Research article

Multi-mode laser-ultrasound imaging using Time-domain Synthetic Aperture Focusing Technique (T-SAFT)

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A B S T R A C T

The Synthetic Aperture Focusing Technique (SAFT) is an imaging algorithm used in laser ultrasonics (LU) to visualise the appearance of defects. However, ultrasonic excited by a pulsed laser has the characteristics of wide bandwidth and multi-mode directivity patterns, leading to common problems in the SAFT process, such as low utilisation of ultrasound information and possible artefacts. To solve these problems, a Multi-mode Time-domain SAFT (MMT-SAFT) algorithm is proposed in this paper. The influence of ultrasonic directivity is discussed according to the imaging depth range, and imaging with multiple LU modes is performed to reduce artefacts. Simulations and experimental results prove the feasibility of the MMT-SAFT algorithm, which not only presents a clearer image of the upper part of defects but also improves image quality compared with time-domain SAFT using a single ultrasonic mode. The proposed technique can provide feasible directions for laser ultrasonic defect imaging.

1. Introduction

In many industries, defects can affect the mechanical strength of structures and shorten their service life. Internal defects, such as inclusions [1], debonding [2], cavitation, and cracks [3], are often more difficult to detect than surface defects because of their concealment. Therefore, inspection and evaluation of internal defects are important for ensuring production safety. Ultrasonic Testing (UT) [4] has proven to be an effective tool with the advantages of low attenuation, strong penetrating ability, and high sensitivity; therefore, it has been widely used in solid defect detection. Conventional UT typically utilises piezo-electric transducers [5] for accurate displacement and phase detection, Capacitive Micromachined Ultrasonic Transducers (CMUT) [6] for array directional detection, Electromagnetic Acoustic Transducers (EMAT) [7,8] for metal detection, and Air-coupled Ultrasonic Transducers (ACUT) [9] for non-contact detection. Among them, piezo-electric transducers are usually used for both ultrasound excitation and detection, and acoustic couplants such as water or glycerin are always used for ultrasound transmission between the transducer and the test piece. Although the introduction of the coupling layer can improve the acoustic coupling efficiency for the detection, the transducer operation must maintain physical contact and a specific detectable angle, which reduces the utilisation of ultrasonic signals.

As another approach to UT, Laser Ultrasonic Testing (LUT) overcomes the many limitations of conventional UT through optical excitation. First, the ultrasound is remotely excited and detected by a laser [10–13]; therefore, the system removes all issues related to ultrasonic coupling. Second, the LUT provides not only possibilities for both wide-band and narrow-band generation, but also for multi-wave-mode generation. In addition, different modes of waves can carry physical information with special directivity patterns [14–16], relating to the location of surface cracks, thickness of the specimen, and internal defects [17–19]. The LUT also has a high spatial resolution [20], which is important for detecting and imaging tiny defects (i.e. diameter ≤0.5 mm).

Many imaging algorithms that are suitable for UT have been developed for defect imaging. One algorithm called the Synthetic Aperture Focusing Technique (SAFT), which originated from radar detection, has proven to be an effective tool for defect imaging using both ultrasonic [21] and laser ultrasonic [22] signals. The frequency domain SAFT (F-SAFT) utilises concepts such as the angular spectrum method (ASM) and phase shift migration (PSM) [23], whereas in the time domain SAFT, delay and sum (DAS) [24] based on geometric relations is employed. The former can perform fast calculations in the frequency domain, while the latter has a more straightforward algorithm and can

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realise pipeline processing. However, in Non-destructive Testing (NDT), an LU signal excited under the thermo-elastic mechanism by laser, to avoid surface damage, is always weaker than that excited under the ablation mechanism. Therefore, it is difficult to excite stronger ultrasonic signals under the thermo-elastic mechanism than under the ablation mechanism. In contrast, it would be more realistic to improve the utilisation of ultrasonic signals. Thus far, only single-mode LU signals have been used for SAFT imaging in previously reported studies, resulting in incomplete use of multi-modal LU signals.

In this study, we take advantage of multi-mode LU generation with various directivity patterns for SAFT imaging. In this regard, a Multi-mode Time-domain SAFT (MMT-SAFT) algorithm is proposed to improve the image quality by considering multiple LU modes at different directivities according to different imaging depths. A customised model is created to simulate the imaging conditions using different parameters in the MMT-SAFT algorithm. Three main parameters, including the distance between the excitation and the detection (denoted as bias), and both the depth and size of defects, are studied to analyse their impact on the imaging of the upper part of defects. Experiments are also performed on these three parameters. According to simulations and experiments, imaging with various bias, depths, and diameters of defects was carried out, and the upper outline of the defect could be recognised. The results show that MMT-SAFT can provide a more completed appearance of defects to improve image quality compared with conventional single-mode T-SAFT.

2. Theory

2.1. Basic principle of the T-SAFT algorithm

Conventional SAFT in UT uses piezo-electric transducers for ultrasound excitation and detection. However, in laser ultrasound, two laser beams, one for excitation and the other for detection, are focused on the surface, overlapped, or separated. As indicated by Scenario ① in Fig. 1, in many studies the excitation (indicated by blue arrows with the letter “E”) and the detection (indicated by red arrows with the letter “D”) are coincided [25]. Although the overlapping of laser sources is easy to achieve, the sharp thermal expansion caused by the excitation laser irradiation saturates the detected signal. However, separated excitation and detection laser spots (indicated by Scenario ② in Fig. 1) can avoid the signal saturation, but the surface skimming acoustic waves may overwhelm the target signals diffracted/reflected from the defect [23]. In this study, the configuration indicated in Scenario ② was used. As shown in Fig. 1(a), the defect P is located at a depth of h, the separation between E and D is denoted as bias, the propagation paths from E to the defect and that from the defect to D are represented by d₁ and d₂, respectively. It should be noted that d₁ = d₂ = d in Scenario ①, whereas this relationship does not always hold in Scenario ②. If the acoustic properties of the isotropic medium are uniform, the velocities of the shear wave (cₛ) and longitudinal wave (cₐ) can be expressed using Eqs. (1), respectively, and are related to the velocity of the surface acoustic wave cᵣ, as described by Eqs. (2)[26].

\[
\begin{align*}
\frac{c_S}{c_L} &= \sqrt{\frac{E_s}{\rho(1+\nu)}} \quad \text{and} \quad \frac{c_L}{c_S} = \sqrt{\frac{E_L}{\rho(1+\nu)(1-2\nu)}}. \\
\left(\frac{c_S}{c_L}\right)^6 - 8\left(\frac{E_s}{E_L}\right)^4 + 24 - 16\left(\frac{c_S}{c_L}\right)^2 - 16\left(\frac{E_s}{E_L}(1-\frac{c_S}{c_L})^2\right)^2 &= 0,
\end{align*}
\]

where \(E_s\), \(\nu\), and \(\rho\) are Young’s modulus, Poisson’s ratio, and density of the material, respectively. It is assumed that, for the ith signal \(S(i,t)\), the excitation is located at position \(E(x_E, z_E)\), the defect is located at \(P(x_D, z_D)\), and the detection is located at \(D(x_D + \text{bias}, z_D)\). If the size of the defect is larger than the acoustic wavelength, then the arrival time of the reflected wave can be calculated by

\[
t(i) = \frac{d_1 + d_2}{c} = \frac{1}{c} \left( \sqrt{(x_E - x_0)^2 + (z_E - z_0)^2} + \sqrt{(x_E + \text{bias} - x_0)^2 + (z_E - z_0)^2} \right),
\]

(3)

where \(c\) is the velocity of the acoustic wave; therefore, the T-SAFT signal amplitude \(A_E\) for detecting point \(P\) can be written as

\[
A\left(x_0, z_0\right)_E = S(i, t(i)).
\]

By considering the contributions of all the signals \(S(i, t(i))\) (\(i = 1, 2, 3...N\)), the overall local signal amplitude \(A\) can be written as

\[
A\left(x_0, z_0\right) = \sum_{i=1}^{N} S(i, t(i)).
\]

(5)

For SAFT imaging, lateral and depth resolutions can be given by [25]

\[
\Delta X = \frac{v}{a} \Delta t \quad \Delta Z = \frac{1}{2} v \Delta t
\]

(6)

where \(\Delta t\) is the ultrasonic pulse duration, \(v\) is the velocity of the ultrasonic wave, and \(a\) is the synthetic aperture dimension, that is, the SAFT imaging area. To improve the depth and lateral resolutions, \(\Delta t\) should be shortened using a laser with a shorter pulse duration. However, during the actual experiment, it is inconvenient to change the laser pulse duration for a shorter \(\Delta t\); thus, in this work, only the dimension of the SAFT imaging area is changed to increase the lateral resolution.

According to previous studies [27], a focused laser beam can easily cause surface ablation. This problem is more dominant when using a point laser source for which the energy distribution is Gaussian-distributed in space, because when this type of point laser source is focused, the energy density in the central area will be high, leading to...
ablative excitation. To mitigate this effect, a line source for thermoelastic generation was used in this study. The ultrasound wave can be obtained with an amplitude approximately one order of magnitude greater than that generated by using a point source per unit laser fluence density, and the attenuation is relatively smaller than that using a point source.

2.2. Influence of the laser ultrasound direction in SAFT imaging

To fully use all ultrasound modes with different directivity patterns in SAFT imaging [14–16,28], the ultrasound propagation directivity patterns were studied. They can be calculated as follows, and satisfy the excitation conditions for a line source under the thermoelastic mechanism [28]:

\[ \text{Ang}_L \propto \frac{x^2 \cos \alpha \sin 2\alpha (x^2 - s^2 \cos^2 \alpha)^{1/2}}{4x^2 \cos^2 \alpha \sin \alpha (x^2 - s^2 \cos^2 \alpha)^{1/2} + (s^2 - 2x^2 \cos^2 \alpha)^{1/2}}, \]

\[ \text{Ang}_T \propto \frac{x^2 (1 - 2 \cos^2 \alpha)^{1/2} + 4x^2 \cos^2 \sin \alpha (x^2 - s^2 \cos^2 \alpha)^{1/2}}{4x^2 \cos^2 \alpha \sin \alpha (x^2 - s^2 \cos^2 \alpha)^{1/2} + (s^2 - 2x^2 \cos^2 \alpha)^{1/2}}, \]

where \( \text{Ang}_L \) and \( \text{Ang}_T \) are the normalised amplitudes of the longitudinal and shear waves, respectively; \( \alpha \) is the included angle between the ultrasound and the surface direction; and \( s_L \) and \( s_T \) are the slowness defined by the reciprocal of the wave speeds \( c_L \) and \( c_T \), respectively. It was previously demonstrated that in a 3-D situation, the ultrasound directivity generated by a line source in the 2-D plane perpendicular to the length of the laser line source is similar to that of the point source [17,29,30]. To study the influence of the directivity of different wave modes, the calculated half-maximum directivity patterns of longitudinal and shear waves for aluminum are shown in Fig. 1(b), assuming \( c_L = 3.34 \text{ m/s} \) and \( c_T = 71 \text{ GPa} \), and the laser is incident perpendicular to the surface at \( \theta = 45^\circ \). It can be seen in Fig. 1(b) that the calculated directivity of longitudinal waves radiating outward has the form of a single lobe (indicated by the blue line) on both sides of the normal with maximum amplitude at about \( 60^\circ \) (due to the symmetry, only the right half of the directivity pattern is shown); the calculated directivity of shear waves has two lobes (indicated by the red line) on both sides of the normal direction, and the amplitude of the main lobe reaches its maximum at \( 30^\circ \) and disappears at about \( 45^\circ \). The defect detection capabilities of both bulk longitudinal and shear waves at different depths can then be analysed based on their directivity patterns. Assuming that the defects at various depths are illustrated by dashed lines in Fig. 1(b), within the dash lined segment \( d_1 d_2 \), the component with the dominant amplitude is the longitudinal wave, so the longitudinal wave can be used for high resolution SAFT imaging in this area; within the dashed line segment \( d_3 d_4 \), the contribution of both longitudinal and shear waves are almost the same, so that both waves can be used for SAFT imaging within this range; within the dashed line segment \( d_5 d_6 \), the shear wave is the main component for SAFT imaging in this area.

2.3. Multi-mode SAFT imaging

The Multi-mode Time-domain SAFT method is an extension of T-SAFT that combines single ultrasound modes based on their directivities. The amplitude of the single-mode T-SAFT can be determined using Eqs. (5), while the multi-mode amplitude can be derived by combining all the target single-mode signals. Assuming that the multiple mode waves are all contained in a laser ultrasound signal, the corresponding contributions of each ultrasound mode in the detected ultrasound signal can be expressed as \( A_1(x, z), A_2(x, z), ... A_n(x, z) \), respectively, so the MMT-SAFT amplitude can be expressed as

\[ A_{\text{MMT}}(x, z) = a_1 A_1(x, z) + a_2 A_2(x, z) + ... + a_n A_n(x, z), \]

where \( a_k (k = 1, 2, 3 \ldots n) \) are normalised imaging coefficients of the corresponding modes that are inversely proportional to the Signal-to-Noise Ratio (SNR). SNR is calculated as \( 20 \log_{10} (P_S / P_N) \), where \( P_S \) and \( P_N \) are the effective values of the signal and noise, respectively. To balance the contributions of all ultrasound modes in MMT-SAFT imaging, \( a_k \) can be expressed as

\[ a_k = \frac{\sqrt{\sum_{i=1}^n \left( S_{ik}(i, t) - \text{mean} \left( S_{ik}(i, t) \right) \right)^2}}{\max \left( S_{ik}(i, t) - \text{mean} \left( S_{ik}(i, t) \right) \right)}, \]

where \( S_{ik}(i, t) \) denotes the \( k \)th mode of the ultrasonic signal, \( m \) denotes the signal length, and \( \text{mean} \) denotes the mean operator.

The threshold \( \tau \) is defined by \( \tau = \max \{ a_k \} / 2 \) for better imaging quality, and if \( a_k \geq \tau \), the \( k \)th mode of the ultrasonic signal is not suitable for MMT-SAFT and should be ignored. Based on the MMT-SAFT algorithm above, a customised model (shown in Appendix) was used to obtain the imaging results. The signal amplitude according to the directivity pattern was calculated using a geometric relationship. The use of the reflection principle ensures that the distance from the excitation to the defect and from the defect to the detection is the shortest.

The model diagram is illustrated in Scenario 2 in Fig. 1(a). In this model, both excitation and detection spots were regarded as line sources (infinite along the \( y \)-direction, and the Gaussian distribution along the \( x \)-direction is finite). The line width of the excitation was set to 0.1 mm to excite multi-mode ultrasound with different directivity patterns. The distance between excitation and detection was fixed at \( \text{bias} \). The scanning path was on the surface with steps of \( \Delta x \), with a total scanning distance of 20 mm. Defect \( P \) with a diameter of \( d = 1 \text{ mm} \) was placed at position \((x_0, z_0)\), where \( x_0 = 10 \text{ mm} \) and \( z_0 = 4 \text{ mm} \). In the simulation, ultrasound modes carrying defect information mainly included longitudinal, shear, and mode-converted waves, while other ultrasound wave modes, such as the skimming longitudinal wave and surface acoustic wave (SAW), which do not contribute to bulk imaging, were ignored. The material was set to aluminum, \( \text{bias} = 2 \text{ mm} \), and an overall scanning distance of 20 mm was set with a moving step of \( \Delta x = 0.05 \text{ mm} \). Fig. 2(a) shows the B-Scan result calculated using this model. The longitudinal, shear, and mode-converted waves reflected from the defect are denoted as \( r_L, r_S \), and \( r_C \), respectively.

The shortest arrival times of \( r_L, r_S \), and \( r_C \) can be determined using the formula \( t_{\text{min}} = \frac{1}{2} \sqrt{\frac{\text{bias}}{c_L^2}} + h^2 \), and are \( \approx 1.3 \mu s \), \( \approx 2.3 \mu s \), and \( \approx 1.7 \mu s \), respectively. It can be found that arrival times of all signals agree with these calculated using given distances and ultrasonic velocities.

Fig. 2(b) shows the single mode SAFT imaging using the longitudinal wave velocity in Eqs. (3). The \( x \)-axis and the \( z \)-axis indicate the horizontal and vertical directions, respectively. The imaging results within a horizontal range of 9–11 mm and a vertical range of 3–5 mm near the defect are presented. The colour in the figure represents the normalised signal amplitude, where red represents a higher value and blue represents a lower value. The dotted circles represent the positions of the defects in the model. The coordinates of the centre of the circle are \((10, 4) \text{ mm}\). The fan-shaped area bounded by the defect edge where the amplitude is greater than 1/2 the maximum value is highlighted in yellow, and it covers approximately 46.7% of the upper half of the defect area. The upper part of the defect imaged by the longitudinal wave, which is divided into the left- and right-side lobes, as shown in Fig. 2(b) is at the depth of 3.5 mm to 4 mm. At a depth of 4 mm to 4.5 mm, there is an arc that intersects and strengthens the left and right side lobes, as indicated. This is an artefact produced by the contribution of the shear wave signal in longitudinal sound velocity imaging.

Fig. 2(c) shows the single mode SAFT imaging results with the shear wave velocity. Compared with Fig. 2(b), the yellow fan-shaped area in Fig. 2(c) is closer to the dotted circle top, and it covers about 47.2% of the upper half of the defect area. In addition, the sound velocity of the shear wave is slower than that of the longitudinal wave; therefore,
the artefact caused by the longitudinal wave mode exists above the top of the shear wave imaging, as indicated at a depth of approximately 3.2 mm to 3.5 mm.

Fig. 2(d) shows the single mode SAFT imaging results using the mode-converted wave velocity. The imaged defect area has a structure similar to that of the shear-wave T-SAFT image in Fig. 2(c). In addition, it can be seen that besides the mode-converted signal, the artefacts resulting from the shear wave have a much higher amplitude, as indicated, which makes the target imaging more difficult to recognise. Therefore, \( a_{\text{mode-converted}} = 0 \) and there is no yellow area.

Fig. 2(e) is the calculated imaging using the MMT-SAFT algorithm. The MMT-SAFT image combines all the single-mode SAFT images mentioned above; thus, the upper contour of the defect is more complete than any SAFT image using single acoustic modes. The yellow fan-shaped area covers approximately 77.8% of the upper half of the defect area, which is larger than the angular range for any single mode. It can also be observed that all artefacts generated using single acoustic modes can be found in the imaging using the MMT-SAFT algorithm, but their amplitudes are suppressed. For the SAFT algorithm using a single ultrasonic mode, when a certain ultrasonic mode is chosen, the velocity of the ultrasonic mode in the SAFT algorithm is fixed; therefore, signals of other ultrasonic modes will generate artefacts owing to the different velocities at other locations. The MMT-SAFT algorithm can superimpose and emphasise the defect area using \( \sum \alpha_4(x, z) \), while the amplitude of the artefacts area remains \( \alpha_4(x, z) \). Table 1 shows the evaluation index of maximum artefact amplitude, and has little effect on the SNR. Moreover, the MMT-SAFT algorithm is conducive to extracting the target signal generated from the defect in the B-scan result. After deducing the possible arrival time of the target ultrasonic signal, a filter in the time domain can be added to better isolate the target signal and further improve the quality of SAFT imaging using a single ultrasonic mode.

### Table 1

|                        | Longitudinal | Shear | Mode-converted | MMT-SAFT |
|------------------------|--------------|-------|----------------|-----------|
| Maximum artefact amplitude (a.u.) | 0.41         | 0.36  | 0.88           | 0.34      |
| SNR (dB)               | 23.8         | 28.6  | 18.9           | 24.7      |
| Percentage of yellow area | 46.7%        | 47.2% | 0%             | 77.8%     |

### 3. Material and methods

#### 3.1. Experiment setup and specimens

To examine the feasibility of the proposed MMT-SAFT algorithm, laser-ultrasonic scanning experiments were performed on several aluminium plate specimens. The target specimens and experimental configuration are shown in Fig. 3(a) and (b), respectively. A pulsed laser (CNI EO-1064-N, BE50528, wavelength of 1064 nm, pulse width of 10 ns, single pulse energy of 1 mJ and repetition frequency of 3000 Hz) illuminated the specimen surface and generated ultrasound waves. The generation laser spot was focused by a cylindrical lens into a line-shaped generation spot with a length of ~5 mm and a width of ~0.1 mm. The incident laser fluence density was \( \leq 250 \text{ mJ/cm}^2 \) (lower than the ablation threshold). A probe laser provided by a Doppler vibrometer (Poltec, OFV-5000, wavelength of 633 nm, bandwidth of DC ~20 MHz) was focused as a detection spot to measure the surface displacement related to the ultrasound. The tested specimen was fixed on an X-Y translation stage. The signal detected by the vibrometer was amplified by an amplifier (MWLA-00020G30, 5 kHz–500 MHz) and transmitted to an oscilloscope (Rigol DS4024, bandwidth 200 MHz) for the A-scan display (sampling time <1 s for each point, averaged 512 times) and data storage.

A prior 1D scan experiment on an aluminum plate without defects was carried out before MMT-SAFT scanning to obtain the directivity patterns and velocities of the corresponding ultrasound modes. The detection laser spot was fixed on the surface, and the generation laser spot moved away from the detection spot with a step of 0.1 mm, finally stopping at 20 mm. The thickness of the plate used in the previous experiment was 8 mm.

The MMT-SAFT scanning path is shown in Fig. 3(c). At the initial position, the distance between the detection spot and the projection of the defect centre to the sample surface was 10 mm. The excitation and detection were bias mm apart and moved together from the left side of...
The effective values of the signals using several processes are required. A band-pass filter was first applied to all data at position \( r_S \) respectively. The experimentally detected raw B-scan data are shown in Fig. 3(e).

Unwanted signals, such as SAW, surface-skimming longitudinal wave, bottom-reflected mode-converted waves, and bottom-reflected shear waves, respectively. The units of the colour bars in (e) and (g) are mV.

![Diagram of specimens](image)

**Fig. 3.** Diagram of: (a) 3 specimens, the picture of Specimen 2 is made by splicing the parts containing defects; (b) experiment setup; (c) top view of scanning; (d) an A-scan of raw data; (e) raw B-scan data set; (f) the processed A-scan data; (g) the processed B-scan data set. SAW, \( r_L \), \( r_C \), \( r_S \) represent SAW, the bottom-reflected longitudinal waves, bottom-reflected mode-converted waves, and bottom-reflected shear waves, respectively. The units of the colour bars in (e) and (g) are mV.

### Table 2

| Specimen | Depth (mm) | Diameter (mm) | bias (mm) | \( \theta \) |
|----------|------------|---------------|------------|----------|
| 1        | 4          | 0.8           | 1.4        | 19.3°    |
| 1        | 4          | 0.8           | 2.5        | 32.0°    |
| 2        | 4          | 0.8           | 3.5        | 41.2°    |
| 2        | 4          | 0.8           | 4.5        | 48.4°    |
| 3        | 4          | 0.1           | 2.5        | 32.0°    |

*This experiment is a reference to other experiments.*

The specimen to the right, with a step of 0.05 mm, and a total moving distance of \( d_T = 20 \text{ mm} \).

Three specimens containing horizontal holes were used in the experiments: Specimen 1, Specimen 2, and Specimen 3. Specimens 1 and 2 were aluminum plates with dimensions of 120 \( \times \) 30 \( \times \) 8 mm\(^3\), and Specimen 3 was an aluminum plate with dimensions of 120 \( \times \) 30 \( \times \) 10 mm\(^3\). An outlook of the defects is shown in Fig. 3(a); the bias and the corresponding directivity angle \( \theta \) in the experiments are listed in Table 2. In Specimen 1, four scans with various biases were conducted; therefore, the influence of bias in the MMT-SAFT algorithm was studied. In Specimen 2, defects at different depths were examined by scans using similar bias; therefore, the influence of the defect depth was studied. In Specimen 3, the optimal parameters for SAFT scans were obtained in the previous experiments, MMT-SAFT imaging with different sizes (diameters) was studied. All the bias values were controlled by the arrival time of the SAW. All surfaces of the samples were polished to maximise the light reflected to the vibrometer.

### 3.2. Laser ultrasound signals processing

As detected ultrasonic signals have broad bandwidth and multimode characteristics, signals used in imaging may be submerged in unwanted signals, such as SAW, surface-skimming longitudinal wave, sound propagating in air (air sound), etc., as shown in the A-scan of raw data at position \( x = 8.75 \text{ mm} \) in Fig. 3(d). It can be seen that the SNR of \( r_S \) is 11 dB, which is calculated by \( 20 \log_{10} (P_S/P_N) \), where \( P_S \) and \( P_N \) are the effective values of the \( r_S \) wave and noise of the entire signal, respectively. The experimentally detected raw B-scan data are shown in Fig. 3(c). \( r_L, r_C, \) and SAW represent the reflected longitudinal wave, reflected shear wave, and SAW, respectively. Because all unwanted signals must be removed and the useful signal must be emphasised, several processes are required. A band-pass filter was first applied to all signals using \( f_L = 0.8 \text{ MHz} \) and \( f_H = 20 \text{ MHz} \), which corresponds to the detection limit of the Doppler vibrometer. Afterwards, a “deflashing” process was used for data adjustment, to reduce the influence of the surface flatness of the specimen, using the following equation:

\[
S_{\text{Sig}}(i, t) = \frac{S_{\text{Sig}}(i, t)}{\sum_{i=1}^{n} (S_{\text{Sig}}(i, t))^2}
\]

where \( S_{\text{Sig}}(i) \) is the signal of the dataset and \( t \) and \( n \) represent the time and length of time, respectively. \( S_{\text{Sig}}(i) \) is an energy normalisation signal, which can avoid the effect of environmental interference and maintain the signal energy at the same level. Finally, adjacent wave subtraction (AWS) \( [31] \) was used to strengthen the useful signal and suppress low-frequency noise:

\[
\Delta S_{\text{Sig}}(i)_\text{deflashing} = \frac{S_{\text{Sig}}(i)_\text{deflashing} - S_{\text{Sig}}(i - 1)_\text{deflashing}}{\max (S_{\text{Sig}}(i)_\text{deflashing})} \quad (11)
\]

\( S_{\text{Sig}}(i)_\text{deflashing} \) and \( S_{\text{Sig}}(i - 1)_\text{deflashing} \) are two adjacent signals detected at two neighbouring points in the inspected area. Laser ultrasound signals, especially bulk waves, are usually weak; for example, the bulk wave \( r_S \) shown in Fig. 3(d) is about 1/24 of the SAW in amplitude, therefore, it can be easily submerged in noise. The fixed excitation-detection distance ensures that bias is a constant, so the SAW can be reduced by AWS. This process can be regarded as an adaptive high pass filter. Thus, tiny rapid changes become prominent, while large slow changes or signals that do not change over time, such as low-frequency components in SAW, surface longitudinal waves, and air sounds, can be significantly reduced. The processed A- and B-scan datasets are shown in Fig. 3(f) and (g), where the surface skimming longitudinal wave has been removed, but the SAW still has remnants. As a result, SAW would have an impact on subsequent imaging. The SNR of the processed \( r_S \) was increased to 20 dB, and the peak-to-peak value of rS was approximately 1.2 times that of the SAW. Both shear-to-longitudinal and longitudinal-to-shear mode-converted waves are close to each other and are represented by \( r_C \) in the figure. The signal process facilitated subsequent MMT-SAFT imaging and highlighted the location of the defects. MMT-SAFT images are presented in the next section.

### 4. Results and discussion

#### 4.1. Directivity patterns and MMT-SAFT imaging

In the prior experiment, the actual directivity patterns in the plate material provided a reference for the bias selection in the MMT-SAFT experiment. The B-scan result after applying a bandpass filter (1–20 MHz) is shown in Fig. 4(a); the skimming longitudinal wave, SAW, the bottom-reflected longitudinal waves, bottom-reflected mode-converted waves, and bottom-reflected shear waves are denoted by \( S_L \), \( R \), \( r_L \), \( r_C \) and \( r_S \), respectively. Note that \( r_C \) denotes both shear-to-longitudinal and longitudinal-to-shear mode-converted acoustic waves,
Fig. 4. Real directivity patterns and MMT-SAFT results: (a) The prior experiment B-Scan result. $S_L$, $R$, $r_L$, $r_C$, and $r_S$ represent the skimming longitudinal wave, Surface Acoustic Wave (SAW), bottom-reflected longitudinal waves, bottom-reflected mode-converted waves, and bottom-reflected shear waves, respectively. (b) Actual directivity patterns extracted from (a) and the simulated directivity patterns. The orange and blue lines represent the experimental directivity patterns of the shear and longitudinal waves, respectively; the yellow and purple dashed lines represent the simulated directivity patterns of the shear and longitudinal waves, respectively. (c–f) Single-mode SAFT imaging of (c) longitudinal wave without a Hanning window, (d) longitudinal wave with a Hanning window, (e) shear wave. (f) MMT-SAFT imaging. In (c–f), the horizontal represents the $x$-axis, the vertical represents the depth $z$-axis (unit: mm), and the unit of colour bar is dB.

because they are superimposed and form an enhancement. According to the Huygens-Fresnel principle, the reflection path of waves must satisfy the principle of the shortest travel distance, and the different directivities of ultrasound wave modes could affect their detection capabilities. The intersection point of the $S_L$ and $R$ waves in Fig. 4(a) indicates the coincidence of the excitation and the detection, therefore, the scanning distance of that point is set as 0 mm. The wave velocities of the longitudinal wave and SAW obtained by fitting are $6169 \text{ m/s}$.
and 2906 m/s, respectively, which are 0.5% and 0.6% different from the theoretically calculated sound velocities of 6197 m/s and 2925 m/s, respectively; thus, the calculated shear wave velocity is 3119 m/s using Eqs. (2). The fitted longitudinal wave and SAW velocities and the calculated shear wave velocity are used for MMT-SAFT imaging. The experimentally measured and simulated directivity patterns of shear and longitudinal waves are shown in Fig. 4(b). As shown by the orange curve, the directivity pattern amplitude of the shear wave has a gradual rise at an angle of \( \langle 0, 61^\circ \rangle \) and a sharp rise at an angle of \( \langle 30^\circ, 38^\circ \rangle \). The maximum amplitude of the shear wave is at \( 38^\circ \), and then a steep fall appears between the angles of \( [38^\circ, 42.5^\circ] \). The directivity pattern amplitude of the longitudinal wave (represented by the blue curve) gradually increases at an angle of \( \langle 0, 61^\circ \rangle \) and then decreases steadily at an angle above \( 61^\circ \). It is worth mentioning that the experimental directivity pattern of the shear wave has a deviation of \( \pm 7^\circ \) from the theoretical directivity pattern, and the experimental directivity pattern of the longitudinal wave has a certain loss around \( 47^\circ \) due to the poor measurement. A head wave [28,32] arriving just ahead of the bulk shear wave arrival overlaps and strengthens with the shear wave at an angle of \( [33.4^\circ, 42^\circ] \), shifting the directivity pattern of the shear wave. However, the head wave does not affect the imaging results of MMT-SAFT because it has almost the same propagation distance and velocity as the shear wave in the overlapped region. In summary, we use the experimental directivity patterns to calculate the subsequent imaging.

Therefore, according to the experimentally obtained directivity patterns, the directivity angles for both shear and longitudinal waves in SAFT imaging using single ultrasonic modes can be determined. The vibration of the shear wave is perpendicular to the propagation; therefore, when the ultrasonic angle between the excitation-defect direction and normal decreases, it is harder for the vibrometer to detect the out-of-plane displacement of the shear wave, that is, in the range of \( x = 0 \) to 4.9 mm \( (\theta = 0 \) to \( 17.0^\circ) \) in Fig. 4(a), the shear wave is too weak to be used for detection of defects. For the longitudinal wave, the maximum amplitude is at \( 61^\circ \), as shown in Fig. 4(b). Therefore, based on these actual directivity patterns, we use the directivity angles \( \theta_\text{L} \in [17.0^\circ, 42.5^\circ] \) and \( \theta_\text{S} \in [0, 61.8^\circ] \), suitable for shear and longitudinal waves, respectively. Similarly, for better imaging quality using the MMT-SAFT, directivity patterns for the corresponding ultrasonic wave modes should also be chosen in these \( \theta \) ranges.

Using the parameters listed in Table 2, the corresponding directivity angle can be calculated as \( 32.0^\circ \), which fits the optimal range of both \( \theta_\text{L} \) and \( \theta_\text{S} \). SAFT imaging results using both single modes and MMT are shown in Fig. 4(e) to (f). It can be observed that in the SAFT imaging calculated using the longitudinal wave velocity, as shown in Fig. 4(e), artefacts created by the shear wave and SAW can be found. To suppress artefacts formed by other ultrasound modes, a Hanning window is applied according to the longitudinal wave arrival time. By extracting the calculated amplitude that is larger than 1/2 of the maximum amplitude, the SAFT imaging result using the longitudinal wave velocity with a Hanning window is shown in Fig. 4(d). It can be seen in the figure that the defect image has two lobes but lacks a roof. A similar procedure is applied to SAFT imaging using the shear wave velocity, and the calculated results are shown in Fig. 4(e). Finally, based on the SAFT imaging results obtained by employing the single ultrasound wave modes shown in Fig. 4(d) and (e), the MMT-SAFT imaging is calculated following the procedure shown in Section 2.3, and the result is shown in Fig. 4(f). By comparing these images, it can be found that, because of the reconstruction with a suitable directivity angle of shear and longitudinal waves, the defect in the MMT-SAFT result shown in Fig. 4(f) has a relatively complete appearance, fills in the missing roof in Fig. 4(d), and the missing side lobes in Fig. 4(e). The MMT-SAFT presents 77.9% of the total defect profile, while SAFT using single ultrasound wave modes presents much less (51.7% for longitudinal waves and 60.3% for shear waves).

In the process of MMT-SAFT, it was found that there are three main factors that affect the imaging results: bias, defect depth, and defect size. These factors are discussed in the following subsection.

### 4.2. The influence of bias on MMT-SAFT imaging

Bias can affect the detection capability of defects at different depths, in combination with the directivity pattern of the ultrasonic modes. Because the directivity patterns remain stable relative to the position of the excitation beam, during the scanning of both beams, the signal amplitude at the defect will vary with the change in the relative position of the defect and the excitation spot. As the excitation point moves from a distance to directly above the defect, and then away from the defect, the directivity angle at the excitation point first decreases and then increases, which results in a different amplitude contribution in the MMT-SAFT. Therefore, we use a characteristic angle \( \theta \) to judge the ultrasound signal amplitude variation owing to the directivity pattern. When the defect, excitation point, and detection point form a right triangle, the displacement at the detection point is the largest, so we set the directivity angle at this time as the characteristic angle \( \theta \), expressed by

\[
\theta = \arctan \frac{\text{bias}}{h}
\]

where \( \theta \) can be \( \theta_\text{L} \) and \( \theta_\text{S} \) for longitudinal and shear waves, respectively. With the help of Eqs. (13), it is also possible to obtain a suitable value of bias by inversion. As mentioned previously, the directivity angle for the shear wave \( \theta_\text{S} \in [17.0^\circ, 42.5^\circ] \), and for the longitudinal wave \( \theta_\text{L} \in [0^\circ, 61.8^\circ] \); then taking an imaging depth of \( h = 4 \) mm, for example, it can be calculated from the expression that the suitable bias is \( \in [1.12, 3.67] \) mm for the shear wave and \( \in [0, 7.46] \) mm for the longitudinal wave.

It is also worth mentioning here that although the calculated theoretical upper limit of bias of the longitudinal wave reaches as far as \( 7.46 \) mm (\( \text{bias} = 61.8^\circ \times 4 = 7.46 \) mm), it is affected by the acoustic attenuation and flatness of the specimen, and the suitable value of bias for the longitudinal wave should be much less. According to the prior experiment in Section 4.1 and by combining the suitable bias of both shear and longitudinal waves, the value of bias is set to \( \in [1.12, 3.67] \) mm.

The experimentally obtained MMT-SAFT results for various bias in Specimen 1 are shown in Fig. 5(a)–(d). The defect used in all these results has a diameter of 0.8 mm, and its real location is illustrated by the red circle. The corresponding characteristic directivity angles, \( \theta \), are listed in Table 2. In Fig. 5(i), it can be found that a better SNR and a better percentage can be obtained when the characteristic angle is close to the angles with a large amplitude in the directivity pattern. In addition, both the percentage of the upper defect surface and SNR reached a peak at \( \text{bias} = 2.5 \) mm \( (\theta = 32.0^\circ) \) with an increase in bias. This occurred because the amplitude of the shear wave directivity pattern is large at an angle of \( [30^\circ, 42.5^\circ] \), whereas the amplitude of the longitudinal wave directivity pattern gradually rises in this angle range. Thus, the MMT-SAFT results have both a better SNR and percentage at the characteristic angles \( \theta = 32.0^\circ \) and 41.2°, as shown in Fig. 5(b) and (c). When \( \theta = 19.3^\circ \) and 48.4°, as shown in Fig. 5(a) and (d), the imaging quality is reduced. As a result, for a better MMT-SAFT result, bias should be chosen in the shear-wave directivity pattern enhanced range.

In addition, it can be seen by comparing the defect signals in Fig. 5(a) to (d) that, as bias increases, the left side of the defect imaging amplitude gradually decreases, while the right side gradually increases. This is because when the bias increases, the longitudinal wave imaging gradually deviates to one side, which can be explained by Eqs. (3). The symmetry axes of Eqs. (3) can be calculated as \( x = x_0 + \text{bias}/2 \) mm, which causes an offset of bias/2 mm to the excitation point in the B-scan and shifts the final defect position of the longitudinal-mode imaging. For the shear wave, although this offset bias/2 mm may also cause a shift in the B-scan, shear-mode defect imaging always concentrates at the top, so the effect is not as large as that of the longitudinal wave.

Although the AWS process can reduce unwanted low-frequency signals, the high-frequency part of the SAW still causes artefacts. To
avoid this influence of the SAW on the final MMT-SAFT imaging, the SAW should be away from the imaging depth, which is realised by selecting a suitable bias that satisfies the inequality

\[
\frac{\text{bias}}{c_R} < \frac{2}{c_L} \sqrt{\left(\frac{\text{bias}}{c_0}\right)^2 + h^2}.
\]

(14)

It can be seen from this equation that, for a more accurate imaging position, choosing a small bias to keep the SAW away from the imaging depth is necessary.

### 4.3. Imaging capabilities of the MMT-SAFT for defects detection at different depths

It can be observed that for single ultrasonic wave modes, the imaging capability varies with the defect depth owing to its specific directivity pattern. In MMT-SAFT, because multiple ultrasonic wave modes are employed, a discussion on the imaging capabilities of MMT-SAFT for defects at different depths is necessary.

Four defects (\(\Phi = 0.5 \text{ mm}\)) in Specimen 2 at depths of 2, 3, 4, and 5 mm were tested, and the calculated MMT-SAFT results are shown in Fig. 5(e)–(h). bias in all these figures is set to 2.5 mm, and the corresponding directivity angles are 51.3\(^\circ\), 39.8\(^\circ\), 32.0\(^\circ\), and 26.0\(^\circ\), as shown in Table 2. The percentages of the upper defect surface and the SNR are shown in Fig. 5(k). A relatively low imaging quality and SNR can be observed in Fig. 5(e) when \(h = 2 \text{ mm}\) because arrival times of both the longitudinal wave and SAW are close (0.77 \(\mu\)s and 0.83 \(\mu\)s, respectively), therefore, the longitudinal wave is submerged in the SAW. MMT-SAFT degenerates into a single SAFT imaging of the shear wave, and only the top part of the defect is imaged. As the depth increases, as shown in Fig. 5(f) to (h), both SNR and percentage shown in Fig. 5(k) have slight decreases. This is because the ultrasonic amplitude attenuates with propagation distance. In addition, when the total scanning path remains constant (20 mm in this study), the defect reflection area approaches the top as the depth increases, and the percentage of the upper surface is reduced.

A similar phenomenon can also be observed in the results obtained by the simulations shown in Fig. 5(m) using similar parameters as the experiment (the bias is set to 2.5 mm, defect diameter is set to 0.5 mm, the defect depth varies from 1.0 mm to 5.0 mm with a step of 0.5 mm). In Fig. 5(m), the horizontal axis represents the \(x\)-axis from 9.6 mm to 10.4 mm, and the vertical axis represents the defect depth. As shown in the figure, as the depth increases, the simulated percentage of the upper defect surface diminishes, and the signal concentration gradually approaches the top of the defect. Both lobes produced by longitudinal wave imaging gradually move toward the top of the defect owing to the gradual decrease in the directivity angle calculated by \(\theta = \arctan(bias/h)\). When the depth \(h < 2.5 \text{ mm}\), the characteristic directivity angle \(\theta > 45.0^\circ\), which is in the range of the longitudinal wave strengthened area but not the shear wave strengthened area; good imaging at both lobes but poor at the top can be achieved. When the defect depth is 2.5 < \(h < 5.0 \text{ mm}\), both lobes produced by the longitudinal wave form an entire roof with shear wave imaging. When the depth is 5.0 > \(h \text{ mm}\), the characteristic directivity angle \(\theta \in [0, 26.6^\circ]\), which is in the range of the shear wave strengthened area, and thus only single-mode SAFT imaging by the shear wave can be obtained.

Therefore, for bias = 2.5 mm, a variety of ultrasonic modes can be used for MMT-SAFT imaging in the depth range of 2.5–5.0 mm within the characteristic directivity angle range \(\theta \in [26.6^\circ, 45.0^\circ]\). In addition, although imaging can be performed outside this angle range, its effect is similar to that of single-mode SAFT imaging, and it cannot obtain a complete defect upper appearance.

### 4.4. MMT-SAFT imagings of different defect sizes

MMT-SAFT images of defects of different diameters were obtained experimentally. Fig. 5(i), (g) and (b) show three MMT-SAFT imaging results with different defect diameters of 0.1, 0.5 and 0.8 mm, respectively. Fig. 5(i) shows both percentage and SNR of the three defects. As the diameter increases, both SNR and the percentage gradually decrease. When the defect diameter is diminished to 0.1 mm, the roof and both lobes form an “X” shape and only one peak can be recognised, as shown in Fig. 5(i). To study the influence of defect sizes, a simulation with various defect diameters was performed.

In the numerical model, defect \(P\) is located at (10,4) mm; the diameter changes from 0.1 mm to 1.2 mm with a step of 0.1 mm, and bias is fixed to 2.5 mm. The corresponding directivity angle of the defect is 32.0\(^\circ\), which is within the suitable directivity angle range of \(\theta \in [26.6^\circ, 45.0^\circ]\). The results of the normalised MMT-SAFT projections of defect diameter from 0.1 to 1.2 mm are shown in Fig. 5(n): 12 black solid lines in the figure are the projections of the defect signal at different diameters on the \(x\)-axis (intercepted the range of 9–11 mm, containing the defect); red solid lines represent where the normalised amplitudes are half of the maximum signal; “defect width” indicates the total signal width where its amplitude is greater than half maximum, and “L-lobe width” and “R-lobe width” indicate signal widths where their amplitudes are greater than half maximum of the left and right lobes, respectively; blue dashed lines represent the changing trend of the defect width and both the left-lobe and right-lobe widths.

It can be seen from the results that as the diameter of the defect gradually increases, the defect imaging gradually changes from a single peak to a two-lobe structure. Taking half of the maximum amplitude as the judgment basis, when the diameter is greater than 0.5 mm, the imaging changes from a single peak to the left and right lobes. This may be because, as the diameter of the defect increases, the defect area that can reflect ultrasonic waves becomes larger, so the propagation paths of ultrasound become inconsistent; thus, the overlapped MMT-SAFT imaging points are different, which makes the imaging amplitude distribution uneven. When both excitation and detection are on the left side of the defect, the area of the defect that can reflect ultrasonic waves is smaller than when both excitation and detection are on the right side. This phenomenon is also observed in the B-scan shown in Figs. 2(a) and 3(g). The data with the minimum arrival time at \(x = 9 \text{ mm}\) of the B-scan represent the position where the defect top is at the midpoint of excitation and detection. The signal amplitudes on the right side (\(x \in (9,13.5) \text{ mm}\) for \(rS\) and \(x \in (9,20) \text{ mm}\) for \(rL\)) are larger than those on the left side (\(x \in (6.7, 9) \text{ mm}\) for \(rS\) and \(x \in (0, 9) \text{ mm}\) for \(rL\)). Thus, the signal amplitude in the imaging result is shifted to the right side.

When the defect diameter is sufficiently small (<0.5 mm), the overall reflection is strong, presenting a single peak in the imaging result. It is worth noting that when the size of the defect is less than 0.5 mm, an “X” shape phenomenon will occur.

Other factors affect the MMT-SAFT imaging results for different defect sizes: the wavelength of the detected ultrasound, the scanning step of the experiment, and the imaging pixel size. Under normal circumstances, the ultrasonic wavelength used for detection needs to be smaller than the size of the object under testing to avoid diffraction, and this is also true in LUT. The temporal pulse width of the ultrasonic wave signal in this study was approximately 100 ns, and the minimum detectable size was \(100 \times 10^{-3} \times \Phi \approx 0.031 \text{ mm}\), which was smaller than the minimum defect diameter 0.1 mm used in the experiment. Furthermore, the scanning step of the experiment should be smaller than the diameter of the defect. Although the scanning step does not affect the detection of the defect, it affects the judgement of the defect size. The size of the detected defect is always larger than the actual defect size, and the detection error is between 1–2 scanning steps. The detection error can be reduced by reducing the scanning step; however, this cannot be completely eliminated. Limited
by the resolution, according to Eqs. (6) and the laboratory equipment, the minimum detectable size is ~0.015 mm in these experiments. In addition, the experiment time increases proportionally as the number of scanning points increases (~8 min for 400 points, ~16 min for 800 points). Furthermore, the imaging pixel size affects imaging quality and time. A higher resolution and imaging quality can be obtained by reducing the pixel size; however, when the pixel size reaches the resolution of the MMT-SAFT algorithm, the imaging quality cannot be further increased. According to both the depth and lateral resolutions expressed in Eqs. (6), the lateral resolution is proportional to the depth; therefore, it is unnecessary to pursue high-resolution imaging without any information on the defect. A rough defect image can be obtained by rapid imaging with a low resolution, and then accurate imaging for a higher imaging resolution can be performed if necessary. In this paper, 0.05 × 0.05 mm² and 0.02 × 0.02 mm² pixel sizes are used for low and high resolutions, taking about 2.4 s and 11.8 s for reconstruction time (imaging area 𝑥∈ [0, 20] mm, 𝑦∈ [0, 8] mm), respectively.

5. Conclusion

Traditional ultrasound imaging uses a single mode of ultrasound signals for imaging, and the remaining ultrasound signals are ignored or removed. To make full use of ultrasound signals, a Multi-mode Time-domain SAFT algorithm was developed for LUT imaging in this study. This imaging algorithm can be used to superimpose SAFT images generated by single-mode ultrasound signals to obtain a better defect shape. In addition, laser-excited ultrasound have unique directivity patterns, which will affect the imaging results. The directivity pattern used in MMT-SAFT was discussed through theoretical calculations and a prior experiment. Subsequently, a customised model suitable for the MMT-SAFT was established, and the effectiveness of MMT-SAFT was verified. Subsequently, the MMT-SAFT algorithm was applied to the experimental results for verification purposes. The distance between the excitation and detection, denoted as bias, was changed for imaging, and a suitable imaging distance was found to avoid the influence of SAW. On this basis, the influence of the imaging depth on the MMT-SAFT was studied, and corresponding experiments were performed. The results indicate that the MMT-SAFT algorithm is suitable for imaging at a depth of 2.5~5.0 mm, with a directivity angle (26.6°, 45.0°) when bias = 2.5 mm. The suitable imaging depth for other bias values can also be calculated using Eqs. (13). In addition, this article discusses the effect of defect size on imaging and calculates the lateral and depth resolutions under the corresponding bias. On the premise that the bias remains unchanged, the MMT-SAFT algorithm can be used to image the appearance of small defects.

CRediT authorship contribution statement

Kai-Ning Ying: Conceptualisation, Methodology, Experiment, Data processing, Programming, Software, Writing – original draft, Writing – review & editing. Chen-Yin Ni: Supervision, Methodology, Experiment, Data processing, Programming, Writing – original draft, Writing – review & editing. Lu-Nan Dai: Methodology, Experiment, Data processing, Programming. Ling Yuan: Methodology, Writing – review & editing. Wei-Wei Kan: Methodology, Funding acquisition, Writing – review & editing. Zhong-Hua Shen: Supervision, Methodology, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Customised simulation

A MATLAB program based on the Huygens–Fresnel principle was designed to solve this problem by analytical calculation. We assume that the ith ultrasonic wave at the excitation can be obtained by

\[ h(t) \propto (x - ct) e^{-4(x-ct)^2/4a^2}, \]  

where \( I_0 \) is the initial amplitude of the acoustic wave, \( a \) is the attenuation coefficient, and \( a = 1.7125 \) for aluminum. When \( x = 20 \) mm, \( I = 0.966I_0 \); thus attenuation is insignificant, and not considered in our calculation.

Therefore, the amplitude at the excitation spot can be expressed as

\[ h(t) = h_0 \cdot \text{Ang}(\theta). \]

As shown in Fig. A.1, a total reflection defect \( P(x_P, y_P) \) with radius \( r \) in space is built. The excitation and detection are positioned at \( E(x_E, y_E) \) and \( D(x_D + \text{bias}, y_D) \), respectively. Suppose that there is an unknown point \( A(x_A, y_A) \) on the defect, the distance \( EA \) is defined as \( d_1 \), and \( DA \) is defined as \( d_2 \). Therefore, the problem can be transformed into finding a point \( A \) on \( P \) where \( AP \) is on the bisector of \( \angle EAD \):

\[ \frac{EA}{|EA|} + \frac{DA}{|DA|} \parallel \hat{AP}. \]  

This equation is a quartic equation and difficult to solve. Therefore, we transform this into a minimum problem using the Huygens–Fresnel principle.

\[ \begin{align*} 
    d_{\text{min}} &= \min \left\{ \sqrt{(x_E - x_A)^2 + y_A^2} + \sqrt{(x_E + \text{bias} - x_A)^2 + y_A^2} \right\}, \\
    (x_A - x_p)^2 + (y_A - y_p)^2 &= r^2. 
\end{align*} \]

\( d_{\text{min}} \) can be obtained by discretisation and the arrival time of acoustic waves can be expressed as \( t(i) = d_{\text{min}}(i)/c \), where \( i \) is the ith excitation spot and \( c \) is the velocity of sound. Thus, the B-scan dataset is

\[ \text{data}(i, t(i)) = h(t(i)) \cdot \text{Ang}(\theta_i). \]
where data is the data array of the calculated B-scan and the running time of the program is approximately 2 s for a B-scan (400 groups, [0, 7] μs for time). The model with the same size takes approximately 12 days (400 groups, 40 min each group) to compute in comsol.

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