Ultrasonic Phased Array Three-dimensional Imaging
Using TFM-based Slice

Changli SUN\textsuperscript{1,2}, Tie GANG\textsuperscript{1}, Peng YU\textsuperscript{1}

\textsuperscript{1} State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, China, 150001; \textsuperscript{2} School of Computer and Information Engineering, Heilongjiang University of Science and Technology, Harbin, China, 150022.

Contact e-mail: gangt@hit.edu.cn

Abstract. In order to facilitate the understanding and evaluation of a defect, a research was conducted about three-dimensional(3D) imaging by ultrasonic phased array. Using a linear array probe to obtain a series of two-dimensional(2D) ultrasound images, through which a 3D image is reconstructed. In the experiment, the probe used is a 64 element linear phased array probe, and the defects are side drilled holes on phased array B-type test piece. In this reconstruction process, the quality of the 2D slice is crucial. In the present study, TFM algorithm was used to obtain high-resolution 2D slices, and then 3D reconstruction was done with isosurface method implemented by programming on MATLAB platform, and a satisfactory 3D image of artificial defects was achieved. In the result, the defects can be segmented by a threshold from 3D image. The results showed that 3D imaging by ultrasonic phased array using TFM-based slice has the advantage of high resolution, and can reflect more information of the true defect fully, and make it easy to understand those information of the defect, such as length, depth, position and orientation.

1 Introduction

In conventional ultrasound test, it is inconvenient for testers to evaluate just by A-scan signals only which are not very intuitive, as shown in Fig. 1. Most non-professionals do not understand what the meaning of this curve is, and it is needed for professionals to extract the related features of the defect signal, including amplitude, time of arrival, the phase relationship and spectral characteristics of the target signal etc., and then analyzed them in order to get useful information about the defects.

UT image displays the data in a 2D view, with distance from the front of the wedge on the X-axis, and depth on the Y-axis. This view is composed of all of the A-scans in a particular setup. The A-scan for each beam is available for use in flaw signal interpretation. By doing mechanical scanning in one direction using a single-element probe in immersion ultrasonic testing, a 2D image of a flat bottom hole, shown in Fig. 2, can be got through the arrangement of the series of signal obtained by the scanning.

Phased Array Ultrasonic Technology(PAUT) has the ability to image the data in the same format as conventional ultrasonic A-scans, and 2D images of time or distance encoded B-scan, D-scan, and C-scans(See Fig. 3.). It is convenient to obtain 2D ultrasound image by
using PAUT. A 2D image is intuitive compared with A-signal curve, however, the information of orientation and morphology about defects are more intuitive in a 3D image.

And for the reason that defects with different spatial distribution has different impact on the components, it is important to get 3D image of the defects. If NDT operator only have 2D images and transform them into 3D image in his mind, human subjectivity factor will be incorporated inevitably, because of his experience and other factors.

![Fig. 1. An A-scan signal](image1)

![Fig. 2. A B-scan image](image2)

For this reason, many domestic and foreign researchers have carried out some researches on 3D imaging based on PAUT. Yan Li converted the flaw data detected by ultrasonic phased array to 3D coordinates, and moved these coordinates to a certain geometric shape of the weld to form a rotating 3D image using MATLAB software\(^1\). But the continuity of the flaw is not very clear. Using 8×8 two-dimensional array probe, Keren Shi etc. achieved a phased array 3D ultrasonic scanning, and displayed volume data. The resulting 3D ultrasound images of cross-hole artificial defects provided the contour and orientation information\(^2\). But its downside is that the image is rough, due to the small amount of data. So KITAZAWA etc. developed a 3D phased array ultrasonic equipment - "3D Focus-UT", and successfully implemented a 3D visualization of flat bottom hole artificial defects with matrix probe\(^3\). However, its equipment is large and control is relatively complex. It is needed to find a high-quality and low-cost 3D ultrasound imaging method, and the present study is to do so.
2 Method and Experiment

2.1 3D Reconstruction

How to obtain 3D images? On the basis of the current 2D imaging, the most direct way is to obtain multiple 2D ultrasound images and then reconstruct them into 3D image by computer. The 2D slices were stacked, and a scalar volumetric data was got. It was rendered using the isosurface technique to achieve volume visualization\cite{4}. An isosurface can be defined as follows. Given a scalar field $F(P)$ with $F$ a scalar function on $\mathbb{R}^3$, the surface that satisfies $F(P)=\alpha$, where $\alpha$ is a constant, is called the isosurface defined by $\alpha$. The value $\alpha$ is called the isovalue. As an isosurface extraction method, the marching cubes (MC) algorithm is a sequential-traversal method that was described in 1987 by Lorensen and Cline\cite{4}. The eight lattice points in two adjacent slices--four in each slice--form a cube, as shown in Fig. 4. The lattice lines shown in the figure define the edges of the cube.

![Fig. 4. lattice points and cube](image)

During MC processing, each cube vertex that has a value equal to or above the isovalue $\alpha$ is marked; all other vertices are left unmarked. If one vertex marked and one unmarked on a cube edge, the isosurface must intersect this edge. Since each of the eight vertices of a cube can be either marked or unmarked, there are $256(2^8)$ possible marking
scenarios for a cube. Each cube marking scenario encodes a cube-isosurface intersection pattern. However, the MC algorithm considers reflective and rotational symmetry, which results in just 15 marking scenarios. The 15 basic cubes cover all 256 possible marking scenarios for a cube. The coordinates and normal vectors of the intersection point were calculated by linear interpolation formula, shown in formula (1).

\[ P = p_1 + (\alpha - V_1)(p_2 - p_1) / (V_2 - V_1) \]
\[ N = N_1 + (\alpha - V_1)(N_2 - N_1) / (V_2 - V_1) \]

(1)

Where \( P \) is the coordinate value of the intersection point, and \( N \) is the normal vector of the intersection point. \( p_1, p_2 \) are the coordinates of the two endpoints (two vertices on either end of the edge). \( V_1, V_2 \) are the gray values of the two endpoints, and \( \alpha \) is the isovalue. \( N_1, N_2 \) are the normal vectors of the two endpoints.

The value of marked vertex is 1, and 0 for unmarked. There will be an 8-bit binary number string \( V_0 \ldots V_7 \) after comparison gray value of each cube's eight vertices with a given threshold value(isovalue \( \alpha \)). There are 256 kinds of such number string. So an index table was used to record the number string and the reflective and rotational symmetry of each cube after being treatment. Through the index table, the facetized isosurface in each cube can be found in the 15 basic intersection topologies, shown in Fig. 5. And in this way, the volume data set was processed in a sequential, cube-by-cube manner, and the whole isosurface was finished.

![Fig. 5. The 15 basic intersection topologies](image)

2.2 Specimen and Testing

The device used in this research are shown in Fig. 6. The targets are 1mm diameter SDHs along 25mm radius on the phased array B-type test block, as shown in Fig. 7. The specimen has been tested by the ultrasonic phased array testing system, these photos of the computer, the phased array control device and the linear array probe configured in this system shown in Fig 6 are not in the same proportion. The parameters of the probe and phased array control unit are listed in table 1 and table 2 respectively. The linear array probe is placed on the top of the test block, and mechanically scan along the X direction as shown in Fig. 7.

![Fig. 6. Testing system, (a) Computer (b) UPA control unit (c) probe](image)
It can be seen from one of the obtained S-scan images, as shown in Fig.8, that the image reflects the cross-section of the side drilled holes, but somewhat distorted compared with the actual shape of the reflector. In the method of stacking many 2D images to reconstruct 3D image, the quality of the 2D images is crucial. Therefore, in this study high-quality 2D images were used to do 3D reconstruction, which were got using total focusing method (TFM) by post-processing the full matrix capture (FMC) data collected with the linear array probe.

![Fig. 7. A PAUT B type test block](image)

<table>
<thead>
<tr>
<th>Table 1. Parameters of array probe</th>
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<tr>
<td>Array type</td>
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<th>Table 2. Parameters of Ultrasonic Phased array device</th>
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2.3 2D Image by Total Focusing Method (TFM)

Lateral move the linear array probe to positions at interval of 1mm, and did data acquisition by full matrix capture (FMC) method. The data set from an n element array has a finite size and is an n × n matrix of time-domain signals from every possible transmitter-receiver element combination. This is referred to as the full matrix and the procedure for obtaining it is referred to as full matrix capture. One high quality imaging algorithm that can only be performed practically by using FMC and post-processing is the total focusing method (TFM). This is a post-processing technique which uses all elements in the array to focus at every
point in the image. The TFM yields a scalar image, in which the array is focused in transmission and reception at every point in the field of view\cite{6}. A detailed description of the method can be found in Ref.[7]. The TFM image of SDHs on the B-type test block was got, shown in Fig.9. Obviously, its’ quality is higher than that of the S-scan image.

Fig. 8. A S-scan image of SDHs on B type test block

Fig. 9. A TFM image of SDHs on B type test block

3 3D Image

FMC data were collected at 11 positions at 1mm intervals on the top of the test block shown in Fig. 7 in the X-axis direction, which were post processed by TFM method and then 11 TFM images were obtained. These 11 images were stacked together in the coordinate system
shown in Fig. 10, and a 3D data volume was got. Using the isosurface method described in Section 2.1, a 3D image of the reflector was reconstructed from this 3D ultrasound data. The resulting 3D image can be rotated to be observed at a convenient visual angle. In Fig.11, the Viewing angle of the 3D image are the azimuth -95 and elevation 30(both in degrees). The viewing angle of Fig.12 is view(-90,0).

In Figure 11, a clear 3D image was implemented of the SDHs in the test block, from which the position and size of the reflectors can be 3D measured, and the spatial orientation of the reflectors are also intuitional visualized in the results. The distance of the two hole at the bottom of imaging area is only half of those between other holes, so the lowest two holes' images connected together in Fig. 11, but when rotated the image to the visual angle view(-90,0) shown in Figure 12, the two reflectors can be visually distinguished.
4 Conclusions

High quality 2D ultrasound image of multiple adjacent reflectors can be got by TFM method to post-process on FMC data collected with linear phased array probe. And stacked these 2D images to 3D data volume, and then 3D reconstruct it by isosurface extraction method, then a 3D imaging of the sound reflector in the test block was achieved. The 3D image clearly reflects the morphology of the SDHs in the specimen, contains more information than that of 2D image and A-signal.

The next step is automatic interpretation after high quality 3D imaging of artificial reflectors with a variety of other shapes by adopting artificial intelligence technology, and eventually applied it to the actual weld defects imaging.

![The viewing angle of view(-90,0)](image)

**Fig. 12.** The viewing angle of view(-90,0)

Acknowledgements

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References


