Research Article

Weighted Full-Focus Defect Detection and Imaging Method Based on Threshold Fusion for Phase Coherence Factor

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Total focus (TFM) ultrasonic inspection imaging only uses the amplitude of defect data for delayed stack imaging (DAS), ignoring the phase information in the echo signal, which easily leads to low imaging resolution and interferes with subsequent quantitative analysis of defect size. To solve these problems, this paper proposes a phase coherence factor (TF-PCF) weighted full-focus imaging method based on threshold fusion: by combining the image sound intensity matrix with mathematical statistics, a reasonable threshold is set to screen out the effective pixels, and the parameter selection rules of the PCI algorithm model are redefined. The simulation and experimental results show that the TF-PCF imaging algorithm can effectively eliminate the noise information in the imaging area, including the artifacts near the defects that are difficult to be processed by PCI. Compared with PCI, TF-PCF has higher ability to quantify defect size. When using p-wave to detect large objects with a large number of defects and complex location distribution, the lateral size quantization error of the TF-PCF imaging algorithm is reduced by 8.5%. When sampling shear wave imaging to detect defects with tilted wedges, the lateral and longitudinal size quantization errors of defects are reduced by 10% and 20%, respectively. The reliability of defect size quantitative analysis is improved. Under the same test conditions, the complexity of TF-PCF model is far less than that of PCI model, which greatly improves the practicability of the algorithm model.

1. Introduction

The full-focus imaging algorithm based on the full matrix data model is a typical non-real-time off-line processing mode [1], and its defect imaging ability is higher than that of the conventional phased array ultrasound technology. Dynamic focusing of ultrasonic emission and reception is realized, which enriches defect information and improves imaging resolution [2–5]. However, in the solution of the full-field sound field [6–9], full-focus imaging technology inevitably produces artifacts due to the isoacoustic path line diffusion and ultrasonic sidelobe energy leakage [10, 11]. Such artifacts are related to the principle of full-focused ultrasonic detection, which is not convenient for direct elimination and affects the subsequent qualitative and quantitative analysis of defects [12–14].

In order to solve this kind of artifact problem, researchers have carried out related work from the algorithm model and signal processing. To solve the problem of primal artifacts in the full-focus algorithm, researchers started to work on an algorithm model and signal processing based on the amplitude information of echo data. In terms of the imaging algorithm model, Li Tianji et al. [13] introduced the traditional range amplitude calibration model into TFM technology. They constructed the phased array TFM-DAC atlas, which significantly improved the quantitative defect accuracy. However, the elimination effect of the calibration model of this kind of algorithm depends on sensor parameters, sample parameters, and acoustic beam incidence Angle, and the algorithm model needs to be recalculated under different working conditions. When the algorithm model contains too many parameters, the computational cost is increased.
and the practicability of the algorithm model is reduced. In signal processing, many scholars have realized artifact removal in defect images by combining classical methods with full matrix data. Among them, Han Song et al. [14] designed an improved wavelet filter by analyzing the DB4 wavelet, which can effectively eliminate artifacts in full-focus images while reducing the computational complexity of the model. Ge Lulu et al. [15] used the time-reversal algorithm to post-process the full matrix data, realized the enhancement of the acoustic beam energy, calibrated the defect location in the image, and improved the imaging resolution. Although the above methods can complete the elimination of artifacts, most signal processing methods need to rely on manual experience to determine parameters [16], which reduces the reliability of the algorithm. In conclusion, when solving the problem of primal artifacts in full-focus imaging, the research methods in literature [12–15] mainly rely on the amplitude information of data and simply delayed overlay imaging. Ignoring the phase information in the echo signal shows a weak ability in suppressing the sidelobe level and cannot deal with artifacts caused by sidelobe energy leakage [17].

Therefore, in the field of image processing, the processing methods that depend on data amplitude information are insufficient. Phase coherent imaging (PCI) in image processing mode has been applied to other fields by other scholars due to its excellent performance [18–23]. Qu Lele et al. [19] used the two-dimensional phase coherence factor weighted radar imaging method to effectively suppress the clutter interference in radar imaging and improve the imaging resolution. Yen, JT and Lou, Y [20] calculated the coherence of ultrasonic channel data from the received radio frequency (RF) data to realize imaging. Compared with the standard beamforming data imaging method, the image contrast (CNR) and speckle signal-to-noise ratio (SNR) were improved. Zhang, MK et al. [21] combined the coherence factor with ultrasonic Lamb wave imaging technology, suppressed the noise in the echo signal and the Lamb wave scattering effect, and improved the imaging resolution.

Research results [19–21] show that phase coherence imaging (PCI) is an adaptive weighting algorithm that can simultaneously improve imaging resolution and SNR, and all such methods have excellent defect representation ability and robustness. However, for the full-focus imaging algorithm, it is rare to improve the imaging quality by using the composite imaging technology combining TFM and PCI. In addition, when using composite imaging technology, the above methods and techniques do not have detailed interpretation and regulation of some very important parameters in the PCI algorithm model. The accuracy of parameter selection largely determines the accuracy of the coherence factor calculated at the last pixel. Especially in full-focus imaging, when there are unidentifiable artifacts in the actual defect image, the PCI algorithm model may identify these pseudo-voxel points as pixels of interest, resulting in the final calculated weighting factor error and unable to get the suppression effect. In addition, if only manual experience is used to determine the Angle parameters in the PCI algorithm model before PCI, the practicability of the algorithm model will be reduced. Moreover, the signal information of other pixels in the same Angle line as the pixel of interest cannot be processed. Based on this, the main contributions of this paper are as follows:

1. In this paper, a phase coherence factor weighting method based on threshold fusion (TF-PCF) is proposed. The effective pixels that meet the conditions are screened out in the defect image, the noise pixels that cannot be recognized by the naked eye are filtered out by threshold, and the parameter selection rules in the PCI algorithm model are redefined. At the same time, the image quality is guaranteed, the number of parameters is reduced, and the noisy pixel information in the same Angle line is efficiently processed.

2. TF-PCF algorithm model reduces the computational complexity and improves the practicability of the algorithm. The TF-PCF method proposed in this paper can reduce the lateral size quantization error while maintaining or even improving the image quality when detecting large objects with large defect size and complex location distribution. In addition, the PCI algorithm can still maintain the above characteristics in the face of other waveform imaging methods.

2. Materials and Methods

2.1. Ultrasound Detection and Imaging. Different from traditional phased array ultrasonic detection, the core of full focusing imaging is based on full matrix data. The full matrix data is transmitted according to the transmitting rule of “one-shot all-receiver,” that is, all array elements of the phased array transducer receive echo information. For ultrasonic phased array with N arrays, its specific full matrix acquisition principle is shown in Figure 1.

Firstly, array 1 is excited to emit excitation ultrasonic wave, and all array chips receive ultrasonic wave to obtain N sets of data defined as \( S_{1i} \sim S_{Ni} \), then array 2 \( \sim N \) is excited successively. Similarly, all array chips receive \( N \times N \) sets of full matrix data. The cartesian coordinate system is established by taking the element direction as the positive direction of the x-axis and the ultrasonic propagation direction as the positive direction of the z-axis, as shown in Figure 2.

The imaging region under the array chip is discretized into grids (pixels). For any pixel point \( P(x, z) \) in the imaging region, the amplitude of this point \( I(x, z) \) is calculated by using the formula:

\[
I(x, z) = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij}(t_{ij}(x, z)).
\]  

In the formula, \( S_{ij} \) represents the echo data signal transmitted by the \( i \)th element and received by the \( j \) element in
the full matrix data. \( t_{ij}(x, z) \) is the sum of the time from a specific point to the transmitting array elements \( i \) and \( j \).

\[
t_{ij}(x, z) = \frac{\sqrt{(x-x_i)^2 + (z-z_i)^2} + \sqrt{(x-x_j)^2 + (z-z_j)^2}}{c},
\]

(2)

where \( c \) is the propagation velocity of ultrasonic wave in the detected object, \( x_i \) is the abscissa of the center of the transmitting array element, and \( x_j \) is the abscissa of the center of the receiving array element. Since the coordinate system as shown in Figure 2 is established during the imaging process, \( z_i = z_j = 0 \).

According to formulas (1) and (2), the amplitude value at each discrete grid (pixel point) can be calculated and distributed within a certain range according to the intensity of sound intensity in the imaging region, so as to obtain the full-focused image of the longitudinal section under the full matrix data acquisition.

2.2. TF-PCF Weighted Full-Focus Imaging. The TF-PCF weighting principle mainly uses the phase information difference between the main and sidelobe signals in the echo signal data to calculate different weighting factors to achieve the effect of suppressing sidelobe energy [24]. In the full-focus imaging area, effective pixels are screened by setting a reasonable threshold, and the weighting factors of other pixels and effective pixels are calculated, so as to realize the weighting of full-focus imaging.

Assuming point \( O \) is the origin of coordinates, for target point \( F(R, \theta_0) \) in Figure 3, the time delay of echo signal received by array element \( A(x, 0) \) is \( t_{fi} \):

\[
t_{fi} = \frac{\bar{r}}{c} = \frac{\sqrt{R^2 + x - 2Rx \sin \theta_0}}{c},
\]

(3)

where \( c \) is the propagation speed of ultrasonic wave in the medium. \( x \) is the abscissa of the center of array element \( A \), and the target point \( F \) is the polar expression. If \( R \geq x \), \( t_{fi} \) can be simplified as follows according to the binomial approximation formula \( (1 + a)^{1/2} = 1 + a/2 \).

\[
t_{fi} \approx \frac{(R + (x/2R) - x \sin \theta_0)}{c}.
\]

(4)

The delay time at non-target point \( P \) can be expressed as:

\[
t_{fi} = \frac{(R + (x^2/2R) - x \sin \theta)}{c}.
\]

(5)

The instantaneous phase \( \phi_p(i) \) at point \( P \) is:

\[
\phi_p(i) = wkT_s + w(x \sin \theta - x \sin \theta_0)
= wkT_s + \frac{2\pi}{\lambda} (x \sin \theta - x \sin \theta_0),
\]

(6)
where $W$ is the angular frequency, $T_s$ is the sampling frequency of the signal, and $\lambda$ is the ultrasonic wavelength. The calculation formula of the abscissa of the element center in the full-focus algorithm is:

$$x = (i - 1)W_p + \frac{1}{2}W_d, 1 \leq i \leq N.$$  (7)

Substitute into equation (6) to obtain,

$$\varphi_i(p) \approx wkT_s + \frac{2\pi}{\lambda}[(i - 1)W_p + \frac{1}{2}W_d] (\sin \theta - \sin \theta_0).$$  (8)

In formula (8), $W_p$ is the spacing of array elements, $W_d$ is the width of array elements, and $wkT_s$ is a constant quantity. Therefore, the phase transformation of different pixels at the same target point is mainly caused by the second term in the formula. When $\theta \neq \theta_0$, for the detection rule of full-focus “one round all receive,” the phase value of $1 \times N$ group can be obtained by the same pixel iterating all receiving array elements. The standard deviation $\sigma(\varphi_i(p))$ of the $N$ sets of phases is taken as the final statistic.

Although the phase of the echo data is similar, the calculated phase value will be large for a set of phases around discontinuous pixels. In order to avoid this phenomenon is not smooth, the introduction of a set of auxiliary data sigma $\sigma'(\varphi_i(p))$. And the minimum $sf$ between $\sigma(\varphi_i(p))$ and $\sigma'(\varphi_i(p))$ is chosen as the estimator.

$$sf = \min \left[ \sigma(\varphi_i(p)), \sigma'(\varphi_i(p)) \right].$$  (9)

**Figure 4:** Flow chart of screening effective pixels.
The calculation rule of \( \sigma'(\varphi_i(p)) \) is as follows:

\[
\sigma'(\varphi_i(p)) = \begin{cases} 
\sigma(\varphi_i(p) + \pi), & \sigma(\varphi_i(p)) < 0 \\
\sigma(\varphi_i(p) - \pi), & \sigma(\varphi_i(p)) > 0 
\end{cases}.
\]  
(10)

The final phase coherence factor calculation (PCF) formula is: as follows:

\[
\text{PCF}(p) = \max \left[ 0, 1 - \frac{\gamma}{\sigma_0} * s_f \right].
\]  
(11)

Type of max \( [ ] \) is to choose the maximum value between two groups of data, to ensure that \( 0 < \text{PCF}(p) < 1 \). \( \gamma \) is the parameter that controls the inhibition effect of PCI. The larger \( \gamma \) is, the stronger the suppression of energy at non-target points will be. Generally, in the actual calculation process, we always set it to 1 to ensure the best suppression effect. \( \sigma_0 = \pi/\sqrt{3} \) is the nominal standard deviation evenly distributed over \([-\pi, \pi]\). When \( s_f = 0 \), it means \( \theta = \theta_0 \). At this moment, the pixel we choose is the target detection point, that is, the defect area, and the PCF \( (p) \) at this time is 1.

The number of parameters of \( \theta_0 \) and the accuracy of parameter selection largely determine the accuracy of the final calculated coherence factor. If only the Angle range containing the largest area of defects is considered \( \theta_0 \), all pixel energy information within the Angle range of scanning will be retained. Therefore, if the pixels within the range of specific acoustic intensity \( \Delta I \) can be screened out, the algorithm can select the pixels that meet the conditions and calculate the specific Angle \( \theta_0(k) \).

When the value of \( \Delta I \) is too large, the defect energy information may be filtered out. If the value is too small, the effect of noise energy suppression cannot be achieved [25].

To retain effective pixel energy information to the maximum extent, according to the nature of normal distribution and combined with the probability density function graph, the sound intensity matrix of the full-focus image is combined with standard deviation and mean value in statistics for threshold selection. The calculation process of the effective pixel intensity threshold is as follows:

The amplitude \( I(x, z) \) of pixels in the imaging area is normalized and transformed into sound intensity data information \( I'(x, z) \), which is stored in the matrix \( I' \) to obtain,

\[
I' = \begin{bmatrix}
I'(x_1, z_1) & I'(x_1, z_2) & \cdots & I'(x_1, z_n) \\
I'(x_2, z_1) & I'(x_2, z_2) & \cdots & I'(x_2, z_n) \\
\vdots & \vdots & \ddots & \vdots \\
I'(x_m, z_1) & I'(x_m, z_2) & \cdots & I'(x_m, z_n)
\end{bmatrix},
\]  
(12)

where \( I'(x_m, z_n) \) represents the sound intensity value of the pixels in the \( m \)th row and the \( n \)th column in a specific discrete rule.

Calculate the average of \( I'(x_m, z_n) \), \( \text{Mean}(I'(x_m, z_n)) \):

\[
\text{Mean}(I'(x_m, z_n)) = \frac{\sum I'(z)}{m \times n}.
\]  
(13)

In the formula, the value of \( m \) and \( n \) depends on the number of discrete pixels in the imaging area.

Let us calculate the standard deviation \( \delta(I'(x_m, z_n)) \) of \( I'(x_m, z_n) \):

\[
\delta(I'(x_m, z_n)) = \sqrt{\frac{1}{m \times n} \sum (I'(x_m, z_n) - \text{Mean}(I'(x_m, z_n)))^2}.
\]  
(14)
of the two simulation tests. The ultrasonic transducer is set as a linear array, and the detailed parameters are shown in Table 1. In the simulation, longitudinal wave is used for non-destructive testing imaging in Q235 homogeneous material.

The full-focus defect imaging figure based on the above simulation model and probe parameters is shown in Figure 6. The amplitude of the final imaging is distributed in the decibel of sound intensity, and the range is [-20dB, 0]. In full-focus imaging, the array chip will form a part of the region with large acoustic intensity energy above the defect due to the superposition principle of the imaging algorithm. Therefore, we set the imaging depth of [18 cm, 40 cm] in the stomatal defect imaging, and the imaging depth of [20 cm, 40 cm] in the crack defect imaging, respectively, to facilitate subsequent discussion.

Figure 6(a) shows the image of stomatal defects. In the sound intensity distribution range [-20 dB, 0], the sound intensity distribution of noise in the image is roughly [-14 dB, -10 dB]. Compared with [-12 dB, -1 dB] of stomatal defects, the overall energy level is lower. But there are signals around the defects that are similar to the noise intensity.

Similarly, the sound intensity distribution of the crack defect in Figure 6(b) is about [-12 dB, -1 dB], and there is also noise around the defect. However, in the image of the crack defect, the sound intensity of the noise is up to -7 dB, and the signal intensity is relatively high.

Figure 7 shows the full-focus imaging image weighted based on TF-PCF. It can be seen intuitively from Figure 7(a) that under the same sound intensity distribution range [-20 dB, 0], the noise signal is eliminated by the algorithm, and the information in the range [-8 dB, -1 dB] of the defect is preserved.

In Figure 7(b), for the selected sound intensity threshold, the information of noisy pixels with higher energy cannot be filtered out. There is a residual artifact phenomenon, which causes certain interference to the suppression effect of the algorithm.

Next, the defect imaging is completed based on different thresholds to verify the effectiveness of the threshold
selection of the method proposed in this paper. Under the condition that other test parameters and test conditions are the same, different thresholds are set to verify the reliability of the above threshold selection method. Figures 8 and 9, respectively, show the PCI weighted imaging results based on different threshold fusion.

Figure 8(a) is compared with Figure 8(b), when the sound intensity threshold is selected to the mean value plus one standard deviation. As for the noise signals distributed in the range of [-14 dB, -10 dB] in Figure 6(a), only the noise in the range of [-14 dB, -13 dB] is eliminated because the sound intensity threshold is selected as too small. On the contrary, for Figure 8(c), when the sound intensity threshold is selected as too large, the defect information is also eliminated, and only the information in the range of [-3 dB, -1 dB] is retained.

Similarly, in Figure 9, by setting different sound intensity thresholds, the reactions from each figure are consistent with those in Figure 8. Therefore, the threshold rule set in this paper is reasonable and effective.

Before effective pixels are not screened, the full-focus images of the two defects in Figure 10 retain the energy signals of all pixels within the Angle range of $\theta_0$. The amplitude energy at the non-converging points of the image cannot be suppressed, and it is too dependent on the selection of $\theta_0$ to solve the problem of preserving noise in the sweep Angle range. Compared with Figure 7, the overall SNR of the image weighted by PCI is lower, but some artifacts in the imaging area are eliminated.

In order to measure the quantization accuracy of defects in images, the defect size quantization error $\Delta H$ is used to evaluate the defect detection ability and representation ability of the imaging algorithm. Quantization difference of defect size $\Delta H$ the specific calculation formula is:

$$\Delta H = \frac{|S' - S|}{S} \times 100\%,$$

where $S$ and $S'$ are the original defect geometric size and the post-imaging geometric size, respectively. The smaller the value of $\Delta H$ is, the closer the defect size after imaging is to the size of the original simulation geometric model, the higher the imaging accuracy is, and the stronger the defect characterization ability is.

Tables 2 and 3, respectively, list the specific size of the two defects imaged by the three algorithms (TFM, PCI, TF-PCF) and the corresponding size quantization error $\Delta H$. Since
there are a lot of defect artifacts around the defects after full-focus imaging, in order to reasonably calculate the size quantization error, we will select the maximum size and area of the defect area to calculate the effective range of the defect.

Compared with the other two methods, the TF-PCF weighting method greatly improves the size representation accuracy of defect images. The quantization errors of the transverse dimension of pores and cracks are decreased from 25% to 37.1%, while the longitudinal dimension quantization error is decreased from 20% to 32%.

Table 2: Defect size table before and after weighted imaging.

<table>
<thead>
<tr>
<th></th>
<th>Blowhole defects</th>
<th>Crack defects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transverse</td>
<td>Longitudinal</td>
</tr>
<tr>
<td></td>
<td>dimensions/mm</td>
<td>dimension/mm</td>
</tr>
<tr>
<td>Simulation model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>size/mm</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TFM/mm</td>
<td>3.5</td>
<td>2.40</td>
</tr>
<tr>
<td>PCI/mm</td>
<td>3.5</td>
<td>2.40</td>
</tr>
<tr>
<td>TF-PCF/mm</td>
<td>3.05</td>
<td>2.05</td>
</tr>
</tbody>
</table>

Table 3: Quantization error table of defect size.

<table>
<thead>
<tr>
<th></th>
<th>Blowhole defects</th>
<th>Crack defects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TFM</td>
<td>PCI</td>
</tr>
<tr>
<td>Lateral size</td>
<td>75%</td>
<td>75%</td>
</tr>
<tr>
<td>quantization error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>dimension quantization error</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
75% and 37.1% to 52.5% and 1.4%, respectively, which is significantly improved compared with the decrease of the longitudinal dimension quantization errors of 17.5% and 16%.

Compared with TFM, PCI can effectively eliminate the noise signal in the image. However, if the \( \theta_0 \) in the PCI algorithm model is not properly selected, the final parameters can be determined by manual experience or naked eye, which will lead to the failure of the algorithm to process the end echo signal with defects. Finally, in the process of defect size quantification, some interference will be produced. Therefore, in the measurement process, we kept the defect size value after PCI weighted imaging consistent with TFM imaging.

3.2. Experiment and Analysis

3.2.1. Experiment 1. To further verify the effectiveness of the proposed method, the 18 – \( \varnothing \) circular through-hole area of the standard test block of the type B phased array (Figure 11(a)) was taken as the test object, and a total of 18 2 mm circular through-holes were numbered from left to right to facilitate the discussion and analysis of subsequent tests. The relevant geometric dimensions are shown in Figure 12. The phased array ultrasonic probe 5.0L128-0.5-10(Figure 11(b)) produced by Shantou Ultrasonic Company was used in the experiment with a central frequency of 5MHz. The full matrix data were captured at a sampling frequency of 40MHz, and the original data obtained from the fully focused phased array equipment were collected for the verification experiment in this paper. In the experiment, the vertical incidence detection method of p-wave was adopted, which was consistent with the detection method of stomatal defects in simulation analysis.

Figure 13 shows the focused image of the test block under different imaging algorithms. The defect images of TFM, PCI, and TF-PCF algorithms are shown. Due to the large number of defects contained in the test block and the complex location distribution, the defects far away from the transducer position received weak energy. In the final imaging, no. 16-18 defects could not be detected. In the distribution range of -20 dB to 0, the amplitude energy less than -20 dB was eliminated.

It can be seen intuitively from Figures 13(b) and 13(c) that, compared with the TFM algorithm, after being weighted by PCI and TF-PCF algorithm, a large number of noisy pixels are eliminated in the specific display range of the image by reducing their amplitude energy by weighting.

However, compared with the PCI method, the artifacts near the stomatal defects were also suppressed. Especially in the noise part directly below the defect, obvious weaken- ing can be seen, and some noise generated by the end echo near the defect is well dealt with.

Table 4 lists the lateral and longitudinal dimensions of defects detected by PCI and TF-PCF algorithms. As the defect energy becomes weaker, the closer it is to both sides of the test block, only a very small amplitude can be seen, and qualitative and quantitative analysis of the defect cannot be carried out. Therefore, when calculating the average value of defect size and size quantization error, only defects 2-13 are considered by combining the imaging conditions of the two algorithms shown in Figure 13.

As can be seen from Table 4, the transverse size quantization error decreased by 9.5% after the TF-PCF weighting method was used for imaging. Therefore, the quantitative impact on the longitudinal size is small, and the defect can still be accurately judged qualitatively.

Meanwhile, in order to observe the energy suppression of effective pixels at each defect, Figure 14 shows the sound intensity energy weighting of defect images (defects 1-13) of the TF-PCF algorithm. It can be seen that within the effective imaging energy range [-20 dB,0], the curve contains 13 peaks representing the amplitude energy of defects 1-13 in the image. After the TF-PCF weighting method, the information of 13 peaks above the threshold line of -12 dB is completely preserved. The information below the threshold line is identified as a noise signal by the algorithm, which is suppressed to different degrees. And the suppressed energy will be lower than the minimum -20 dB.

From the imaging range of [-20 dB,0], the threshold value selected in this paper conforms to the probability distribution. In the case of normal distribution of echo data, the amount of data above the threshold line accounts for most of the total amount of data, and the effective data of defects are retained.

Under the same condition of other parameters, the order of magnitude of \( \theta_0 \) in PCI and TF-PCF algorithm models is compared, and the complexity of the two algorithm models is compared in a more intuitive way. The order of magnitude of \( \theta_0 \) in the actual operation process of the two algorithm models is shown in Table 5.
The experimental results show that the number of parameters $\theta_0$ in the TF-PCF algorithm model decreases from 121987 to 12985, which reduces the number of parameters by 89.3% and greatly reduces the model complexity. Moreover, the TF-PCF algorithm model does not need to determine the value of $\theta_0$ through manual experience, which improves the practicability of the model.

3.2.2. Experiment 2. To test the reliability of the proposed method under the condition of incident wave defect detection at different inclinations, experiment 2 was carried out. The geometric dimensions of the transverse section of the object to be tested are shown in Figure 15. The vertical crack on the bottom surface in Figure 16 is taken as the detection object (the part circled by the yellow ellipse). The 5.0L64-0.5-10 probe produced by Shantou Ultrasonic Company (Figure 17(a)) and sa325S-55S wedge (Figure 17(b)) are used in the crack defect detection experiment. The center frequency of the probe is 5 MHz, the wedge is an oblique wedge, and the equipment imaging mode is shear wave imaging.

At the same sampling frequency of 40MHz, the full matrix original data in ultrasonic testing equipment was collected according to the full matrix data acquisition method for subsequent imaging. The setting of the imaging region is consistent with that of the full-focus ultrasonic detection equipment, with a horizontal distance of 20 mm~50 mm and a depth range of 0 mm~25 mm. The imaging results completed by different algorithms are shown in Figure 18.

Figure 18(a) shows full-focus imaging using the original data of the equipment. The noise signal in the imaging area has less energy, which can well represent the crack defect, but there are artifacts near the defect echo signal. Both PCI
and TF-PCF algorithms shown in Figure 18(b) and Figure 18(c) can eliminate part of artifacts well. When the original data is well presented, the imaging quality of the two algorithms is similar. However, compared with Figure 18(b), TF-PCF (Figure 18(c)) can observe that artifacts near defects are eliminated, and these energies are suppressed as background information within the display range of [-20 dB, 0 dB].

It can be seen from Figure 18 that the imaging effect of the crack is good and its location is accurate, but the quantitative judgment of the crack size has different degrees of deviation. The transverse and longitudinal dimensions of the crack defects in Figure 18(b) are about 2.4 mm and 13.6 mm, respectively. The transverse and longitudinal dimensions of the defect weighted by TF-PCF (Figure 18(c)) are about 1.8 mm and 12 mm, respectively. By introducing the size quantization error $\Delta H$, the TF-PCF weighting method can reduce the lateral and longitudinal size quantization errors by 10% and 20%.

It can be seen from the longitudinal size obtained by the two algorithms that there is a big deviation from the original size. Because the experimental wedge uses an oblique wedge, and the incident wave is the shear wave. Considering the attenuation factor of the acoustic beam energy in the wedge and the workpiece, the original full matrix data collected has not gone through gain calibration. Therefore, the algorithm is insensitive to the longitudinal size of the crack defect and deviates greatly from the original size.

In order to observe and analyze the specific pixel amplitude energy situation, Figure 19 shows the amplitude situation after weighted by TF-PCF method. In the effective decibel display range [-20 dB, 0], the Angle values of pixels above the sound intensity threshold line -10 dB are contained in $\theta_0(k)$, so that the final calculation result of PCF is 1. Therefore, the amplitude energy corresponding to the pixel is preserved, and the pixel amplitude signal below the threshold line is weighted with different phase factors due to different weight ratio values.

Similarly, in order to discuss the complexity of PCI and TF-PCF algorithm models, Table 6 lists the order of magnitude of $\theta_0$ of the two algorithm models in the actual operation process.

Under the same image region discretization rules and the same algorithm operation, the magnitude of $\theta_0$ involved in TF-PCF algorithm model is much smaller than that of PCI. Finally, the imaging quality of TF-PCF is not lower than that of the other two algorithms, and it can reasonably process some noise signals near the defects.

### 4. Discussion

The experimental results show that the TF-PCF method proposed in this paper can eliminate most of the artifacts in full-focus imaging, improve the signal-to-noise ratio of the image, and reduce the quantization error of the defect size.

However, the proposed method is limited by some weak defect energy detection cases. As shown in Figure 13(c), this is because the deflection Angle of the transducer relative to the defect position is too large, resulting in weak energy at the defect, resulting in the loss of individual defect information in the image, and reducing the SNR, and the quantization error result of the defect size depends to some extent on the quality of full-focus imaging.

When considering other types of ultrasonic imaging (s-wave), the proposed algorithm can still maintain its effectiveness. Figure 17(c) intuitively shows that in the s-wave imaging mode, the imaging quality based on the proposed method is high, and the quantization errors of the transverse and longitudinal cracks are effectively reduced.
The quantization ability of the defect size presented by the algorithm in the experiment is consistent with that of the numerical simulation.

Compared with PCI method, TF-PCF can flexibly deal with some noise information near defects and redefine the rule of artifact removal. TF-PCF can greatly reduce the quantitative error of defect size in the image by comparing the defect size after imaging with the two algorithms.

In addition, the selection of threshold in TF-PCF algorithm model is reasonable to some extent. According to Figures 14 and 19, within the effective imaging range of [-20 dB, 0], the data above the threshold line accounts for most of the total data in the effective range. And retain a large number of defect effective data, the error rate is low.

As explained in the theoretical section, the order of magnitude of \( \theta_0 \) in TF-PCF algorithm model is much smaller than that of PCI weighting algorithm model, and the complexity of the model is lower than that of PCI weighting algorithm model. Furthermore, the model complexity compared in the paper is simply by comparing the number of a particular parameter in the algorithmic model and does not include the human effort carried out prior to imaging.
5. Conclusions

In this paper, a TF-PCF weighted algorithm model is proposed for full-focus imaging of defect detection. The method can suppress all non-effective pixels amplitude energy, at the same time keep defect information effectively and eliminate defects image place artifacts and improve the image SNR. And the model complexity of TF-PCF algorithm is lower than that of PCI weighted model algorithm.

TF-PCF can be used in many applications, such as p-wave detection for large objects with multiple porosity defects and complex location distribution, and incident detection for crack defects with inclined wedges. Show an excellent ability of defect qualitative method in this paper, after false as part of the near to eliminate defects, based on the method of implementation of defect data reconstruction images can still with the shape of the defect of test block to maintain good consistency, the image of defect location accuracy is higher, more conducive to position through the defect in the image more accurately.

Compared with PCI, the method presented in this paper has a higher quantitative ability of defect size. Experimental results show that the proposed method can reduce the transverse dimension quantization error by 8.5% when detecting large objects with a large number of defects and complex location distribution using the longitudinal wave; a sampling of shear wave imaging detection with inclined wedge defect, this method still has a strong ability of quantitative defect size, and horizontal and vertical size quantization error reduced by 10% and 20%, respectively. Moreover, the quantitative ability of defect size can be demonstrated in numerical simulation.

In the future, the efficiency of the proposed method can be further improved to meet the needs of industrial real-time imaging.

Data Availability

The experimental data are collected by commercial equipment and cannot be provided due to the confidentiality agreement signed with the company.
Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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