3D Reconstruction and Calculation Methodology of Defect Using Ultrasonic Phased Arrays

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Abstract. In recent years, there has been a rapid development and application in the use of ultrasonic phased arrays for non-destructive examination, it’s a relatively mature technology to detect over the location and general size of defect. For a better visualization and evaluation, a few researchers have done some work on three-dimensional reconstruction of defects. This paper proposed a 3D reconstruction and calculation methodology, which using a linear phased array probe detection system to collect scanning data, combining with image algorithm on MATLAB platform, then realized the 3D reconstruction and calculation of defects. To verify the reliability of the method, we made two contrast test blocks, including different hole defects. The optimal characterization performance of the methodology will be achieved when the reconstruction model can better characterize the actual defect and the volume calculation results are close to the true values. The experimental results shows the reconstructed 3D models are continuous and smooth, which can reflect the types of defects. The calculated values of volumes are close to the true values, whose calculation errors were all less than 10%, and the maximum error was less than 2% after error compensation. Besides, the speed of defect reconstruction is more faster than traditional methods. For three-dimensional reconstruction and quantitative analysis of defect, it has important significance and practical values.

Introduction

In industry, on one hand, in the process of production and manufacture, it is easy to appear defects such as porosity, crack and slag inclusion. On the other hand, high-end equipment is usually working in harsh environment such as high temperature, strong pressure, heavy load and so on. It will cause parts fatigue, corrosion, burns and cracks damage and affect the normal work of the equipment, what’s worse, it can eventually cause structural failure. Therefore, reliable inspection and maintenance during manufacture and in-service operation are crucial to ensure safety and to protect the environment against catastrophic failure [1].

There exist various methods for defects inspection by using ultrasonic phased arrays. In order to observe spatial structure more intuitively and realize three-dimensional visualization of defects, a few researchers have done some research on the three-dimensional reconstruction of defects. Svetoslav I. Nikolov, Jrgen A. Jensen proposed a 3D real-time synthetic aperture imaging method based on rotating phased array transducer, this method combines the mechanical moving phased array with synthetic emission aperture imaging, and does not need to weight the image quality, obtaining a better spatial resolution [2]. Shi Keren realized three dimensional reconstruction of horizontal hole with data got by 8x8 two-dimensional array probe [3]. Li Yan used the ultrasonic phased array sector scan method to carry out full volume inspection of the weld seam, and moved the detection coordinates to the weld seam of a certain geometric shape. He used MATLAB...
software to form a rotatable 3D image, realizing the 3D visualization display of the inspection data and multi-angle observation [4]. Changli Sun, Tie Gang proposed a 3D imaging method for water-immersed ultrasonic defect detection using phased array ultrasonic probes. By acquiring B-scan images of defects and using MATLAB platform, three-dimensional visualization of defects was realized, which provided convenience for observing the spatial distribution of defects [5]. So KITAZAWA developed a three-dimensional phased array ultrasound equipment system "3D Focus-UT", achieving a three-dimensional visualization of flat-bottomed holes with data from scanning by matrix array probe [6]. Yoichi Ochiai, Takayuki Hoshi proposed an ultrasonic suspension method based on ultrasonic standing wave to locate millimeter-sized polystyrene particles and make them move in a certain direction in 3D. The results showed this direction can better control the spatial movement of fine particles [7]. Sun Changli and Chi Dazhao proposed a three-dimensional synthetic focusing imaging method without moving the ultrasonic probe. By collecting the complete set of ultrasonic response data in the space below the probe, and processing test blocks, the three-dimensional image data of ultrasonic imaging were obtained [8].

This paper aims at presenting a 3D reconstruction and calculation methodology to represent spatial performance of defect, as well as to calculate the volumes of defects. Through the reconstructed 3D model, we made a preliminary identification of defects, and obtained a more accurate results of defects volumes. In order to verify the feasibility of the method, we designed and manufactured two test blocks, which included different size holes in various depth. Combining ultrasonic phased array device with computer software, we got a series of C scan pictures in different depth. Then we used these sequential pictures to reconstruct 3D model of defect. Finally, the methodology was verified when actual volume values were close to calculated values.

**3D Reconstruction and Calculation Methodology**

Ultrasonic phased array has many different display modes, such as A-scan, C-scan, S-scan and B-scan. Figure 1 shows some ultrasonic views in a block. The red regions indicate defects, and C view shows the defect performance at a certain depth. It is feasible to obtain a series of C views in different depth of a block. According to continuity theory, when the distance between two adjacent C views is small enough, we can use these sequential C views to reconstruct the real three-dimensional structure of the defect by equivalent facet algorithm. And then, we approximately calculate the defect area of each C view picture by means of image processing.

In order to calculate the volume of defect, we use $S_i$ (i from 1 to n) to represent the area of C view picture(i) that includes defect region, $\Delta d_i$ represents the distance between two adjacent pictures. So, the volume of defect can be approximately expressed as:
\[ V = \sum_{i=1}^{n} \Delta d_i \cdot S_i. \]  

(1)

According to continuity theory, when \( \Delta d_i \) is small enough, the defect area is continuously varying with the depth. Therefore, we assume that the defect area of the picture \((i)\) is approximately equal to the average value of picture \((i-1)\) plus picture \((i+1)\), it can be expressed as:

\[ S_i = \frac{S_{i-1} + S_{i+1}}{2}. \]  

(2)

In the process of the detection, we can adjust \( \Delta d_i \) to the same value \( \Delta d \), so the former equation can be simplified as:

\[ V = \frac{\Delta d}{2} \sum_{i=1}^{n-2} (S_i + S_{i+2}). \]  

(3)

And then, the equation (3) can be replaced as:

\[ V = \frac{\Delta d}{2} \sum_{i=4}^{n-2} (S_i + S_{i+2}) \]

\[ = \frac{\Delta d}{2} \cdot ((S_1 + S_3) + (S_2 + S_4) + \ldots + (S_{n-2} + S_n)) \]

\[ = \Delta d \cdot (S_1 + S_2 + \ldots + S_n) - \frac{\Delta d}{2} \cdot (S_3 + S_4 + \ldots + S_{n-1} + S_n). \]  

(4)

From equation (4), the result is only related to the parameters \( \Delta d \) and \( S_i \), it is means the more accurate the parameters \( \Delta d \) and \( S_i \), the more accurate the result will be.

**C-scan Pictures Extraction**

Table 1 shows some parameters of the instrument OmniScan MX2, and table 2 includes the linear array probe parameters. Figure 2 demonstrates the fabricated blocks with various size hole defects in different position. In order to obtain C-scan pictures of the defect in various depth, we set some parameters of the ultrasonic phased array instrument at different detection process, including sound velocity of material, scanning speed, focusing depth, scanning angle, gate position etc.

For better imaging results, we let linear array probe scan along the direction of the hole length at a slow speed, at the same time, continuously adjust the device’s gain, until a clearly stable defect picture appeared.
After detection, read out the detection data on the software TomoView 2.10, then merged the data through volumetric merge process. While the resolution of ultrasound axis and index axis were set to value of 0.1mm, we can get a small distance between two adjacent C-scan pictures. After that, we could obtain C-scan pictures including defect regions by adjusting the ultrasound axis. Figure 3 illustrates C-scan pictures of the hole defects at various depth in test block 1 and block 2.

![C-scan pictures of the hole defects at various depth](image)

(a)Defect 1, the Φ4mm hole defect, whose center is at 15mm depth in block1. (b)Defect 2, the second Φ4mm hole defect, whose center is at 7mm depth in block 2. (c)Defect 3, the Φ3mm hole defect, whose center is at 7mm depth in block 2. (d)Defect 4, the Φ3mm hole defect, whose center is at 15mm depth in block 2.

Figure 3. C-scan pictures at different depth of the defects in test blocks.

### Image Processing

For subsequent 3D model reconstruction and calculation, it is necessary to obtain clear defect area in C-scan pictures at last, therefore, image processing is essential to exclude noise and other less important information. The image processing steps as follows:

1. Extract R/G/B components from the original C-scan pictures, and retain defect area component, then perform grayscale conversion.
2. Filter the grayscale C-scan picture by overrun pixel smoothing (OPS)filtering method.
3. Obtain edge of the defect through edge detector.
5. Extract fidelity defect image by binary processing.

As a case study, we used one of the C-scan pictures of the test block 1 for illustration. As shown in Figure 4(a), the picture illustrates C-scan conditions at a certain depth of the Φ4mm hole defect. From Figure 3, we can see this picture shows the largest defect area, which is match with the diameter section of the hole defect. To visualize it, we call this C-scan picture the neutral layer. Through the image processing above, the effect is shown in Figure 4(b)~(f). And then, we got all of the binary images from every C-scan picture about block 1, as shown in Figure 5(a). Similarly, we
got the binary images of other C-scan pictures about test blocks, as shown in Figure 5(b)~(d).

(a) The neutral layer C-scan picture of the Φ4mm hole defect in test block 1 (b) Shows the R component of defect area (c) Shows the result of grayscale transformation (d) OPS filtering method and normalization result (e) The consequence through Canny operator (f) Closing operation result.

Figure 4. C-scan pictures image processing.

Figure 5. Binary pictures at different depth of the defects in test blocks, (a)~(d) refer to defect 1-4.
Defects Three-dimensional Reconstruction

The three-dimensional visualization of defects can not only display the defects, but also provide a preliminary judgment on the types of defects. In preceding steps, we have obtained different depths binary section images of defects. Through sequentially reading the defect sections according to their correct location and orientation by using equivalent facet algorithm in MATLAB, defect three-dimensional models were reconstructed. However, there exist an interval between two adjacent sections, which will create an error. Because it is impossible to get completely continuous C-scan pictures, Figure 6 shows the principle. For compensating discontinuous intervals between adjacent pictures, meanwhile, making the surface of constructed model coherent and smooth, we used parameter 5 to create patch objects for adjacent sections through multiple tests by equivalent facet algorithm. The final three-dimensional reconstruction models are shown in Figure 7. The surface of the constructed 3D model are smooth, besides, the reconstructed model are approximate to a cylinder, which are match with the spatial characteristic of the actual defect holes.

Figure 6. The Principle of three-dimensional reconstruction using sequential C-scan.

Figure 7. 3D model reconstruct results of four defect holes.(a)~(d) refer to defect 1 to 4.

Defect Quantification

Defect quantification analysis mainly includes two dimensional parameters analysis and three dimensional parameters analysis. Two dimensional parameters mainly refer to defect area, perimeter, long axis and short axis, while three dimensional parameter mainly refers to defect volume. By 8 domain labeling algorithm, combining with image processing function in MATLAB, we calculated the two dimensional values of the above parameters.

Table 1. OmniScan MX2 parameters used in experiments.

<table>
<thead>
<tr>
<th>Instrument parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display size (cm)</td>
<td>26.4</td>
</tr>
<tr>
<td>Display resolution(mm)</td>
<td>0.264</td>
</tr>
<tr>
<td>Pulse width(ns)</td>
<td>30~500,resolution 2.5</td>
</tr>
<tr>
<td>System bandwidth(MHz)</td>
<td>0.75~18(-3dB)</td>
</tr>
<tr>
<td>Scanning type</td>
<td>S scan and linear scan</td>
</tr>
<tr>
<td>Digital frequency(MHz)</td>
<td>100</td>
</tr>
<tr>
<td>A scan refresh frequency(Hz)</td>
<td>60</td>
</tr>
<tr>
<td>Probe type</td>
<td>Probe size(mm)</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Linear array</td>
<td>8x8</td>
</tr>
</tbody>
</table>

From Table 1, the resolution of the instrument is 0.264mm, marking the resolution $\gamma$. For binary picture $i$, it is assumed that the total number of pixels in the defect region is $N$, so the defect area can be expressed as:

$$S_i = N_i \cdot \gamma^2.$$  \hspace{1cm} (5)

Supposing the pixel points in the boundary of the defect region is $n_i$, so the defect perimeter is given by:

$$C_i = n_i \cdot \gamma.$$ \hspace{1cm} (6)

Assuming that the number of pixels about longest line distance in defect region is $L$, so the long axis is given by:

$$La = L \cdot \gamma.$$ \hspace{1cm} (7)

Similarity, assuming the number of pixels about shortest line distance in defect region is $l$, the short axis is given by:

$$Sa = l \cdot \gamma.$$ \hspace{1cm} (8)

Through above analysis, the preliminary two dimensional quantification results can be counted. In order to verify the validity of image processing function, we read the pixel matrix of each binary image, and retrieved pixel numbers of long axis and short axis. At last, it shows the pixel numbers of long axis and short axis are different from the result by image processing function, which will cause an error in defect areas and perimeters. For compensating the error, we measured the actual short axis and actual long axis of the defect based on the measurement cursor and reference cursor in TomoView. On account of the actual results, we calculated the error percentage and compensated the error of corresponding parameters. For simplification, we named short axis error as $\alpha$ while long axis error as $\beta$. When using these two parameters to compensate the area of binary pictures, the compensating defect area can be written as:

$$S_{\alpha \beta} = S \cdot (1 + \alpha) \cdot (1 + \beta).$$ \hspace{1cm} (9)

From binary pictures, it illustrates the defect area approximates a rectangular, the length and width of the rectangular corresponding to the actual long axis and short axis respectively, whose approximate area value can be calculated by using the rectangular area formula. By analyzing the compensating area and rectangle area, we found there existed a small difference between the two results, which made us regard the compensating area as the defect region area.

In order to get actual volume of the defect sections, we use integral to calculate the volume, as shown in Figure 8, it shows the side view of the defect hole. X-axis represents the neutral layer, while the upper limit and lower limit depend on the number of defect slices on each side of the neutral.
From Figure 3, the number of defect slice on both sides of the neutral layer are 4 slices and 6 slices respectively, so the actual volume of the defect can be expressed as:

\[ V_\varepsilon = h \cdot 2 \int_{-d}^{d} \sqrt{r^2 - x^2} \, dx. \]  

(10)

The value of parameter \( d \) is 0.1mm, and parameter \( h \) demonstrates the depth of the defect hole, whose value is 10mm, and parameter \( r \) stands for radius, whose average value is 2.00mm measured by a vernier caliper.

Through above defect quantification procedure, we obtained two-dimensional parameters and three-dimensional parameters of the four defect holes at last. The calculation error of volume are shown in Table 3.

<table>
<thead>
<tr>
<th>The defect</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter(mm)</td>
<td>4.00</td>
<td>3.93</td>
<td>2.88</td>
<td>2.90</td>
</tr>
<tr>
<td>Center depth(mm)</td>
<td>15</td>
<td>7</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Calculation results(mm³)</td>
<td>36.444</td>
<td>89.551</td>
<td>68.768</td>
<td>82.301</td>
</tr>
<tr>
<td>Actual results(mm³)</td>
<td>39.528</td>
<td>93.666</td>
<td>76.032</td>
<td>76.584</td>
</tr>
<tr>
<td>Absolute error(mm³)</td>
<td>3.084</td>
<td>4.115</td>
<td>7.264</td>
<td>5.717</td>
</tr>
<tr>
<td>Percentage of error</td>
<td>7.8%</td>
<td>4.4%</td>
<td>9.6%</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

**Experimental Results**

Figure 7 demonstrates the reconstructed 3D models of defect holes. The surfaces of these reconstructed models are coherent and smooth through equivalent facet algorithm, and the spatial performances of the reconstructed models are similar to the realistic characteristics of defect holes, it can better reflect the shapes and directions of the defects and provide a preliminary judgement for the type of the defect. Figure 9 shows the fluctuation of coefficients \( \alpha \) and \( \beta \), in which the two coefficients are always around 15%. Table 3 demonstrates there exists a small error of volume between the results of image processing and actual results, and the calculation errors are all within 10%, it proves the proposed defect quantification method is effective. Table 4 displays a small difference between the calculation results and contrast value compensating results, the error is very small that supports taking 15% as the mean value of compensation coefficients. Besides, compared the imaging time of full-focus mesh acceleration algorithm [9] with equivalent facet algorithm adopted in this paper, the latter can reduce the time required for three-dimensional reconstruction of defects, the results are shown in Table 5.
Figure 9. Area compensation coefficient \( \alpha \) and \( \beta \) in different depths section pictures. Rows one to four from the top represent defects 1 to 4 respectively.

<table>
<thead>
<tr>
<th>The defect</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculation results (mm(^3))</td>
<td>36.444</td>
<td>89.551</td>
<td>68.768</td>
<td>82.301</td>
</tr>
<tr>
<td>15% compensating results (mm(^3))</td>
<td>35.714</td>
<td>89.447</td>
<td>68.955</td>
<td>82.468</td>
</tr>
<tr>
<td>Absolute error (mm(^3))</td>
<td>0.73</td>
<td>0.104</td>
<td>0.187</td>
<td>0.167</td>
</tr>
<tr>
<td>Percentage of error(‰)</td>
<td>20.0</td>
<td>1.2</td>
<td>2.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 5. Time comparison of defect image reconstruction.

<table>
<thead>
<tr>
<th>Equivalent facet algorithm</th>
<th>Full-focus mesh acceleration algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Defect 1</td>
</tr>
<tr>
<td></td>
<td>Defect 2</td>
</tr>
<tr>
<td></td>
<td>Defect 3</td>
</tr>
<tr>
<td></td>
<td>Defect 4</td>
</tr>
</tbody>
</table>

From the results of experiments, the proposed 3D reconstruction and calculation methodology has been well validated through experimental measurement, the reconstructed 3D models were continuous and smooth, while the speed of defect three-dimensional reconstruction is faster, and the defect volumes are closer to the actual values. It should be pointed out that the upper and lower surfaces of these reconstructed models are not closed, because it is difficult to collect all depth slice pictures of the defect, in small defect region, the energy of ultrasonic sound can not clearly display the defect, instead, it often occurs a blurred edge owing to the scattering noise. So, only the slice pictures (C-scan pictures) with clear edge and complete outline will be extracted for image processing.
Discussion

As it can be seen from the solution of the defect volume, the more accurate the areas of the binary pictures, the more accurate the calculation of the volume. From equation 9, we used coefficients $\alpha$ and $\beta$ to compensate the areas of the binary pictures defect regions, then, we adopted equation 4 to calculate the volume of defect holes by using the compensated areas, and the error between the calculation results and the real results is less than 10%, which can prove that the compensation coefficients $\alpha$ and $\beta$ are important to the calculation of volume. Through the preliminary analysis of these two parameters, we found that the values of the two coefficients are mostly within 10%~20%, Figure 9 shows the fluctuation of coefficients $\alpha$ and $\beta$ in different binary section pictures.

From Figure 9, it can be seen that the coefficients $\alpha$ and $\beta$ fluctuate with the depths of the binary section pictures. However, the values of the coefficients are always around 15%. Therefore, we assumed that the defect pixels information extracted by image processing function has an error with the defect pixels of the original defect image, for obtaining a more accurate defect areas, it should be compensate about 15% respectively in short axis and long axis of the binary section pictures. Because $\alpha$ and $\beta$ are always going to fluctuate around 15%, it suggests us to use the value to compensate defect areas, then the volume of the defect can be obtained by using equation 4. One simple way to verify the assumption, is to use the contrast value to compensate the defect areas after calculated by image processing function, the closer the two results are, the more reliable the assumption becomes.

The results are showing in Table 4, there exists a small difference between the calculation results and contrast value compensating results, the maximum error is 20‰, while the minimum error is only 1.2‰, which can certainly support our assumption. The results inspire us when we use the image processing function to get two-dimensional parameters of the defect section pictures, such as short axis, long axis, perimeter and area, it is effective to regard contrast value 15% as the mean value of coefficients $\alpha$ and $\beta$, which is efficient for calculating the volume of defect. However, there are still existing shortcomings in the procedure of obtaining the volume of defect. On one hand, the binary section pictures are the key factors for reconstructing the 3D model of defect, meanwhile, it will directly affect the upper and lower limits of the integral formula for calculating the defect volume. On the other hand, the applicable premise of equation 4 is that the interval between adjacent section pictures is small enough, but the actual minimum interval can only reach 0.1mm. These shortcomings need to be further researched in the next step.

Conclusions

A 3D reconstruction and calculation methodology is introduced to display and quantify the defects in the parts. This method takes advantage of computer image processing technology to deal with the original C-scan pictures. Combined with variety of image processing procedures, clear binary slices pictures are obtained at last. And then, three-dimensional models of the defects have been reconstructed based on equivalent facet algorithm, whose surfaces are clear, coherent, and the spatial characteristics are similar to the real defect hole, meanwhile, defect reconstruction speed is more faster, which can improve the efficiency of defect three-dimensional reconstruction. In order to get the preliminary parameters of the defects in every binary section picture, the error between the image processing function and the actual results, two compensation coefficients $\alpha$ and $\beta$ are raised and calculated. Afterwards, the defects volumes have been calculated by using the compensated areas of binary section pictures through approximate formula, and the maximum error was less than 2% after error compensation, which has important practical significance for quantitative defect detection.

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References


