Research Article

Experimental Study on Lateral Resolution of Phased Array Ultrasonic Testing of Irregular Structure Weld Defects

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Irregular structure welds are used in numerous military industries. This paper is interested in how to utilize phased array ultrasonic testing (PAUT) to identify and locate irregular structure weld defects. In this paper, CIVA simulation results were compared with inspection results of known defects and were found to be in very good agreement. This shows the feasibility of CIVA simulations. The coupling, among process parameters, affects the amplitude drop value from the peak to the trough of defects signal response, which represents the lateral resolution of internal weld defects and affect the imaging quality directly. Thus, the proper setting of detection parameters is critical to improve the testing efficiency and the imaging quality. This paper uses the response surface methodology (RSM) to design the test and conduct a factorial test to analyze the effect of each parameter. Modelling of the parameters and the response is conducted through center composite design (CCD) to analyze the coupling among multiple parameters and the reliability of the model. In the process of PAUT, the response surface plot, contour plot and the initial design domain of process parameters were combined for weld defects to determine the optimal parameters rapidly and correctly. Besides, CIVA simulation could further verify optimized detection parameters and position in industry site. Finally, irregular structure weld defects were identified accurately with PAUT imaging.

1. Introduction

Ultrasonic waves have been used for over 60 years in the medical and industrial fields. Ultrasonic testing (UT) is the most widely used nondestructive testing (NDT) method to inspect parts, measure dimensions and evaluate material properties. More recently, phased array ultrasonic testing (PAUT) was developed to generate images of parts under inspection and has demonstrated many advantages in terms of probability of detection and inspection cost [1]. Over the past decade, PAUT has been applied to ensure the quality of safety-critical components in the nuclear industry, aerospace, machinery, shipbuilding and oil and gas industries [2–5]. Indeed, PAUT imaging allows the visualization of cracks, porosities or other voluminal defects of test block by controlling the direction of acoustic beam and the size and position of focus. For the best and quickest imaging in the industrial field, it is necessary to select a few parameters properly, such as detection frequency, focus depth, testing waveform, scan angle and its resolution. Improper selection
of parameters will affect the sound field energy and the imaging quality of defects, which results in the low-resolution images, artefacts, and incorrect testing [6, 7]. Thus, many researchers have been conducted on the influence of multi-parameter on the response. Initially, RSM was mostly used in biomedical research to achieve optimal ratio and better efficacy [8, 9], and it was introduced into industry. Porcaro[10] focused on the influence of important model parameters such as thickness of the plates, geometry of the block, material properties of the plates and loading conditions on the response of the connections, and relating the normal and shear forces acting on the rivet was generated. Singh, Vasantharaja and Liu [11–13] focused on the important process parameters for welding technique, such as welding current, welding speed, torch speed, electrode tip angle and frequency of the vibrations induced in molten welding current, weldingspeed,torchspeed,electrodetipportantprocessparametersforweldingtechnique,suchas

In the field of PAUT imaging, Wang [15] compared the welding zone defects imaging results, when the ultrasonic waveform data are processed by the traditional dynamic depth focusing and total focusing method. However, the effect parameters have not been researched in the program. They did not emphasize the impact of different testing parameters on imaging quality. Marillia [16] optimized the phased array probe to maximize amplitude and improve energy transmitted into the part under inspection. When increasing the number of elements to improve the imaging quality, imaging artefacts were introduced due to constructive interference at high propagation angles. Clay, Wang [17, 18] found that geometric parameters for phased array transducer, especially the array aperture, play a decisive role in the imaging resolution. However, the influence of the size of the array element on the sound field and the influence of other detection parameters on the imaging resolution are not considered, and thus the theoretical research results have limitations for the guiding significance of practical engineering applications.

Therefore, this paper discussed the coupling relationship between multiparameters and response of PAUT welding defects by RSM approach. With CIVA simulation platform, it analyzed the test block to be inspected by modeling according to the detect parameters and discussed the reliability of CIVA simulation based on the simulation results. It designs test points by RSM to analyze the influences of parameters including transducer center frequency, the number of elements and focal length on the amplitude difference between the peak and the trough of response. Taking the CIVA simulation to verify the optimization parameters and test position, this method would reduce detection and debugging times in industry site. In addition to improving detection speed, imaging quality is also guaranteed.

2. Modeling

2.1. CIVA Simulation Platform. CIVA can provide a large number of signal processing methods and it integrates various reconstruction tools for synthetic focusing. Besides, it can extract and combine signals from data collection or phased array simulation results to produce the best focusing effect at designated points. In CIVA, different transducers are selected in the ultrasonic module to simulate the whole testing process for the defective test block. Amplitude and time difference of each echo are predicted, and the geometric shapes of the defects are obtained. In the simulation, the transducer can be a contact transducer, a water immersion transducer, a double crystal transducer, a series transducer or a rectangular or round transducer. The test blocks can be built-in geometric models such as plate, cylinder, vertebral body, pipeline, and rivet, or nonstandard 2D model drawn in CIVA platform and imported 3D models.

In this paper, known defects can be configured, such as porosity, slag inclusion, crack, incomplete fusion, incomplete penetration, poor adhesion, and loose delamination. It is time-consuming to obtain a preferable defect imaging during the PAUT of irregular weld defects, which needs to adjust the testing parameters many times. To solve this problem, this test took a different combination of parameters as guide the setting of PAUT detection parameters. Therefore, CIVA is used to replace the experiment, which shortens the actual detection time and is thus an effective means of PAUT welding defect.

2.2. CIVA Feasibility Verification. A 32-element transducer with transverse wedge parallel to the welded seam is used to inspect the transverse defects of the test block to be inspected to cover the complete welding area. The test block to be inspected has seven horizontal through holes with a diameter of 1 mm and the length of 10 mm, as shown in Figure 1(a). CIVA is used for defect simulation, and the PAUT is used for actual test of the test block. By comparison, it is found that our model is feasible.
2.2.1. CIVA Simulation of Defective Test Block. Based on the actual working conditions, a three-dimensional model of a defective irregular structure weld test block is built as Figure 1(b). In CIVA simulation, the material of test block is configured as carbon steel with a density of 7.8 g/cm³, a longitudinal wave velocity of 5900 m/s and a transverse wave velocity of 3230 m/s. The transducer is configured as a 32-element contact linear array transducer with a center frequency of 5 MHz, array element spacing of 0.1 mm, width of 0.5 mm and aperture length of 19.1 mm. The focusing mode is configured as flat focusing with focusing depth of 40 mm. The excitation mode configured as full excitation (sector scan) with the scan angle ranging from 35° to 70°, the step value being 1. The wedge is configured to be Plexiglas one with a leading edge of 16 mm, trailing edge of 26 mm, height of 26 mm, width of 20 mm and its longitudinal wave speed of 2330 m/s. The transducer is placed 20 mm away from the left edge and 22 mm away from the leading edge of the welded seam. The step value along the Y-axis is 1 mm, the steps are 20, while the step value along the X-axis is 0. The other parameters are configured by default.

After configuring the parameters in CIVA simulation, we will run the platform according to the focusing rule. The receiving rule is the same as the transmitting rule. For the simulation test, we select C-scan which can inspect quickly in a large scope and sector scan which can inspect defects correctly and flexibly. The C-scan and sector scan maps generated from CIVA simulation are shown in Figure 2(a).

It can be seen that there are only four marked horizontal through holes in Figure 3(a) because defects 5, 6 and 7 are covered by defects 1, 2, 3 and 4 due to the scan angle. However, seven horizontal through holes are marked in Figure 2(b).

2.2.2. Actual Testing of Defective Test Block. Based on the actual working conditions, the portable phased array ultrasonic device M2M is used to inspect the defective test block. The testing is performed under the same conditions and parameters as in the CIVA simulation. The parameters of the transducer and wedge are shown in Table 1 and Table 2, respectively. In addition, the transducer gain is 20 dB, the delay is 28.7 μs, the sampling frequency is 100 MHz, the pulse width is 100 ns, and other parameters are the same as in the CIVA simulation.

After the parameter configuration, the defective test block is tested. The maps of C-scan and sector scan under actual working conditions are shown in Figure 3.

The defects marked 1 and 2 in the horizontal through holes in Figure 1 are selected for comparison between the simulation and the actual testing.

According to Table 3 and Table 4, the difference between defect 1 and defect 2 in position, angle and length is small and unchanged, which shows that the simulation results are basically consistent with the actual structure and the actual device detection results. That confirmed the feasibility of designing PAUT device based on CIVA simulation. Also, the optimized testing process parameters with CIVA simulation are suitable for PAUT of weld defects.

3. Response Surface Analysis

The response surface method (RSM) is a set of statistical techniques designed to find the best response value, considering the uncertainty or variations in the values of input variables [19]. RSM is a sequential method, which can be divided into three parts: (1) Factorial text. This part aims to analyze the main effect of factors and prepare for adjusting the design domain; (2) To find a high-order polynomial model between multiple parameters and their responses, this paper uses center composite experimental design for fitting. The RSM model would be judged the reliability by $P$-value, $R^2$ and F-value of lack-of-fit term. (3) Adjusting the optimal region of parameters. It is generally adjusted according to practical engineering experience or theories of relevant disciplines. In this paper, the whole RSM experiment took the ‘Design Expert 11’ software to design, mathematical statistics and parameter optimization are carried out by RSM. In the simulation test, three factors of ultrasonic phased array testing, such as transducer center frequency, focal length and number of elements, are taken as dependent variables, and the amplitude difference between the peak and the trough is taken as the response. Based on this, the factorial analysis experiment is carried out. The three-factor three-level factorial design is coded, and the main effect of each factor and the interaction among the three factors are analyzed by calculating the variance. To meet the requirements of actual testing, the initial design domains of dependent variables are set as follows: transducer center
Figure 2: Diagram of simulation: (a) C scanning; (b) sectorial scanning.

Figure 3: Actual testing: (a) C scanning; (b) sectorial scanning.

Table 1: Parameter configuration of Olympus-linear 5L32-A11 T55°.

| Elements | Center frequency (MHz) | Number of elements | Center distance of elements (mm) | Incident dimension (mm) | Width (mm) |
|----------|------------------------|--------------------|---------------------------------|-------------------------|------------|
| Value    | 5                      | 32                 | 0.6                             | 9.1                     | 10         |

Table 2: Parameter configuration of wedge Olympus-SW55 SA11-N55S.

| Elements | Angle | Height (mm) | Length (mm) | Width (mm) | Wave velocity |
|----------|-------|-------------|-------------|------------|---------------|
| Value    | 36°   | 26          | 42          | 20         | 2330 m/s      |

Table 3: Comparison of testing depth and scanning angle between horizontal through holes 1 and 2.

| Sectorial scanning | Simulation | Test |
|--------------------|------------|------|
| Max detection depth| NO.1 37.66 mm | NO.2 32.83 mm |
| Scanning angle     | NO.1 47°   | NO.2 51°   |

Table 4: Comparison of fixed length of defects between horizontal through holes 1 and 2.

| C Scanning | Simulation | Test |
|------------|------------|------|
| -6 dB      | NO.1 9.09 mm | NO.2 8.85 mm |
| Defect fixed length | NO.1 9.21 mm | NO.2 9.02 mm |
frequency = [7, 13], focal length = [18, 42], and number of elements number = [19, 53].

3.1. Factorial Test. In the factorial design, multi-factors are taken as the objects to find out the main effect of one or two factors and the interaction among other factors. In this experiment, the three factors of transducer center frequency, focal length and the number of elements are coded at three levels, and the coded values are configured as Table 5 according to their initial design domains.

The test points are designed according to the three-factor three-level coding, where Y (dB) is the amplitude drop value from the peak to the trough of defects signal response. The specific 12 test points would be generated in the software ‘Design Expert 11’, and shown in Table 6.

The test points in Table 6 are entered into the Design Expert 11.0.01 and the variance is shown in Table 7.

According to Table 7, it is found that P(X1) < 0.0001, P(X2) < 0.0001 and P(X3) < 0.0001, which shows that the transducer center frequency, focal length and the number of elements have significant influence on the response and have the main effect. The P-value shows that there is significant experimental interaction among multiple factors, indicating that the three parameters are not independent of each other. The change of any one parameter will directly affect the interaction effect among other factors. Besides, the significance of each coefficient of the regression equation is determined by F-value and P-value. The decisive coefficient of the third-order regression equation is \( R^2 = 0.9994 \), which shows that 99.94% change of response can be explained by the model.

3.2. Center Composite Design. To further optimize parameters of the model, three-factor five-level coding of CCD is adopted, as Table 8. The three factor are X1(Center Frequency), X2(Focal Length) and X3(Number of Elements), and each parameter has five level, above level, below level, zero level, r point from zero level(±r). And that corresponds to +1, -1, 0, +1.68, and -1.68. Based on the initial factorial experiment, the mathematical model is optimized by adding axial points and central points, so as to minimize the variation of regression coefficients and improve the accuracy of the model.

The test points are designed 20 times based on CCD three-factor five-level coding in the software ‘Design Expert 11’, as shown in Table 9. Y (dB) is the amplitude difference between the peak and the trough.

The multivariate quadratic equation based on Table 9 is more compatible with current data. Pre-R2 is 0.5947 and Adj R2 is 0.8935. The difference between them is less than 0.2, indicating that the model is feasible and more reliable for future data analysis. Therefore, the regression model is shown to be a ternary quadratic equation. Based on the analysis of the variance of the CCD regression model, Table 10 is shown as follows.

The F-value of the ternary quadratic regression model in Table 10 is 18.71, which indicates that the model is meaningful. In addition, when P-value<0.0001, there is only 0.01% change that the model is not compatible, and the noise is most likely the cause for this. The coefficient of determination of model fitting is R2 = 0.9440. The result reveals that 94.4% of the change of response is due to the change of parameters, that is, the interference is very small. Furthermore, the Adeq precision is 16.750, the F-value of lack-of-fit term is 4.54, and the P-value is 0.0612 > 0.05. These three values do not definitely indicate that the model does well in fitting, but they can be used to analyze and predict the amplitude difference between the peak and the trough.

To obtain the ternary quadratic regression equation, the coding and response of the three factors are considered and the quadratic regression equation is analyzed. Therefore, the amplitude difference between the peak and the trough with respect to transducer frequency, focal length and element can be expressed as a ternary quadratic regression equation with two decimals as follows.

\[
Y (dB) = 5.19 + 1.27^*X1 + 1.25^*X2 + 1.73^*X3 + 0.4^*X1X2 + 0.35^*X1X3 + 1.78^*X2X3
- 0.58^*X12 - 0.81^*X22 - 0.65^*X32.
\] (1)

3.3. Optimal Value Range of Process Parameters. The three parameters of PAUT are analyzed in pairs for the interactive effect. The contour plot and the response surface plot of testing are obtained by selecting two of the three parameters arbitrarily. The contour plot reflects how significant and complex the interaction between two variables is. Semicircle indicates that the interaction between two variables is not significant, while semiellipse indicates that the interaction is significant. Therefore, the interaction between transducer frequency and focal length and the number of elements is insignificant, as Figure 4(a) and 4(b), while the interaction between focal length and the number of elements is significant as Figure 4(c). The other parameters are set to level 0.

Based on the initial design domain and the response surface plot and contour plot of the influence of two factors on amplitude drop value from the peak to the trough of defects signal response, the intervals of each factor are X1 = [10.9,15], X2 = [32.3,50] and X3 = [41.1,64] when the amplitude drop value Y is greater than 6 dB. Therefore, the
initial domain can be optimized, and the optimal value range of the three parameters is: $X_1 = [10.9, 13]$, $X_2 = [32.3, 42]$ and $X_3 = [41.1, 53]$.

The optimal range of parameters is configured by Design Expert 11.0.01, and stepwise regression method is used within a feasible region. The optimal process parameters are recommended as follows: the transducer center frequency is 13 MHz, the focal length is 42 mm, and the number of elements is 53. The predicted value of amplitude drop value from the peak to the trough of defects signal response is 9.94 dB. In this case, the amplitude difference based on the statistical model is 9.91 dB. There is a very small difference

| Table 5: Three-factor three-level coding. |
|------------------------------------------|
| Independent variable | Symbol | −1 | 0 | 1 |
| Center frequency | $X_1$ (MHz) | 7 | 10 | 13 |
| Focal length | $X_2$ (mm) | 18 | 30 | 42 |
| Number of elements | $X_3$ | 19 | 36 | 53 |

| Table 6: Test points and response values in Factorial test. |
|----------------------------------------------------------|
| NO. | $X_1$ | $X_2$ | $X_3$ | Y |
| 1 | −1 | −1 | −1 | 0.5 |
| 2 | 1 | −1 | −1 | 3 |
| 3 | −1 | 1 | −1 | 0.7 |
| 4 | 1 | 1 | −1 | 1.8 |
| 5 | −1 | −1 | 1 | 1.3 |
| 6 | 1 | −1 | 1 | 2.2 |
| 7 | −1 | 1 | 1 | 5.6 |
| 8 | 1 | 1 | 1 | 11.1 |
| 9 | 0 | 0 | 0 | 5 |
| 10 | 0 | 0 | 0 | 5.2 |
| 11 | 0 | 0 | 0 | 5.1 |
| 12 | 0 | 0 | 0 | 4.9 |

| Table 7: Analysis of variance of interactive factors. |
|------------------------------------------------------|
| Source | Sum of squares | Df | Mean square | F value | P value |
| Model | 44.359a | 8 | 5.545 | 332.694 | <0.0001 | Significant |
| $X_1$ | 4.351 | 1 | 4.351 | 261.075 | 0.0001 |
| $X_2$ | 0.061 | 1 | 0.061 | 3.675 | <0.0001 |
| $X_3$ | 3.251 | 1 | 3.251 | 195.075 | <0.0001 |
| $X_1 \times X_2$ | 0.011 | 1 | 0.011 | 0.675 | 0.0031 |
| $X_1 \times X_3$ | 0.451 | 1 | 0.451 | 27.075 | 0.0046 |
| $X_2 \times X_3$ | 25.21 | 1 | 25.21 | 1512.30 | <0.0001 |
| $X_1 \times X_2 \times X_3$ | 4.50 | 1 | 4.5 | 270.00 | 0.0005 |
| Curvature | 8.40 | 1 | 8.40 | 504.10 | 0.0002 |
| Pure error | 0.0500 | 3 | 0.0167 |
| Cor total | 96.73 | 11 |

A. $R^2 = .9994$ (Adj. $R^2 = .9981$)

| Table 8: CCD test design factors and coding values. |
|-----------------------------------------------------|
| Independent variable | Symbol | $-1.68$ | −1 | 0 | 1 | $1.68$ |
| Center frequency | $X_1$ (MHz) | 5 | 7 | 10 | 13 | 15 |
| Focal length | $X_2$ (mm) | 10 | 18 | 30 | 42 | 50 |
| Number of elements | $X_3$ | 8 | 19 | 36 | 53 | 64 |
between the predicted value of our model (0.03 dB); therefore, it is highly reliable.

4. PAUT of Weld Test Block

The ordinary carbon steel Q235 is selected as the material of irregular structure weld test block. The single-sided V-shaped groove seam is welded by manual arc method, and the weld reinforcement is 0.3 mm. The test uses a workstation, M2M PANTHER, phased array testing system, Olympus-linear PAUT transducer with center frequency of 10 MHz and Olympus wedge. Engine oil is taken as the coupling agent. The test bench is shown in Figure 5.

To meet the requirements of actual testing, the amplitude drop value from the peak to the trough of defects signal response of the horizontal through holes 1 and 2 (with a center distance of 2 mm) should be greater than 6 dB. The parameter combination to guide the actual testing is determined according to the optimal feasible region of process parameters. The range of transducer center frequency is A [10.9, 13], the range of focal length is B [32.3, 42], and the range of the number of elements is C [41.1, 53]. Because there is only one transducer with a center frequency of 10 MHz in actual testing, the center frequency is set as 10 M, the focal length is set as 42 mm, and the number of elements is set as 53. After substituting the process parameters (10, 42, 53) into the regression model, the theoretical value of the amplitude difference is found to be 8.49 dB. It is predicted that the defects 1 and 2 can be clearly displayed in the sector scan map. When this parameter is used in PAUT of weld defects of the test block, the sector scan map and A-scan map are as follows.

Table 9: Test points and response values of CCD.

| NO. | X1 | X2 | X3 | Y   |
|-----|----|----|----|-----|
| 1   | -1 | -1 | -1 | 0.5 |
| 2   | 1  | -1 | -1 | 3   |
| 3   | -1 | 1  | -1 | 0.7 |
| 4   | 1  | 1  | -1 | 1.8 |
| 5   | -1 | -1 | 1  | 1.3 |
| 6   | 1  | -1 | 1  | 2.2 |
| 7   | -1 | 1  | 1  | 5.6 |
| 8   | 1  | 1  | 1  | 11.1|
| 9   | -1.68 | 0 | 0 | 1.2 |
| 10  | 1.68 | 0  | 0 | 5.6 |
| 11  | 0  | -1.68 | 0 | 1.3 |
| 12  | 0  | 1.68 | 0 | 4.2 |
| 13  | 0  | 0  | -1.68 | 0.4 |
| 14  | 0  | 0  | 1.68 | 6   |
| 15  | 0  | 0  | 0  | 4.8 |
| 16  | 0  | 0  | 0  | 5.3 |
| 17  | 0  | 0  | 0  | 5.1 |
| 18  | 0  | 0  | 0  | 4.9 |
| 19  | 0  | 0  | 0  | 5.2 |
| 20  | 0  | 0  | 0  | 5   |

Table 10: Variance analysis TABLE of regression model.

| Source            | Df | Sum of squares | Mean square | F value | P value |
|-------------------|----|----------------|-------------|---------|---------|
| Model             | 9  | 128.78         | 14.31       | 18.71   | <0.0001 |
| X1                | 1  | 22.17          | 22.17       | 28.99   | 0.0003  |
| X2                | 1  | 21.35          | 21.35       | 27.93   | 0.0004  |
| X3                | 1  | 40.84          | 40.84       | 53.42   | <0.0001 |
| X1X2              | 1  | 1.28           | 1.28        | 1.67    | 0.2248  |
| X1X3              | 1  | 0.98           | 0.98        | 1.28    | 0.2840  |
| X2X3              | 1  | 25.21          | 25.21       | 32.96   | 0.0002  |
| X1^2              | 1  | 4.79           | 4.79        | 6.26    | 0.0313  |
| X2^2              | 1  | 9.37           | 9.37        | 12.25   | 0.0057  |
| X3^2              | 1  | 6.03           | 6.03        | 7.89    | 0.0185  |
| Residual          | 10 | 7.65           | 0.76        |         |         |
| Lack of fit       | 5  | 6.27           | 1.25        | 4.54    | 0.0612  |
| Pure error        | 5  | 1.38           | 0.28        |         |         |
| Cor total         | 136.43 | 19             |             |         |         |

\[ R^2 = 0.9440 \]

Adeq precision = 16.750
It can be seen from Figure 6(a) that five defects of the test block are clearly displayed. Due to the specified parameters and scan angle, two defects are covered, while the defects 1 and 2 are clearly displayed. According to Figure 6(b), the amplitude difference is 8.91 dB. There is a slight difference between the amplitude difference and the theoretical value. Therefore, we can analyze the coupling among multiple parameters by simulation and obtain the optimal process.
parameters. In this way, the PAUT imaging speed and accuracy can be improved. As mentioned in the standard of PAUT, defects can be detected with low-cost low-frequency PAUT transducers for test block with thickness of 40 mm in industry site. However, the PAUT transducer of 10 MHZ was chosen without considering the cost in this paper to achieve a higher distinction between two adjacent defects at the same depth. Meanwhile, a higher defect imaging resolution can be revealed as well.

5. Conclusion

This paper conducts tests on the lateral resolution of PAUT of weld defects. We find the coupling relationship and the value range of parameters by using CIVA simulations and RSM, which increases the speed and accuracy of parameter configuration in actual testing and improves the imaging resolution of the defect map. The conclusions are summarized as follows:

(1) The simulation software CIVA is used to carry out simulation tests when the external conditions and parameters (transducer center frequency, focal length, and the number of elements) are the same. By comparing the simulations with the actual tests, we find that the position, angle and length of defects are very small and unchanged. The finding indicates that the CIVA simulation has high repeatability and reliability.

(2) By conducting factorial test, we clarify the interaction among the parameters and find that the effect of each parameter is significant. By CCD, we build a regression model Y(dB) of the response function of the amplitude difference and confirm its feasibility by the insignificant lack-of-fit terms. Based on the initial design domain of three variables, the response surface relationship among parameters and the corresponding contour plot, it is found that the optimal ranges of the three parameters affecting the lateral resolution are $X_1 = [10.9, 13]$, $X_2 = [32.3, 42]$ and $X_3 = [41.1, 53]$.

(3) The transducer center frequency in actual testing is 10 MHZ. We substitute the parameters (10, 42, 53) within a feasible region into the regression model and calculate the theoretical value of amplitude difference, which is 8.49 dB. Since a theoretical value greater than 6 dB meets the requirement of lateral resolution of defects, we can rapidly configure parameters of the phased array ultrasonic and carry out testing. The amplitude drop value from the peak to the trough of defects signal response is 8.91 dB and
clear imaging of the defect map can be obtained rapidly.

For different industrial sites irregular structure welding block, the optimization parameters would be changed with RSM. The quality of the PAUT imaging changes as well. In order to improve the imaging capability or to achieve the best imaging results, it would be of great interest to customize specific probe according to optimization parameters.

[20].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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