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Numerical simulation of the acoustic characteristics of internal defects in heterogeneous concrete

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ABSTRACT

A numerical model of heterogeneous concrete with randomly distributed aggregates is established based on phased array ultrasonic testing (PAUT) with full-matrix capture (FMC) imaging. Using this model, the effects of individual defect characteristics parameters (depth, size, and orientation) and multi-defect interactions on acoustic fields are systematically analyzed. The results show that increasing defect depth markedly degrades imaging quality *due to cumulative attenuation, and a minimum detectable void diameter of 40 mm is identified. When the crack angle beyond 45° or the crack length shorter than 20 mm, no signal can be observed. Under multi-defect conditions, close spacing (≤50 mm) results in overlapping signals and localization errors due to interference between signals, whereas sufficient spacing produces clear and distinct defect images.The smaller the angle between the two defects and the vertical direction, the easier the separation of the two signals.These findings provide effective technical support for extending array ultrasonic nondestructive evaluation to concrete structures with complex internal defects.*

Keywords: numerical concrete; array ultrasonic; total focusing method; multi-defect interaction.

1. Introduction

1.1 Research Background

Concrete, as a fundamental material in the construction field, plays a crucial role in the infrastructure projects such as high-rise buildings, bridges, tunnels, and dams owing to its excellent durability and mechanical properties(Xiao and Huang, 2023). However, during both casting and in-service, local damages such as cracks and voids are susceptible to occur inside concrete structures under the coupling of environmental erosion (e.g., chloride ion permeation, carbonation), alternating mechanical stresses (including dynamic load and foundation settlement), and material aging (such as insufficient hydration reaction, creep) (Wang, 2022; Ge et al., 2023; Ghafouri, et al., 2024). These local damages will weaken the overall load-bearing capacity, accelerate the deterioration processes such as steel corrosion and concrete spalling, and may ultimately result in structural cracking, water leakage, or even catastrophic accidents (He et al., 2020; Barbara, S. et al., 2016; Sorilla et al., 2024). Traditional detection methods (such as rebound method and coring method) have limitations such as low precision and high destructiveness. In contrast, the array ultrasonic technology employs multi-array full-matrix full-focusing imaging, which enables rapid identification of defects such as bond failures, crack direction and void distribution in concrete, and provides detailed information for the internal structure and damage state of concrete(Havugarurema et al., 2020; Wang et al., 2021; Feng et al., 2020; Su Fen et al., 2023). However, large-scale application of array ultrasound testing on engineering sites can be inefficient and costly. To address this, the finite element method employs strategies such as Virtual Substitution of Physical Entities and Pre-Simulation-Driven Optimization to rapid analysis of complex scenarios, making it an effective approach to ensure the safety and integrity of concrete structures (Carcangiu et al., 2015).

1.2 Research Status

Accurate detection of internal defects in concrete structures is crucial for ensuring engineering safety. Array ultrasonic technology has gained increasing attention due to its efficiency and non-destructive nature. Currently, numerous researchers have conducted numerical simulation studies. Grajçevci et al.(Grajçevci et al., 2024) performed experimental and numerical analysis of reinforced concrete columns under load and compared the results with design code predictions. Cheng et al.(Cheng et al., 2024) used COMSOL software to simulate the acoustic field in nuclear power plant concrete with preset defects. Their results showed that as the deflection angle of the array ultrasound increased from 0° to 45°, the acoustic wave delay time rose from 40.86 μs to 64.19 μs, while the acoustic pressure amplitude in the defect area exhibited significant attenuation. The underlying mechanism of this phenomenon was revealed by Zhang et al. (Zhang et al., 2022), who confirmed that ultrasonic scattering attenuation was highly sensitive to the inherent randomness of concrete and represents the dominant factor in overall ultrasonic energy attenuation. To enhance detection accuracy, Zhang et al.(Zhang et al., 2024) demonstrated that increasing the number of array elements and reducing element spacing resulted in clearer imaging. The physical basis of this approach was quantitatively validated by Wang et al. (Wang et al., 2017): when the element width was 1 mm, the total displacement at the focus was 1.7 times greater than when the width was 0.1 mm. Increasing the number of array elements from 8 to 32 led to an 8 mm change in total displacement at the focus. Regarding defect detection limits, the influence of crack angle and burial depth were further investigated by Xiao et al. (Xiao et al., 2020) . They found that as the crack angle decreased from 90° to 70°, the minimum detectable size increased from 0.63 mm to 2.23 mm; similarly, increasing the burial depth from 6 mm to 24 mm enlarged the minimum detectable size from 0.42 mm to 1.36 mm. A complementary finding was reported by Ju et al. (Ju et al., 2023), indicating that void width had a more pronounced influence on peak frequency than void depth. Addressing concrete heterogeneity, Sun et al.(Sun et al., 2023) established a two-dimensional random aggregate concrete model using MATLAB and COMSOL, concluding that wave scattering at the aggregate-mortar interface complicated ultrasonic wave propagation. This conclusion was further supplemented by Zhang et al.(Zhang et al., 2023), who emphasized the decisive impact of random aggregate distribution on waveform behavior. Wang et al.(Wang et al., 2022) confirmed the influence of aggregate geometry and content on ultrasonic propagation. Kordi, A et al.(Kordi, et al., 2022) integrated simulation with practical application by developing finite element models of bridges under various loads to detect structural damage. Despite substantial progress in single-factor studies, few works interrogate the coupled effects of heterogeneity and multi-defect interactions on array imaging performance. This gap motivates our study, which builds a random-aggregate model and systematically links defect attributes to measurable ultrasonic signatures.

1.3 Research Objective

In this study, a numerical concrete model with randomly distributed aggregates was developed using COMSOL Multiphysics, incorporating array ultrasonic technology. The effects of both single defects and the interaction of multiple defects on the propagation characteristics of acoustic field were systematically analyzed. The relationships between defect type, size, position, orientation, and the corresponding ultrasonic detection signals were identified. The research results provide technical support for the practical application of array ultrasonic technology in concrete quality assessment.

2. Materials and Methods

In this paper, the internal defects of concrete were detected using an A1040 MIRA 3D ultrasonic tomography scanner (Fig. 1a). The concrete specimen (Fig. 1b) containing a cylindrical artificial defect of Φ60 mm × 650 mm was manufactured according to the standard ACI 211.1-91 (2009) and ASTM C143/C143M-20 (2020). and its geometric size is 640 mm (length) × 795 mm (width) × 650 mm (height). The detailed composition of the concrete with C30 is shown in Table 1.

Table 1. Composition of C30 concrete

Material	Cement	Sand	Gravel	Water	Admixture	Additive
Quantity /(kg/m^3)	340	740	1056	127	7.9	60

Fig. 1. Testing equipment and specimen.

(a) A1040 MIRA 3D ultrasonic tomography scanner; (b) specimen

2.1 Measurement of Acoustic Velocity and Frequency

Fig. 2 exhibits the defect imaging results detected by array ultrasonic equipment at different excitation frequencies. In the baseline testing, the acoustic velocity of concrete v = 2250 m/s (with an error range of ±2.5%) was calibrated by bottom-wave signals. Comparative experiments were carried out by gradually adjusting the excitation frequency within the range of 20 to 45 kHz. As the frequency increased from 20 to 45 kHz, the corresponding signal-to-noise ratios (SNR) were measured as -2.7 dB, 10.6 dB, 13.4 dB, 15.3 dB, 13 dB, and 9.5 dB. Accounting for SNR, detection error, and defect contour clarity collectively, optimal imaging performance was achieved at 30 kHz. Therefore, 30 kHz was selected as the characteristic frequency for subsequent numerical simulations.

Fig. 2. Defect imaging of array ultrasonic equipment at different frequencies.

(a) 20 kHz; (b) 25 kHz; (c) 30 kHz; (d) 35 kHz; (e) 40 kHz; (f) 45 kHz

2.2 Finite element model establishment and verification

To simplify the calculation, a two-dimensional concrete numerical model with dimensions of 640 mm (length) × 400 mm (width) was established. Based on the polynomial random distribution function, the dual-graded random polygonal aggregates were generated following the process illustrated in Fig. 3(a). The finite element model containing a circular void of Φ60 mm was illustrated in Fig. 3(b). and the center coordinate of the circular void was positioned at coordinates (200 mm, 300 mm) within the model.

Fig. 3. Random aggregate model generation.

(a) Flowchart for generating random polygon aggregates; (b) 2D concrete numerical model

Based on the solid mechanics-elastic wave propagation model, the excitation signal was applied through displacement boundary conditions. A Hanning window function was selected as the excitation signal, specifically defined as:

$$x = 0.5t \times (1 - cos(\frac{2\pi f_0 t}{3})) \times sin(2\pi f_0 t) \quad \text{where} \quad t \leq \frac{3}{f_0} \tag{1}$$

where f_0 is the frequency of excitation signal, and t represents time.

The full matrix capture-total focusing method (FMC-TFM) detection mode was simulated using a parametric scanning methodology. Appropriate values for density, Young's modulus, and Poisson's ratio were selected to ensure that the acoustic velocity within the model closely matched actual conditions. The equivalent acoustic velocity of concrete (V_{eff}) was derived using a volumetric fraction-weighted approach to approximate the experimental measured acoustic velocity of 2250 m/s. The formula for is expressed as:

$$V_{eff} = V_{agg} \times \frac{S_{agg}}{S} + V_{mor} \times \frac{S_{mor}}{S} \tag{2}$$

where V_{agg} and V_{mor} are the acoustic velocities of the aggregate and mortar, respectively; S_{agg} and S_{mor} represent the areas of the aggregate and mortar, respectively; S is the two-dimensional target area. The results are robust to small changes in material parameters (Young's modulus, and Poisson's ratio) given that wave speed is recalibrated (Siorikis et al., 2024).

The reliability of the finite element model was validated using MATLAB full matrix capture-total focus method (FMC-TFM) imaging. The mesh size was set between 1/10 and 1/6 of the wavelength, and the calculation time step was defined as 1/20 of the acoustic wave period. Convergence verification reveals that finer meshes and reduced time steps exert negligible effects on the output results. The accuracy of the model was assessed by comparing the shape, position, and geometric size of the total focusing defect imaging results with the actual prefabricated defect. If the error exceeded the predefined accuracy threshold of 5%, material parameters were iteratively adjusted, the equivalent acoustic velocity was recalculated, and the mesh refined until the numerical results satisfied the preset accuracy requirements. The final optimized material properties are summarized in Table 2.

Table 2. Material properties

	Mortar	**Aggregate**
Material density	2100kg/m^3	2500kg/m^3
Young's modulus	9GPa	15GPa
Poisson's ratio	0.18	0.15

3. Results and Discussion

3.1 Calculation results of single defect homogenous concrete

To eliminate the interference of multiphase heterogeneous components on acoustic properties, a homogeneous concrete model with a void was established. Fig. 4 shows the signal echo under the ' one transmitting and eight receiving ' array configuration. As shown in Fig. 4, the characteristic waveform corresponding to the void defect is clearly identifiable. Moreover, quantitative analysis reveals that for the defect with depth (*H*) of 310 mm and diameter (*D*) of 60 mm, the corresponding defect wave reception time is measured to be 2.75×10^{-4} s.

Fig. 4. Echo signal diagram. (a) without defect; (b) with void defect

The original pressure signals collected by the eight probes are processed using differential techniques, and the time-domain response characteristics of each probe are shown in Fig. 5. The maximum amplitude corresponding to the defect signal (A_{max}) received by each probe is determined by analyzing the pressure time-domain distribution. A_{max} serves as an indicator of defect echo intensity, with relevant data summarized in Table 3. As seen in Table 3, A_{max} exhibits a trend of first increasing and then decreasing from probe 1 to probe 8, and A_{max} of probe 4 is the largest. Therefore, probe 4 is selected as analytic object in this study.

Table 3. A_{max} received from eight probes

Probe number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A_{max}/*10^{10}Pa	2.50	3.69	3.71	3.86	3.83	3.70	3.50	2.46

Fig. 5. Pressure signal diagram after difference processing

3.2 Effect of depth and size of single void defect in heterogeneous concrete on array ultrasonic imaging

Fig. 6 presents the MATLAB total focusing imaging results for defect with identical diameter (60 mm) at varying depths of 110 mm, 210 mm, 310 mm, 410 mm, and 510 mm. As illustrated in Fig. 6, the imaging quality noticeably declines as the defect depth increases. This phenomenon is primarily attributed to the gradual absorption and scattering of acoustic energy by the medium during propagation (Xue et al., 2020). Specifically, the continuous energy loss due to material absorption and scattering during ultrasonic wave propagation, which significantly reduces the effective energy reaching the distal defect surface.The scattering effect accumulates as the propagation distance increases, resulting in some energy deviation from the original propagation path and a consequent reduction in signal energy reaching the defect zone (Asadollahi and Khazanovich, 2019). Furthermore, the beam width progressively expands as propagation distance increases. This beam diffusion phenomenon causes the acoustic energy to become more dispersed at a long distance, and the energy density per unit area is reduced, resulting in a decrease in imaging resolution (Sun et al., 2023). Additionally, when the defect is close to concrete surface, the side lobes generated by the array transducer will receive the defect reflection signal, resulting in artifacts in Fig. 6a (Peng et al., 2024).The relative amplitude of these artifacts (side lobes) is significantly lower than the main defect signal, so they do not obscure defect detection except in the shallowest case.

Fig. 6. MATLAB total focusing imaging for defect at different depths

Table 4 lists the location and shape information of defect signal at different depths, where H represents the defect depth, h denotes the defect imaging depth, D_V is the vertical dimension of imaging defect shape, and D_H is the horizontal dimension of imaging defect shape. Δh represents the absolute error of depth, which is defined as follow :

$$\Delta h = \left| \left(H - \frac{D}{2} \right) - h \right| \tag{3}$$

Since the defect imaging depth h represents the depth from the surface to the top surface of the defect, while the actual defect depth H is measured from the surface to the center of the defect, it is necessary to subtract $D/2$ when calculating the absolute error. ε is the relative error. The specific formula is as follows :

$$\varepsilon_V = \frac{|D - D_V|}{D} \times 100\% \quad (4)$$

$$\varepsilon_H = \frac{|D - D_H|}{D} \times 100\% \quad (5)$$

$$\varepsilon_h = \frac{\Delta h}{h} \times 100\% \quad (6)$$

where ε_V is the relative error in the vertical direction; ε_H is the relative error in the horizontal direction; ε_h is the relative error of depth.

As shown in Table 4, the absolute error between *h* and *H* remains within 10 mm for defect at *H* = 110 mm and 210 mm. When *H* increases to 310 mm, there is a significant error between the detected defect shape and the actual defect shape. As *H* further increases to 410 mm, the defect imaging becomes blurry, and the shape error further increases.

Table 4. Location and shape information of defect signal at different depths

H/mm	**110**	**210**	**310**	**410**	**510**
h/mm	87.2	176.4	268.3	363.0	469.5
Δh/mm	7.2	3.6	11.7	17.0	10.5
D_V/mm	89.0	44.1	59.1	-*	-
ε_V	48.3	26.5	1.50	-	-
D_H/mm	38.5	53.2	70.2	-	-
ε_H	35.8	11.3	17.0	-	-

*Cases with no discernible imaging are denoted by '-' in the table.

For defect depths ranging from 110 mm to 510 mm, the corresponding A_{max} received by probe 4 are measured as 9.31×10^{10} Pa, 4.16×10^{10} Pa, 2.75×10^{10} Pa, 1.98×10^{10} Pa and 1.91×10^{10} Pa, respectively. It is observed that A_{max} increases as the distance between the defect and the probe decreases. This further verifies the attenuation of ultrasound energy during propagation due to absorption and scattering effects.

Holmes et al. (2005) proposed an Array Performance Index (API) based on the characteristics of the point spread function. The API is defined as the ratio of the defect amplitude area at half-wave height (A_{-6db}) to the square of wavelength (λ^2). The formula for is expressed as:

$$API = \frac{A_{-6db}}{\lambda^2} \quad (7)$$

This index effectively captures the trade-off between main lobe width and side lobe level in the imaging point spread function. It quantitatively evaluates defect imaging quality by considering the propagation and attenuation of acoustic wave in space. Fig. 7 shows the spatial distribution of the point spread function at H of 310 mm. Generally, a smaller API value corresponds to higher imaging resolution and better detection effect.

Fig. 7. Spatial distribution of point spread function at H of 310mm

For defect depths ranging from 110 mm to 510 mm, the corresponding API values are 0.43, 0.43, 0.78, 1.09, and 1.51, respectively. It can be shown that the deeper the defect, the larger the API value, indicating lower imaging resolution, which is consistent with the MATLAB imaging results.

Fig. 8 presents the MATLAB total focusing imaging of defect with uniform burial depths (310 mm) at varying diameters from 20 mm to 60 mm. As shown in Fig. 8, as the diameter of the defect decreases, the imaging quality gradually decreases. When the diameter reaches 40 mm, the defect imaging begins to blur; further reduction below 30 mm results in ineffective detection of the detect. Additionally, the measurement error of D_V progressively increases with decreasing defect diameter.

Fig. 8. MATLAB total focusing imaging of defect at different sizes.

(a) 20mm; (b) 30mm; (c) 40mm; (d) 50mm; (e) 60mm

Table 5 illustrates the peak pressure signal amplitudes collected by Probe 4 across various defect diameters. It shows that A_{max} increases with the enlargement of D. Owing to the nonuniform distribution of aggregates, A_{max} exhibits shows slight fluctuations within the defect diameter range of 40 mm to 60 mm, rather than strictly following a monotonically increasing trend.

Table 5. Maximum amplitude of pressure signal with different defect sizes

D/mm	**20**	**30**	**40**	**50**	**60**
A_{max}/*10^{10}Pa	1.77	2.46	2.83	2.79	2.75

When ultrasonic wave propagates in concrete, reflection or scattering will occur when it encounters defects, resulting in signal waveform distortion and amplitude attenuation. Therefore, the type and size of defects can be inverted by signal analysis (He et al., 2020).

3.3 Effect of angle and length of single crack defect in heterogeneous concrete on array ultrasonic imaging

Fig. 9 presents the MATLAB total focusing imaging of cracks with identical geometries (depth = 310 mm, length = 60 mm) at varying angles θ (0°, 15°, 30°, 45°, and 60°). It can be seen from Fig. 9 that when θ is 0°, the defect signal is the most significant. With the increase of θ, the bottom wave signal is gradually enhanced, while the defect signal is gradually weakened. When θ reaches 45°, the defect signal becomes indistinguishable. This is attributed to the fact that when acoustic wave is vertically incident, it undergoes scattering upon encountering cracks at different angles, resulting in a decrease in the energy reflected back to the probe, while simultaneously increasing the relative intensity of bottom wave signal (Xue et al., 2020).

Fig. 9. MATLAB total focusing imaging of crack at different angles.

(a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60°

Table 6 documents the peak pressure signal amplitudes acquired by Probe 4 across varying crack inclination angles. It can be seen that when θ is 0°, A_{max} reaches its peak, and the detection sensitivity is the highest. As θ increases, A_{max} gradually decreases, and the defect signal is basically unidentifiable until θ = 45°. This is mainly due to the increase in the crack angle causing the ultrasonic reflection wave to deviate from the probe's reception direction, making it difficult for the probe to effectively receive all the reflection signals, resulting in a significant reduction in the signal amplitude.

Table 6. Maximum amplitude of pressure signal at different crack angles

θ/°	**0**	**15**	**30**	**45**	**60**
A_{max}/*10^{10}Pa	5.91	3.89	1.56	0.76	0.50

Fig. 10 illustrates the MATLAB total focusing imaging for horizontal crack with uniform depth (310 mm) at varying lengths (60 mm, 50 mm, 40 mm, 30 mm, and 20 mm). It can be seen from Fig. 10 that as crack length (L) decreases, the defect signal gradually weakens. When L is less than 40 mm, the defect signal becomes noticeably blurred, and further reduction below 20 mm renders the crack difficult to effectively detect. This indicates that shorter cracks may lead to a significant reduction in the reflected ultrasonic energy, making it challenging for the received echo signals to meet the requirements for clear imaging.

Fig. 10. MATLAB total focusing imaging of crack with different lengths.

(a) 60mm; (b) 50mm; (c) 40mm; (d) 30mm; (e) 20mm

Table 7 summarizes the peak pressure signal amplitudes acquired by Probe 4 for cracks of varying lengths. It can be seen that A_{max} decreases with smaller L. Additionally, compared to circular cavity defect with equivalent horizontal dimension, the signal amplitude of crack defect is generally higher. This difference is mainly due to the fact that crack is perpendicular to the acoustic wave axis, making the reflected signals more easily received by the probe. In contrast, the scattering effect caused by the surface curvature of the cavity defect significantly increases the loss of acoustic wave.

Table 7. Maximum amplitude of pressure signal at different crack lengths

L/mm	**60**	**50**	**40**	**30**	**20**
A_{max}/*10^{10}Pa	5.91	4.72	3.52	3.05	2.41

3.4 Interaction between multiple defects

Fig. 11 shows the MATLAB total focusing imaging of two defects in the vertical direction. Defect (a) has a buried depth of 310 mm and a diameter of 60 mm, with defect (b) of 20 mm diameter located directly above it. The vertical distances between the two defects (H_{ab}) are set to 50 mm, 70 mm, 100 mm, 120 mm, and 150 mm, respectively. As shown in Fig. 11, when H_{ab} is 50 mm, defect (b) is completely covered by the signal of defect (a) due to the acoustic field superposition effect, making it unidentifiable. When H_{ab} increases to 70 mm, although the two defects can be distinguished, the signal strength of defect (a) is significantly reduced. As H_{ab} further increases to 100 mm, the imaging contours of both defects become clearly distinguishable. With a continued increase in H_{ab}, the acoustic field coupling effect between the defects gradually diminishes, eventually allowing two independent defect signals to be observed.

Fig. 11. MATLAB total focusing imaging of two defects in vertical direction.

(a) 50 mm; (b) 70 mm; (c) 100 mm; (d) 120 mm; (e) 150 mm

When H_{ab} is 50 mm or 100 mm, the received A_{max} is 3.70×10^{10} Pa or 3.33×10^{10} Pa, respectively, both exceeding A_{max} of a single defect (2.75×10^{10} Pa). This indicates signal interference between two defects at this time, which may lead to defect misinterpretation. When H_{ab} is 70 mm, A_{max} decreases to 2.66×10^{10} Pa, which is lower than the value for a single defect. This confirms the presence of complex acoustic interference between the defects. When H_{ab} increases to 120 mm, two distinct echo signal characteristics can be clearly identified, demonstrating that the interference between the defects becomes negligible at this spacing.

Table 8 summarizes the variations in defect imaging depth and shape size under different H_{ab}. As shown in Table 10, when H_{ab} is 50 mm, the defect signal exhibits an overall upward shift, resulting in a significant deviation between the defect imaging depth (h) and the defect depth (*H*). This deviation is primarily attributed to the signal superposition effect. When H_{ab} increases to 70 mm, the signals from the two defects begin to separate, and the relative error in defect imaging depth reaches its minimum. As H_{ab} increases to 100 mm, the error in imaging depth becomes consistent with that of a single defect. However, the relative error in shape size remains noticeably larger compared to the single defect, indicating that mutual interference between the two defects has not been completely eliminated.

Table 8. Defect imaging depth and shape size under different H_{ab}

H_{ab}/mm	Single defect	50	70	100	120	150
h/mm	268.3	257.3	280.7	267.6	271.9	273.0
ε_h	4.2	8.1	0.1	4.4	3.4	2.5
D_V/mm	59.1	68.2	28.1	48.4	52.7	53.8
ε_V	1.5	13.7	53.2	19.3	12.1	10.3

Fig. 12 shows the MATLAB total focusing imaging for defect (b) with diameters of 20 mm, 40 mm, and 60 mm when H_{ab} is fixed at 100 mm. It can be seen from Fig.12 that when the diameter of defect (b) is 40 mm, the defect imaging signal is more significant than that of defect (a) with larger diameter. When the diameter of defect (b) increases to 60 mm, defect (a) cannot be identified. This phenomenon is attributed to the reflection, scattering or refraction (shadow effect) when the ultrasonic wave encounters defects or interfaces in concrete. Larger defects will reflect a large amount of acoustic energy, resulting in energy attenuation in the underlying region, making it difficult to detect defects below (Carcangiu et al., 2014).

Fig. 12. Defect (b) total focusing imaging under different diameters in MATLAB.

(a) 20 mm; (b) 40 mm; (c) 60 mm

Fig.13 shows the MATLAB total focusing imaging of two defects in the horizontal direction. Defect (a) has a buried depth of 310 mm and a diameter of 60 mm, with defect (b) of Φ20 mm located directly to its left. The horizontal distance of the two defects (L_{ab}) is set to

50 mm, 70 mm, 100 mm, 120 mm, and 150 mm, respectively. As shown in Fig. 13, when L_{ab} increases from 50 mm to 100 mm, defect (b) cannot be clearly identified. Notably, the strongest signal in the bottom wave appears on the right side of the midline, indicating that the ultrasonic wave experiences more severe attenuation on the left side during propagation, further confirming the presence of defect (b) on the left side of defect (a).

Fig. 13. MATLAB total focusing imaging of two defects in horizontal direction.

(a) 50 mm; (b) 70 mm; (c) 100 mm; (d) 120 mm; (e) 150 mm

Table 9 lists the maximum amplitude of pressure signals received by Probe 4 under different L_{ab}. It can be seen that with the increase of L_{ab}, A_{max} of defect (b) initially increases and then decreases, reaching its peak when L_{ab} is 120 mm. When L_{ab} is 50 mm, 70 mm or 150 mm , A_{max} is less than the maximum amplitude of 2.75×10^{10} Pa when a single defect exists.

Table 9. The maximum amplitude of pressure signals received under different L_{ab}

L_{ab}/mm	50	70	100	120	150
A_{max}/*10^{10}Pa	1.94	2.10	3.36	3.48	2.60

Table 10 summarizes the variations in the position of defect imaging signal under different L_{ab}, where L_1 denotes the distance from the defect imaging signal to the left edge, and L_2 represents the distance from the prefabricated defect to the left edge. The formula for the relative error of the imaging position is expressed as:

$$\varepsilon_L = \frac{|L_1 - L_2|}{L_2} \times 100\% \tag{8}$$

As shown in Table 10, when the defect (b) is located within 150 mm in the horizontal direction of defect (a). it has minimal influence on the horizontal position accuracy of defect (a).

Table 10. Defect imaging depth and shape size under different L_{ab}

L_{ab}/mm	Single defect	50	70	100	120	150

L_l/mm	184.4	187.8	188.0	185.7	186.1	184.8
ε_L	7.8	6.1	6.0	7.2	6.9	7.6
D_H/mm	70.2	65.2	70	75.9	78	75.8
ε_H	17.0	8.7	16.7	26.5	30.0	26.3

Fig. 14 shows MATLAB total focusing imaging of defect (b) with diameters of 20 mm, 40 mm, and 60 mm when L_{ab} is fixed at 100 mm. As shown in Fig. 14, the increase in the diameter of defect (b) does not significantly impact on the imaging signal of defect (a) in the horizontal direction.

Fig. 14. Total focusing imaging of defect (b) under different diameters in MATLAB.

(a) 20 mm; (b) 40 mm; (c) 60 mm

Fig. 15 shows MATLAB total focusing imaging of two defects in the 45° direction, where defect (a) has a burial depth of 310 mm and a diameter of 60 mm. Defect (b). located at a 45° direction to the left of defect (a). has a diameter of 20 mm .All angles are measured relative to the vertical direction. The spacing between two defects at 45° ($L_{A45°}$) is set to 50 mm, 70 mm, 100 mm, 120 mm, and 150 mm, respectively. As shown in Fig. 15, when $L_{A45°}$ is 50 mm, numerous artifacts appear in the imaging. As $L_{A45°}$ increases to 70 mm, the number of artifacts decreases. When $L_{A45°}$ reaches100 mm, a weak signal from defect (b) can be observed. At $L_{A45°}$=120 mm, two distinct defect signals can be clearly identified. It is worth noting that when $L_{A45°}$ is 150mm, the signal of defect (b) gradually disappears.

Fig. 15. MATLAB total focusing imaging of two defects in 45° direction.

(a) 50 mm; (b) 70 mm; (c) 100 mm; (d) 120 mm; (e) 150 mm

Table 11 lists the maximum amplitude of pressure signals received by Probe 4 under different $L_{A45°}$. From Table 11, it can be observed that as $L_{A45°}$ is 50 mm, the maximum pressure signal amplitude is only 1.27×10^{10} Pa. When $L_{A45°}$ is 70 mm, A_{max} reaches the peaks, which may be attributed to signal superposition from both defects. When $L_{A45°}$ increases to 100 mm, A_{max} decreases significantly, and there is still some interference between the two defects. As $L_{A45°}$ continues to increase, the interference effects progressively weaken, and A_{max} gradually increases again.

Table 11. The maximum amplitude of pressure signals received under different $L_{A45°}$

$L_{ab45°}$/mm	**50**	**70**	**100**	**120**	**150**
A_{max}/*10^{10}Pa	1.27	4.29	2.19	2.66	2.96

Table 12 summarizes the defect imaging positions and dimensional parameters under different $L_{A45°}$. As shown in Table 12, when Defect (b) is located in the 45° direction, it has minimal impact on the accuracy of the imaging depth (*h*) of Defect (a). When $L_{A45°}$ is less than 100 mm, the horizontal position and shape size of defect (a) are different from those of single defect. However, when $L_{A45°}$ reaches or exceeds 100 mm, defect (b) has no significant effect on either the position accuracy or the shape accuracy of defect (a). which is close to the imaging results of single defect, indicating that the acoustic field interference effect between the two defects has been significantly reduced.

Table 12. Defect imaging positions and dimensional parameters under different $L_{A45°}$

$L_{A45°}$/mm	**Single defect**	**50**	**70**	**100**	**120**	**150**
h/mm	268.3	270.7	267.2	266.3	267.6	271.5
ε_h	4.2	3.3	4.6	4.9	4.4	3.0
L_l/mm	184.4	196.1	175.0	182.7	185.1	186.1
ε_L	7.8	1.9	12.5	8.7	7.5	6.9
D_V/mm	59.1	72.0	56.8	58.0	56.9	61.3
ε_V	1.5	20.0	5.3	3.3	5.2	2.2
D_H/mm	70.2	64.1	103.8	68.9	68.5	68.9
ε_H	17.0	6.8	73.0	14.8	14.2	14.8

Fig. 16 shows MATLAB total focusing imaging of defect (b) with diameters of 20 mm, 40 mm, and 60 mm when $L_{A45°}$ is set to 100 mm. As shown in Fig. 16, increasing the diameter of defect (b) has not significantly affected the imaging signal of defect (a). By comparing the imaging results at different orientations (0°, 45°, and 90°) when the spacing between the two defects is 100 mm and the diameter of defect (b) is 40 mm (as shown in Fig. 12b, Fig. 14b, and Fig. 16b). it can be seen that when defect (b) is positioned directly above defect (a). defect (b) is presented completely, while defect (a) appears relatively blurred due to the shadowing effect. When the defect (b) is located at 45° in the horizontal direction of defect (a). the two defects are clear, complete and independent. When the defect (b) is located on the left side of the defect (a). the defect (b) becomes blurred because it cannot be fully focused.

Fig. 16. Defect (b) total focusing imaging under different diameters in MATLAB.

(a) 20 mm; (b) 40 mm; (c) 60 mm

4. Conclusions

The influence of single defect characteristics and multi-defect interactions on the acoustic field are systematically analyzed based on COMSOL software and MATLAB software. The main conclusions are as follows:

(1) As the defect depth increases, the imaging quality decreases significantly. When the defect is too close to the surface, artifacts will appear to interfere with the detection results. When the defect diameter decreases to 40 mm, the imaging begins to blur. Further reduction in diameter to 30 mm or less makes it difficult to effectively identify the defect signal.

(2) As the crack angle increases, the bottom wave signal gradually strengthens, while the defect reflection signal correspondingly attenuates. When the crack angle reaches 45°, the defect features completely disappear. As the crack length shortens, the defect reflection signal gradually weakens. When the crack length is reduced to less than 40 mm, the defect in the imaging begins to blur. If the crack length is further reduced to below 20 mm, the defect signal becomes undetectable in the imaging.

(3) For secondary defect directly above the main defect, only a single defect signal is observed when the spacing is less than 50 mm. Two defects become distinguishable at spacing exceeding 70 mm, and the imaging becomes clearer as the spacing increases further. For secondary defect to the left of the main defect, the two defects cannot be clearly resolved when their spacing falls within the range of 50 mm to 100 mm. For secondary defect at 45° to the main defect, when the distance between the two defects is within 100 mm, the two defects can be distinguished, and when the distance is 150 mm, the secondary defect imaging is blurred. In general, the smaller the angle between the secondary defect and the main defect in the vertical direction, the easier the two defect signals are separated.

The present study primarily addresses the randomness of concrete aggregates and the interactions between multiple defects, without considering additional factors such as heterogeneous moisture distribution or embedded materials (e.g., reinforcing steel) that may influence defect characteristics. Based on the consideration of the engineering site, future research may focus on the following directions: expanding the simulation scale (e.g., employing 3D models or more complex concrete structures), investigating the effect of high-humidity environment on ultrasonic attenuation, and studying the influence of embedded materials such as reinforcing bars on acoustic wave reflection.

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