part. It can be seen from Fig.3 that each array element at transmission is excited by the pulse signals with the same frequency and the ultrasonic wave is launched by the preset time delay method with electronic circuit controlled. Ultrasonic waves which have different phase positions overlap and interfere mutually in the space, forming a new wave front and composite beam. At receiving, the corresponding echo signals are compensated by a certain delay in line with different arrival times of the echo at different array elements described by Zheng[10]. Subsequently, signals are combined and overlapped to strengthen the echo signals in the undetermined direction. In the same time, echo signals in other directions are weakened and even offset. Finally, real-time display of the combined signals in images is achieved.
2.2.2. Radiated sound field. Since radiated sound field is often used to describe acoustic pressures at different points, it is the basis to study the principle of phased array ultrasonic imaging described by Chen et al. [11]. Amplitudes and phases are same at different points on the piston-type transducer surface[12] (Fig.4). Therefore, the sound pressure at any point in the sound field can be calculated by the integral equation:

\[
p(\vec{r}, t) = j \frac{k \rho_0 c_0}{2\pi} u_e e^{j(\omega t - \alpha)} \int_S \frac{e^{-jkR}}{R} dS
\]

where \(\vec{r}\) is the spatial position of field point. \(\rho_0\) denotes the medium density. \(c_0\) expresses the acoustic velocity. \(k\) reflects the number of waves and \(k = 2\pi/\lambda\). \(j\) represents the imaginary unit, \(j^2 = -1\). \(R\) is the distance from the transducer surface element to the field point. \(u_e e^{j(\omega t - \alpha)}\) shows the vibration form of the acoustic source.

![Fig. 4 Single-source transducer and its coordinate system](image)

If a linear array transducer is composed of \(N\) array elements, the radiated sound field is described by Zheng[13]:

\[
p(\vec{r}, t) = j \frac{\rho_0 c_0}{2\pi} \sum_{i=1}^{N} k_i u_i e^{j(\omega_i t - \alpha_i)} \int_{S_i} \frac{e^{-jk_ir_i}}{r_i} dS
\]

where \(u_i\) shows surface vibration of the array element \(i\). \(\omega_i\) is the angular frequency of surface vibration of the array element \(i\). \(\alpha_i\) is the initial phase of surface vibration of the array element \(i\). \(k_i\) is the wave number of the array element \(i\). \(j\) represents the imaginary unit, \(j^2 = -1\). \(r_i\) denotes the distance from the surface element of the array element \(i\) to the field point. \(S_i\) is the area of the array element \(i\).

In general case, all elements in the same array make the synchronous uniform vibration in the same media. In other words, \(\omega_i\) and \(k_i\) are equal in all media. Sound pressures at different points in the sound field can be gained from the Eq.(1) and (2). Different colors represent different strengths of the
sound pressure at different scanning regions. Real-time imaging is feasible by PAUT based on this principle.

3. Data analysis and discussions

3.1. C-scan results of PAUT

The perfect and smooth surface after grinding is used as the testing surface. The scanning direction of phased array sensor is from top to bottom on its surface and the direction of "gu-shaped" defect of the back is upward. The depth direction is indicated by h, and the scanning surface depth is h = 0mm. C scanning of the steel plate[14] is accomplished by the phased array probe. The C-scan image is shown in Fig.5, which are the top and cross-sectional views of the scanning region. The horizontal axis is the scanning axis (path of the probe) and the vertical axis is the stepping axis (length of the probe). The right palette represents the depth of defect on the metal composite plate[15], which is expressed by different colors. The light blue is the normal region and other colors reflect regions with defects.

Fig.5 shows a C-scan complex artificial defect in the scanning region without focusing. The color in the defect region changes from yellow to red, indicating the uneven depths of the defect. As shown in Fig.5, No.1 indicates that the minimum depth of the defect that can be detected in the plate is 10.15mm, and No.2 means that the maximum depth of the defect can be detected is 11.51mm, and the defect depth range is 0-1.36mm.

![Fig. 5 C-scan results of PAUT](image)

Five different focusing depths were set up in the experiment to obtain C-scan 2D cross-section defect images (Fig.6) on five different depth. The minimum and maximum depths measured at different focusing depths are as shown in Table 1.

![Fig. 6 C-scan images obtained at different focusing depth h values for the specimen](images)

| Focusing Depth h (mm) | Minimum Depth (mm) | Maximum Depth (mm) |
|-----------------------|--------------------|--------------------|
| 10.94                |                    |                    |
| 11.14                |                    |                    |
| 11.34                |                    |                    |
| 11.54                |                    |                    |
| 11.74                |                    |                    |
Tab. 1 The minimum and maximum depths measured at different focusing depths

| h    | defect depth | NO.1 | NO.2 | depth range |
|------|--------------|------|------|-------------|
| 10.94| 9.39         | 11.10| 0~1.71|
| 11.14| 9.36         | 11.15| 0~1.79|
| 11.34| 9.36         | 11.18| 0~1.82|
| 11.54| 9.39         | 11.18| 0~1.79|
| 11.74| 9.36         | 11.15| 0~1.79|

As shown in Fig.6(a), No.1 represents that when the focal depth for PAUT is \( h = 10.94 \)mm, the minimum depth value of defects that can be detected in the plate is 9.39mm, and No.2 represents the maximum depth value of defects that can be detected is 11.10mm; The defect depth range is 0-1.71mm.

As shown in Fig.6(b), when the focal depth for PAUT is \( h = 11.14 \)mm, the minimum depth value of the defect that can be detected in the plate is 9.36mm, and No.2 is the maximum depth value that can be detected at=11.15mm; The defect depth range is 0-1.79mm.

As shown in Fig.6(c), when focal depth for PAUT is \( h = 11.34 \)mm, the minimum depth value of the defect that can be detected in the plate is 9.36mm, and No.2 is the maximum depth value that can be detected at 11.18mm; The defect depth range is 0-1.82mm.

As shown in Fig.6(d), when focal depth for PAUT is \( h = 11.54 \)mm, the minimum depth value of defects that can be detected in the plate is 9.39mm, and No.2 is the maximum depth value of defects that can be detected at 11.18mm; The defect depth range is 0-1.79mm.

As shown in Fig.6(e), when focal depth for PAUT is \( h = 11.74 \)mm, the minimum depth value of defects that can be detected in the plate is 9.36mm, and No.2 is the maximum depth of defects that can be detected at 11.15mm; The defect depth ranges from 0 to 1.79mm.

Obviously, the depth range of defect detected by PAUT focusing is larger than that detected by non focusing, while the depth range of defect C-scan images with different focusing depth has small difference. At the same time, it can be seen from the C-scan images with different focusing depths that the defect contour is obviously different with different focusing depth, and the color of the same area is different.

3.2. 3D volume rendering method

Each image in Fig.6 was treated as follows(Fig.7). Firstly, the threshold value was obtained by image binarization method using iterative partitioning, which can save more image information and reduce background and noise interference[16]. Secondly, the median filtering of binary images was used to eliminate some isolated noises[17]. Finally, closed operation of filtered image was used to fill the interior cavity, connect the adjacent target and smooth its boundary.
The 2D sectional image information of the defect was obtained according to the above processing, and a 3D matrix was established to obtain a 3D volume dataset $D$ with dimensions of $x \times y \times 5$. The above processed 2D images were constructed into 3D volume rendering data sets. In order to avoid excessive 3D data sets, only some specimens with artificial defects were reconstructed and the data were smoothed. According to the volume data value $f(x,y,z)$, each pixel was interpolated in space to obtain the volume data information; Different color values and opaqueness values were assigned to different types of voxels according to the gradient and illumination model where each data point was located, and the semitranslucent color values of all data at the same pixel point were combined to form and reconstruct the image fragments. At present, two methods are used to synthesize image fragments: one is to iterate from front to back, and the other is to iterate from back to front. We used the forward–backward iterative method to synthesize the image, assuming that $C_{\text{now}}$ is the color value of the i-th voxel, $\alpha_{\text{now}}$ is the opacity, $C_{\text{in}}$ is the color value of the entering i-th voxel, $\alpha_{\text{in}}$ is the opacity, $C_{\text{out}}$ is the color value after the i-th sampling point, and $\alpha_{\text{out}}$ is the opacity. The relationship between color value and opacity can be expressed as follows:

$$C_{\text{out}} \alpha_{\text{out}} = C_{\text{in}} \alpha_{\text{in}} + C_{\text{now}} \alpha_{\text{now}} (1 - \alpha_{\text{in}})$$  \hspace{1cm} (3)

$$\alpha_{\text{out}} = \alpha_{\text{in}} + \alpha_{\text{now}} (1 - \alpha_{\text{now}})$$  \hspace{1cm} (4)

Then, the cumulative projection of the data set on the display plane was calculated. The 3D volume rendering reconstruction slice was constructed and the equivalent surface was rendered, and the angle, color, light of the display were adjusted. After cumulative projection of the treated defect images, a 3D complex artificial defect in the plate was finally obtained, as shown in Fig.8.
4. Conclusions
In order to detect complex defects in metal plates, a three-dimensional reconstruction method of metal plate defects based on ultrasonic phased array concentrating imaging is proposed. Using ultrasonic phased array equipment to scan the surface of the sample with different focus depths. Then preprocess the obtained C-scan image, and perform three-dimensional reconstruction based on the defect contour. Finally, the three-dimensional visualization of metal plate defects is realized.

The results show that PAUT can accurately detect the shape of defects with different depths. Three-dimensional reconstruction of C-scan images with different focus depths conforms to the actual shape of defects. This method can intuitively reflect the true shape distribution of defects in metal plates. However, due to the influence of edge detection, the test result of length may deviate greatly from the true value. In future studies, we will consider how to avoid this effect. In a word, the three-dimensional inspection of internal defects of specimens can be realized by using ultrasonic phased array focused detection technology and three-dimensional reconstruction method, which has good adaptability and economy and achieved remarkable results in nondestructive inspection.

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