Non-destructive laser-ultrasonic Synthetic Aperture Focusing Technique (SAFT) for 3D visualization of defects

Chen-Yin Ni, Chu Chen, Kai-Ning Ying, Lu-Nan Dai, Ling Yuan, Wei-Wei Kan, Zhong-Hua Shen
School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
School of Science, Nanjing University of Science and Technology, Nanjing 210094, China

Abstract

The Laser Ultrasonic (LU) technique has been widely studied. Detected ultrasonic signals can be further processed using Synthetic Aperture Focusing Techniques (SAFTs), to detect and image internal defects. LU-based SAFT in frequency-domain (F-SAFT) is developed to visualize horizontal hole-type defects in aluminum. Bulk acoustic waves are non-destructively generated by irradiating a laser line-source, and detected using a laser Doppler vibrometer at a point away from the generation. The influence of this non-coincident generation-detection on the equivalent acoustic velocity used in the algorithm is studied via velocity mappings. Because the wide-band generation characteristic of the LU technique, frequency range selections in acoustic wave signals are implemented to increase Signal-to-Noise Ratio (SNR) and reconstruction speed. Results indicate that by using the LU F-SAFT algorithm, and incorporating optimizations such as velocity mapping and frequency range selection, small defects can be visualized in 3D with corrected locations and improved image quality.

1. Introduction

Ultrasonic Testing (UT) including conventional piezoelectric methods [1,2] and Laser Ultrasonic (LU) techniques [3–6], is widely used in defect detection, location and evaluations. The Synthetic Aperture Focusing Technique (SAFT) is one of the imaging algorithms [1] for generating 2D and 3D imaging of defects by synthesizing ultrasonic signals from small aperture transducer(s) to improve the lateral resolution using point-by-point scanning. SAFT algorithms can be categorized as the Time domain SAFT (T-SAFT) [1,7] and Frequency domain SAFT (F-SAFT) algorithms [8–15]. Compared with the T-SAFT, rapid implementation is an important advantage of F-SAFT when it is used in practical situations [1,7,8], especially real-time imaging.

Conventional F-SAFTs mainly deal with defects inspection in homogeneous media, while the PSM SAFT method, first proposed in the field of Seismology [12] and based on similar foundation, such as angular spectrum approach, was introduced to deal with UT in regular multilayer materials [2]. Furthermore, this method was also adapted to accurately image irregularly layered objects by considering phase shift changes induced by anisotropic ultrasound velocities [11].

The LU techniques have characteristics such as non-contact and non-destructive testing [3–5], and can be conducted in wide frequency bands, on curved complex surfaces, or in hostile environments [6,8]. Successful demonstrations have been produced for detecting cracks in stainless steel plates [16] and imaging the layering of curved interfaces [9,10] using the LU-SAFT. The algorithm was also applied to detecting and imaging of other industrial devices and complex structures [17]. More applications can be found in the field of Photoacoustic imaging [7,8]. To date, to the best of our knowledge, applications of the LU-based SAFT method require coincident generation and detection by focusing on the same point, ablative generation using point laser sources, resulting in destructive specimen testings [2,9,11,13–19]. Using line sources can improve the echo signal amplitude in the thermo-elastic generation, but conventional F-SAFT cannot be directly applied as a precondition of coincident generation and detection fails. Inspired by works that extend the PSM method for imaging irregularly layered objects [11], we propose to adapt the F-SAFT to solve problems existing in previous LU-SAFT techniques.

In this paper, the LU-based F-SAFT algorithm is developed for 3D visualization of defects in specimens, separated generation and detection commonly used in LU applications is considered. Bulk acoustic waves are nondestructively generated in the thermo-elastic regime with a line-source provided by a pulsed laser and detected using a laser Doppler vibrometer at a point away from the generation area. The influence of thermal expansion on the detection induced by the generation can...
be avoided. Aluminum samples with horizontal hole-type of defects are experimentally tested. By studying the equivalent acoustic velocity in the F-SAFT algorithm and exploiting velocity mappings obtained at various generation-detection distances, the defect location ability can be improved. Narrow-band piezoelectric transducers are often utilized in studies related to F-SAFT [2,11,13–15]. However, it is difficult to directly extend this method to LU applications due to the wide-band generation characteristic of the LU technique. To solve this problem, a frequency range selection in acoustic wave signals is realized in reconstruction. A transverse perforation 0.2 mm in diameter is successfully detected, and another transverse perforation 0.5 mm in diameter is visualized in 3D. The results presented in this paper can provide rapid technical solutions for laser ultrasonic Non-Destructive Testing and Evaluation (NDT&E) and Photoacoustic imaging.

2. Theory

2.1. Basic principle of the F-SAFT method

A Schematic of the LU setup is shown in Fig. 1. The experimental details are provided in Section 3.1. In this study, to avoid the high requirements for detecting devices, and to enhance the signals from the defect, a laser line source is adopted to generate LU waves. Different modes of ultrasonic waves generated by the line source are scattered by the defect into shear wave and longitudinal waves. According to Huygens’ Principle, the defect is treated as an exploding source, and the actual ultrasound propagation is regarded as a process of ultrasonic signal radiation from the defect into the sample bulk and to the surface. Under the thermoelastic generation assumption, more energy is allocated to the shear waves with a directivity pattern, and the shear waves scattered by the defect can be separated from the longitudinal waves by the delayed arrival time. As the line source is used, in its perpendicular 2D plane that crosses the line’s midpoint, the k₁ components are small and assumed to be 0 for simplicity in practical implementations. In this case, the method can be derived from the 2D scalar wave equation [12].

Using the Fourier transform over x, z and t in the two-dimensional wave equation, one obtains

\[
\left(-k_x^2 - k_z^2 + \frac{\omega^2}{c^2}\right) P(k_x, k_z, \omega) = 0
\]  

(1)

where \( P(k_x, k_z, \omega) \) is the Fourier transform of the ultrasound pressure field \( p(x, z, t) \) at position \( x, z \) and time \( t \), \( k_x \) and \( k_z \) represent wave vectors propagating along the x and z directions, respectively. When only the nontrivial solution to Eqs. (1) is discussed (\( P(k_x, k_z, \omega) \neq 0 \)), \( k_x, k_z \), and \( \omega \) must satisfy the dispersion equation:

\[
k_x^2 + k_z^2 = \frac{\omega^2}{c_{eq}^2}
\]  

(2)

Where \( c_{eq} \) is the equivalent velocity of the considered ultrasound mode in the exploding source approximation [2]. If the transform is only taken over \( x \) and \( z \), one obtains:

\[
\left(-k_x^2 - \frac{\partial^2}{\partial z^2}\right) P(k_x, z, \omega) = 0
\]  

(3)

we have the following solution:

\[
P(k_x, z, \omega) = P(k_x, z_0, \omega) \exp \left(i k_x (z - z_0)\right)
\]  

(4)

In Eqs. (4), \( P(k_x, z_0, \omega) \) represents the two-dimensional Fourier transform of the acquired ultrasound field on the sample surface. The scanning plane is often defined as the \( z_0 = 0 \) plane, so Eqs. (4) is expressed as:

\[
P(k_x, z, \omega) = P(k_x, 0, \omega) \exp \left(i z \sqrt{\frac{\omega^2}{c_{eq}^2} - k_x^2}\right)
\]  

(5)

Eqs. (5) shows that the two-dimensional Fourier transform of the ultrasound field at another depth \( z \) is obtained by multiplying the ultrasound field’s two-dimensional Fourier transform in the \( z_0 \) plane by a phase shift factor related to \( k_x \) and \( \omega \). The F-SAFT algorithm assumes that the defect is a sound source, so it should have the strongest response at \( t = 0 \). Since a source at the particular depth will result in a maximally concentrated response at \( t = 0 \), a high-resolution image line at \( z \) is obtained simply by reading out \( p(x, z) \) by

\[
p(x, z) = \int \int P(k_x, z, \omega) \exp(i k_x x) dk_x d\omega
\]  

(6)

2.2. F-SAFT algorithm modification using laser line source

In previously reported LU F-SAFT studies [9,10,16–20], point sources are always used for ultrasonic generation, and the prior SAFT analysis were based on the coincident generation and detection. However, using point sources has two drawbacks: (1) the generated ultrasound waves’ amplitudes attenuate significantly with the propagation distance, so it is more difficult to detect target far away from the generation-detection pair; and (2) to generate ultrasound waves with sufficient amplitudes, ablation mechanism are used for point source so the surface can easily be damaged by laser irradiation. To overcome these drawbacks, a line-shape laser source is used for generation in this study. The line source not only improves the signal amplitude for far/deep detection, but also helps control the laser fluence density within thermo-elastic generation compared with using point source. The requirements for the detecting equipment is also relaxed. However, since the propagation of ultrasound waves generated by a line source is different from that generated by a point source, the F-SAFT algorithm should be adapted for line generation. It was previously demonstrated that the directivity is similar to the point source in direction normal to the line source [6], while the ultrasound wave front parallel to the line source is similar to a plane wave [21] in the symmetric 2D plane for reconstruction except some amplitude attenuation due to diffraction. 3D visualization of defects can be obtained by stacking the series of resulting images in the \( x-z \) plane at various \( y \) positions.

As shown in Fig. 1(a), in previous LU-SAFT studies, the generation (represented by “G” and the red arrows) and the detection (represented by “D” and the green arrows) are coincident (scenario 1). In practical LU tests, to avoid the thermal expansion’s influence caused by generation laser irradiation on the detection point, the generation and detection laser spots are often separate [6,22] as shown by scenario 2 in Fig. 1(a). In both scenarios, the actual ultrasound propagation paths are indicated by solid lines with arrows, while the equivalent ultrasound propagation paths in the exploding source approximation of the F-SAFT algorithm are indicated by dashed lines with arrows. In scenario 2, the separation between “G” and “D” is indicated by \( \Delta x \). Propagation paths from “G” to the defect and from the defect to “D” are represented by \( d_1 \) and \( d_2 \), respectively. When generation and detection are coincident or the distance between them is negligible compared with the depth of the defects from the sample surface (such as in scenario 1 in Fig. 1(a)), the actual two-way propagation (shown by the solid line with a double arrow in scenario 1) is represented by the one-way propagation process (denoted by the dashed line with a single arrow in scenario 4) of the ultrasound in the F-SAFT algorithm at a velocity \( c_{eq} \) equals to half of the original velocity \( c_{eq} = c_0 / 2 \). But for scenario 2, the separation distance \( \Delta x \) between the two laser spots varies both distances from the generation to the defect \( d_1 \), and that from the defect to the detection \( d_2 \). The detected signals’ arrival times. In this case, the relationship \( c_{eq} = c_0 / 2 \) is not satisfied and needs to be further investigated. In Section 4.1, the influence of \( \Delta x \) on defect detection is studied in detail, and we will show that without any adaption, this method will lead to error in the defect’s position that can be fixed by velocity mapping.
3. Material and methods

3.1. Experimental setup and samples

Fig. 1(b) shows a diagram of the experimental setup. A pulsed laser with a wavelength $\lambda = 1064$ nm, a single pulse energy $E_p = 1$ mJ, and a repetition frequency $f = 3000$ Hz is used to generate ultrasound waves in tested specimens. The generation spot is focused by a cylindrical lens into a line-shape spot at a length of $\sim 4$ mm, and a width $< 0.1$ mm. The laser fluence density is limited to $< 250$ mJ/cm$^2$. A laser vibrometer (Polytec, OFV-5000, OFV-505, wavelength $\lambda \sim 633$ nm, bandwidth DC~20 MHz) is used for ultrasound detection. The tested sample is placed on a two-dimensional translation stage. During a 2D scan, both generation and detection laser spots are fixed and do not move, while the tested sample is moved with the translation stage. In each scanning position, the signal detected by the vibrometer is amplified by an amplifier (MWLA-00020G30, 5 kHz~2 GHz, 30 dB) and transmitted to an oscilloscope (Rigol DS4024, bandwidth 200 MHz) for display and data acquisition. The signals acquired are sent to a computer for post-processing, calculation and results presentations.

The samples used in this paper are two aluminum blocks. Both have dimensions of $200 \times 30 \times 8$ mm$^3$ (length-width-height). On the side of one of samples, two transverse perforations both with a diameter of $w \sim 0.5$ mm and a length of $l \sim 10$ mm are obtained using a micro-drill: one is illustrated in Fig. 1(a) as an example. The distances between the upper surface of both transverse perforations and the top surface of the sample (depth) are $h \approx 4.75$ mm and $h \approx 3.75$ mm, respectively. The distance between these two transverse perforations in the $x$-direction is 20 mm. In the other sample, there is another transverse perforation with a diameter of $w \approx 0.2$ mm, a length of $l \approx 1$ mm and a depth of $h \approx 3.2$ mm.

It has been widely reported in many studies [23–25] that the LU signals generated in thermo-elastic regime have specific directivity; in other words, the concentration of ultrasound waves is not in the direction normal to the sample surface, but at a $\sim 60$ degree from the sample surface. To detect reflected/diffracted ultrasound wave with specific directivity, a prior experiment must be conducted to analyze the influence of the acoustic wave’s directivity on the reflected/diffracted acoustic signal. To accomplish this, a 1D scan measurement is conducted on an $\sim 8$ mm thick intact aluminum plate. As shown in the inset of Fig. 1(c), the detection point is fixed on the sample surface, and the generation is initially $\sim 30$ mm away from the detection. During the 1D scan, the generation gradually approaches the detection point in a scanning step of 0.1 mm, after passing the detection point, the generation laser spot stops at $\sim 30$ mm on the other side of the detection. The B-Scan result is shown in Fig. 1(c), the skimming longitudinal wave, Surface Acoustic Waves (SAW), the shear wave reflected from the sample’s bottom surface and the longitudinal wave reflected and mode-converted from the shear wave at the bottom of the sample are denoted by “L”, “R”, “rS$_{Bottom}$” and “rL = S$_{Bottom}$”, respectively.

As arrival times of ultrasonic signals propagating along the sample surface change linearly with the generation-detection source distance, skimming longitudinal waves and SAW signals appear as two straight lines. The slope of each line represents the velocity of the corresponding ultrasound mode. The straight line constructed by the skimming shear wave is covered by the SAW signal due to a similar propagation velocity. In this case, it is difficult to directly measure the shear wave velocity using the 1D scan measurement, so it is obtained using the following equation:

$$v_{shear} = \sqrt{\frac{E}{2(1+\nu)\rho}} \approx 3179 \text{ m/s},$$

where Young’s modulus $E = 71$ GPa, density $\rho = 2.81$ g/cm$^3$ and the Poisson’s ratio $\nu = 0.25$ are provided by the sample’s manufacturer. Due to the nonlinear change in the propagation distance, the signal “rS$_{Bottom}$” exhibits a parabolic shape, so the sound velocity of the shear wave can also be obtained by using nonlinear regression to fit this signal, which is $c_{shear}^{fitting} \approx 3091$ m/s, and is in good agreement with this paper’s value. Except for the central area around $y = 0$ mm, the reflection can be observed when the distance between generation and detection reaches as far as $\sim 23$ mm, and the shear wave’s maximum amplitude appears between $t = 7$ $\mu$s and $t = 8$ $\mu$s as indicated by the red rectangular frames. These observations indicate: (a) except the region where $\theta =
0° (θ = 0° at the normal direction of the sample surface), acoustic waves within the directivity angle of θ ≈ 55.6° may produce detectable reflection/diffraction; (b) the corresponding maximum directivity angle of the detectable acoustic signal is θ ≈ 41°. This bottom reflected shear wave also indicates that these results corresponds the detection of the shear wave with optimized directivity in Ref. [23].

3.2. Experimental procedure

Using the previously described experimental setup, experiments are conducted using the following steps and as illustrated in Fig. 1(d):

Step 1. The experiment starts, and the generation laser is turned on by the computer;

Step 2. The initial test point is shown by "G" (for generation) and "D" (for detection) in Fig. 1(d) in the upper-left corner of the tested area. After waiting \( t_w = 0.1 \) s for signal averaging, the first ultrasound signal is recorded;

Step 3. "G" and "D" move along the positive y direction in scanning step of \( \Delta y \) mm, after \( t_w \), the next ultrasound signal is recorded;

Step 4. Step 3 is repeated until the scanning distance along the y direction reaches \( S_y \) mm, then "G" and "D" move along the positive x direction in scanning steps of \( \Delta x \) mm. After waiting \( t_w = 0.1 \) s, the ultrasound signal is recorded;

Step 5. "G" and "D" scan a distance of \( S_x \) in scanning steps of \( \Delta x \) mm along the negative y direction, then move along the positive x direction in scanning steps of \( \Delta x \) mm;

Step 6. Steps 3~5 are repeated until the entire scanning area illustrated by the gray region in Fig. 1(d) is tested, and the generation laser is turned off.

Step 7. After measurements at all the scanning positions, the data are categorized according to the y coordinate. The F-SAFT algorithm is applied to each set of data, a set of images describing the detected area in \( x-z \) planes at each y position are obtained, and then the 3D image is generated by arranging all of these images in the order of \( y \).

During the experiment, the acquired ultrasound signal is averaged 128 times at each position for an improved SNR. The time consumed for data averaging at each experimental point is \( \approx 0.043 \) s, so the waiting time of \( t_w = 0.1 \) s is sufficient for the data-averaging process. The samples were visually inspected before and after one measurement of \( \approx 2500 \) scans, and no damage can be found in the scanned area.

4. Results and discussions

Experiments are conducted by following the previously described procedure. In the experiment, the scanning steps along the two directions are \( \Delta x = \Delta y = 0.2 \) mm and the corresponding overall scan distance are \( S_x = 9.8 \) mm and \( S_y = 10 \) mm, respectively. The defects are placed approximately in the center of the scanning area along the \( x \) direction, and the distance between the lower edge of the scanning area and that of the sample is \( s = 5 \) mm. The data acquired are then processed using our F-SAFT algorithm. The ultrasound mode used in our calculations is the shear acoustic wave mode, so \( c_0 = c_{0,\text{shear}} = 3179 \) m/s.

The defect that scatters the generated LU wave is regarded as a surface consisting of point sources that emit acoustic waves omnidirectionally. The echo signals detected on the sample surface are then processed in the Fourier space, where the acoustic field is represented by a superposition of plane waves at different angles with different spatial frequencies. No spatial frequency selection is performed. Therefore, the scattered acoustic waves detected on the sample surface at all the propagation angles are collected and used in the reconstruction. Among all directions of generated LU waves, both directions with larger wave amplitudes and other directions are included. The involvement of waves in directions with insufficient signal amplitude may lead to a lower SNR and slightly reduce the reconstruction quality, but the location of the reconstructed defect does not change, and the final reconstruction result is not significantly affected.

4.1. Influence of \( \Delta x \) on the defect’s location

As introduced in Section 2.1, for coincident generation and detection as indicated by scenario \( \varnothing \) in Fig. 1(a), \( c_{eq} = c_0/2 \), where \( c_0 \) is the shear wave velocity. When the stand-off distance (indicated by \( \Delta x \) in scenario \( \varnothing \) in Fig. 1(a)) is introduced, both \( d_1 \) and \( d_2 \) in scenario \( \mathcal{X} \) in Fig. 1(a) change, so the detected signal’s arrival time changes. This will cause \( c_{eq} \) and \( c_0/2 \) to no longer be equal, eventually producing a vertical shift in the detected defect’s position. To study the influence of \( \Delta x \) on the defect’s location, a set of scans along the \( x \)-axis above a defect (diameter \( w = 0.5 \) mm) with various \( \Delta x \) values are realized. On one hand, \( \Delta x \) should not be zero in order to avoid the influence of thermal expansion caused by the generation on the detection, on the other hand, \( \Delta x \) should be kept in a small value to keep the scattered shear wave mode away from the SAW mode. In our case, \( \Delta x \) is selected between 0.2 mm and 2.5 mm. The upper surface of the tested defect is at \( \approx 3.75 \) mm. After calculating all the data acquired using our F-SAFT algorithm, images indicating the upper surface of the defect in the \( x-z \) plane are obtained, and the detected depths of the defect’s upper surface are extracted accordingly. The black circles in Fig. 2(a) show the depth variation of the defect detected at different generation-detection distances \( \Delta x \). The detected defect depth is deeper as \( \Delta x \) increases. To solve this problem, the equivalent velocity \( c_{eq} \) must be modified according to the variation of \( \Delta x \). In these experiments, no significant change in the detected location in the \( x \) direction can be found with the variation of \( \Delta x \).

Eqs. (5) is rewritten as follows:

\[
P(k_x, z, \omega) = P(k_x, z_0, \omega) \exp \left( \frac{iz}{c_0} \sqrt{1 - \frac{c_0^2}{c_{eq}^2} \frac{k_x^2}{k_0^2}} \right)
\]  \( (7) \)

The propagation of pure shear waves can be decomposed in orthogononal directions. In other words, the wave propagation in the \( x \)-direction and the \( z \)-direction can be considered independently. For the wave components in the \( x \)-direction or the \( z \)-direction, the total propagation distance projected in one of the orthogonal directions will be the same for scenario \( \varnothing \) and scenario \( \mathcal{X} \) as shown in Fig. 1(a), while the actual propagation distance from the defect to the generation and detection spot would be \( d_1 + d_2 \) for the case of scenario \( \varnothing \), but \( 2d \) for the case of scenario \( \mathcal{X} \). Letting \( q_1 = \frac{\Delta x}{2d} \), one obtains

\[
P(k_x, z, \omega) = P(k_x, z_0, \omega) \exp \left( izk_1 \sqrt{1 - \frac{k_0^2}{k_1^2}} \right) \]  \( (8) \)

The individual curve of \( q_1 \) and the imaging depth must be calculated for different \( \Delta x \) values. The curve of \( q_1 \), when \( \Delta x = 0.48 \) mm is shown in Fig. 2(b). For calculation efficiency, all \( q_1 \) curves calculated at different \( \Delta x \) values can be saved and recalled when the same \( \Delta x \) values are used in future experiments.

The results indicated by the red square in Fig. 2(a) shows the correct detected defect’s depth using the calculated \( q_1 \) curve presented in Fig. 2(b). After applying velocity mapping, the detected depth remains stable around the defect’s depth as \( \Delta x \) varies.

4.2. Frequency range selection in defect visualization

In wide-band generation, multiple frequency components can be used in the F-SAFT algorithm. To optimize the imaging quality, it is necessary to choose a suitable frequency range of the ultrasound waves used for imaging. Calculated images from the experimental results of the defect (\( w = 0.5 \) mm, upper surface at \( h \approx 4.75 \) mm) at \( S_y = 7.4 \) mm,
\[ \Delta x \approx 0.48 \text{ mm} \] with frequency range of 5.4–13.1 MHz and 3.1–15.4 MHz are shown in Fig. 3. Because the depth of the defect’s upper surface is \( h \approx 4.75 \text{ mm} \), the projection of the generation source with optimized shear wave directivity to the defect on the upper surface is \( \sim 4.1 \text{ mm} \). Since the separation of \( \Delta x \approx 0.48 \text{ mm} \), a total scan distance in \( x \)-direction of 10 mm ensures that scanning points with optimized shear wave directivity are included in the scan area.

In Fig. 3(a) and (b), the horizontal and vertical axes represent the \( x \) and \( z \) directions shown in Fig. 1(a), and the color indicates the signal amplitude. In Fig. 3(a) and (b), signal enhancements occur at approximately \( \sim 5.2 \text{ mm} \) and \( \sim 4.8 \text{ mm} \), indicating the location of the defect’s upper surface. The signal enhancement shown in Fig. 3(b) is stronger and more concentrated than that shown in Fig. 3(a). This is straightforward evidence demonstrating that the contribution of additional frequency components in a wider frequency range improves the imaging quality.

However, as previously mentioned, the SAFT algorithm can be extremely time-consuming. The time consumed should also be considered. Generally, more frequency components used in the algorithm will result in longer calculation times. In this case, determining of the frequency component range requires comprehensively considering not only the imaging quality, but also the calculation time. Thus, when \( f_\gamma \approx 9 \text{ MHz} \) (the central frequency of the shear wave detected in our experiment) at the center, 8 frequency ranges are used: 6.2–12.3 MHz, 5.4–13.1 MHz, 4.6–13.9 MHz, 3.8–14.6 MHz, 3.1–15.4 MHz, 2.3–16.2 MHz, 1.5–16.9 MHz, and 0.8–17.7 MHz. In each frequency range, the SNR obtained from the area indicated in the red rectangular box and the calculation time are shown in Fig. 3(c).

In Fig. 3(c), the horizontal axis represents the number of frequency ranges previously introduced, the left and right vertical axes represent the SNR (denoted by the black circle symbol) and the time consumed (denoted by the red square symbol) for the F-SAFT calculations, respectively. As the frequency components increases, the SNR first increases and then slightly decreases as the time consumed increases monotonically. The increase in the SNR is caused by the frequency components containing information on the defect contributing to the calculated imaging as previously mentioned. However, further increasing the number of frequency components introduces not only components without defect information (mainly in higher frequency range), but also noise (mainly in lower frequency range). As a result, although the frequency range in use widens, these useless components decrease the overall imaging quality. The continuous increase in time consumed is simply because the calculation must be repeated when more frequency components are involved. Based on this analysis, the optimal frequency range is found at the point with the maximum SNR, while the time consumed is reasonable (within 0.25 seconds per frame here). As a result, the optimal point in Fig. 3(c) is at (5, 16), which means the optimal frequency range for such defect is 3.1–15.4 MHz. Of note, this frequency range may not be optimal for other objects with different shapes. The spectra of scattered waves generally vary according to the scattering object’s dimensions. However, for defects with similar shapes and dimensions, the frequency range should be adequate.

In addition, an extra illustration of results obtained in different algorithm phases with optimizations presented above are shown in Fig. 4(a)(c). Data are obtained from a set of experiments testing transverse perforations with a diameter of \( w \approx 0.5 \text{ mm} \) (top surface at \( h \approx 4.75 \text{ mm} \)). During the measurements, the separation between the generation and detection is \( \Delta x \approx 2.17 \text{ mm} \). In Fig. 4, the horizontal and vertical axes represent the scanning distance in the \( x \)- and \( y \)-directions, respectively. A comparison of the image constructed from the raw data (Fig. 4(a)) and the image after the frequency selection (Fig. 4(b)), demonstrates that the background noise is effectively filtered so that the signal representing the upper surface of the defect is more prominent after applying the frequency selection. However, the location of the maximum signal depth is still lower than its real location due to the separation of \( \Delta x \) between generation and detection lasers. Fig. 4(b) and (c) show that after applying the velocity mapping, the locations of the detected signals is corrected. Of note, we selected the frequencies before velocity mapping for a better visual presentation, and the order of modifications did not influence the final result.

For further verification the improved F-SAFT algorithm is also applied to data acquired from the sample containing a defect with a diameter of 0.2 mm. Because the defect is shallow (\( l \sim 1 \text{ mm} \)), only a 1D scan was conducted. The experimental parameters are: \( \Delta x \approx 0.48 \text{ mm} \), 3.1–15.4 MHz of the selected frequency range. To better identify the defect with this diameter, the scanning step and distance are \( s_z = 0.1 \text{ mm} \) and \( S_z = 10 \text{ mm} \). The result is shown in Fig. 4(d). The signal indicates that the defect is prominent and can be identified. The depth of the detected signal corresponds with the defect’s actual depth. Therefore, the F-SAFT algorithm’s reliability and the effect of optimizations are verified. The calculation time of a 2D image is \( \sim 0.2 \text{ s} \), while using our T-SAFT with the same software and hardware, the calculation time for processing the same experimental data is more than 5 s.

### 4.3. Final 3-D imaging results

By calculating all the data acquired in the 2D scan described in Section 3.2 using the F-SAFT algorithm along with the optimization discussed in Section 4 (\( \Delta x \approx 0.48 \text{ mm} \), the frequency range is 3.1–15.4 MHz), the 3D image of the defect (\( w \approx 0.5 \text{ mm} \), \( h \approx 4.75 \text{ mm} \)) is obtained. To more clearly show the defect’s signals, a signal amplitude threshold of \( 0.5A_{\text{max}} \) is used (Full-Width-at-Half-Maximum, FWHM), where \( A_{\text{max}} \) is the maximum of the calculated signal amplitude. The result after discarding all of the data below the threshold are shown in Fig. 5. From Ref. [9], the resolution along the \( x \) and \( z \) directions are \( R_{\text{sz}} = \frac{1}{2}v\pi\approx 0.2 \text{ mm} \) and \( R_{\text{sx}} = \frac{1}{2}v\pi\approx 0.1 \text{ mm} \), where \( v \) is the shear wave velocity, \( \Delta t \) is the ultrasonic pulse duration, and \( a \) is the dimension of the synthetic aperture. The resolution along the length of the line source can be determined by measuring the tip of the defect, as illustrated in Fig. 5(e) and it is \( R_{\text{sy}} \approx y_{FWHM} - y_{\text{end}} \approx 2(5.18 - 4.6) = 2.38 \text{ mm} \).
1.16 mm. This low resolution is due to the characteristics of the line source generation and can be improved by repeating a scan using the line source and scanning direction perpendicular to the previous scan. On this basis, we performed spatial interpolation following the procedure described in Ref. [9] on the data along the x direction. Of note, the spatial interpolation reduces the size of pixels in the x direction in the result from 0.2 mm to 0.1 mm, but does not improve the algorithm’s resolution. Because fewer calculations are required and more vector calculations are involved in the algorithm than the T-SAFT algorithm, the overall calculation time for the 3D result is ∼32 s, while the calculation time is more than 2 h for the same data using the T-SAFT algorithm. By further comparing with the experiment time (∼1200 s), this time-consuming problem of T-SAFT algorithm becomes more evidence.

Rod-like signals representing the defect are evident in both overview of reconstructed results using T-SAFT and F-SAFT algorithms shown in Fig. 5(a) and (b). Otherwise, very little background noise is found, indicating that a 0.5 $A_{\text{max}}$ amplitude threshold is effective for visualizing similar defects. The similarity between reconstruction results using T-SAFT and F-SAFT algorithms confirms that the F-SAFT algorithm functions similarly despite a significant reduction in computation time.

In the front-view of the results (Fig. 5(c)), the signal along the x axis is 2 pixels, considering the spatial interpolation involved, and the width in the x direction is ∼0.2 mm. A comparison of the measurements’ lateral resolution (0.2 mm in each direction) demonstrates that the width is slightly narrower. This occurs because the signal presents on the upper surface of the defect, rather than the body. To better understand this, a more precise translation stage should be used so scans with a refined scanning step much smaller than the size of the defect can be realized in the future.

In the top-view shown in Fig. 5(d), the rough length of the detected signal agrees with the actual defect length. Although it is difficult to accurately determine the defect tip’s position using a line source with a certain length due to the characteristic of ultrasound wave front generated by the laser line source, the defect’s length can be estimated using the defect tip’s signal amplitude location at FWHM. Fig. 5(e) shows the averaged signal (6 pixels per cross-section in the x–z plane, 2 pixels in the x– direction and 3 pixels in the z– direction) along the y– direction. The FWHM is located at ∼5.18 mm, which corresponds with the actual defect length. However, to more accurately determine the defect length, other measures, such as a different LU source, should be added.

In our experiments, to obtain diffracted ultrasound signals with better SNR, we always set the line source’s long axis parallel to transverse perforations. Additional experiments indicated that the signal amplitude decreases when the line source is not parallel to the defect. The defect signal becomes indistinguishable when the line source is perpendicular to the defect. This sensitivity to the defect directivity is primarily due to the laser line source used for generation. If the laser line source is perpendicular to the defect, only acoustic waves at the intersection of the propagating wavefront line and the defect interacts and is consequently scattered. This causes the detected signals to vanish. Therefore, this defect directivity sensitivity does not depend on the algorithm (T-SAFT or F-SAFT), but the shape of the source.
However, this method's limitation on the defect directivity can be compensated by scanning twice with line sources perpendicular to each other, or using different types of generation sources according to the anticipated defect shapes.

Noise can be suppressed using the spatial frequency selection to limit the acoustic waves in directions with sufficient signal amplitudes and controlling the aperture or giving suitable weight to different directions. The overall reconstruction quality can be further improved by considering the contributions of the directivity patterns. However, using our method, the reconstructed results and SNR will only improve within the area covered by the LU waves propagating in directions with relatively higher signal amplitudes. The results in other areas will be compromised by the loss of information from relatively weak signals. Selecting the best weighted factor of different spatial frequencies according to the directivity patterns and detection position to improve the reconstruction quality with smaller blind area is the goal of our future work.

5. Conclusion

A frequency-domain SAFT algorithm was developed for laser ultrasound applications. It is applicable when the generation and detection are separate. In this F-SAFT algorithm, the influence of the separation of generation and detection lies in the change in the equivalent velocity, so the fixed equivalent velocity does not apply. To fix this problem, modifying the equivalent velocity on the generation-detection distances is studied, and equivalent velocity curves along the detection depths at specific generation-detection distance were obtained. These equivalent velocity curves can be used to compensate for variations in the detected depths of targets caused by generation and detection separation. This F-SAFT algorithm was applied to experimental results for verification. Non-destructive tests and visualizations of defects were realized, bulk acoustic waves were generated by irradiating a laser line source provided by a pulsed laser and detected by a laser Doppler vibrometer at a point away from the generation irradiating area. After calculations using the F-SAFT algorithm and optimization such as changing the equivalent velocity, frequency range and threshold settings, a transverse perforation 0.2 mm in diameter was detected and another 0.5 mm in diameter was visualized in 3D.

We expect that our F-SAFT algorithm and these verifiable experimental observations will contribute to defect evaluation/reconstruction using LU SAFT techniques, and even NDT&E methods in general. This study provides useful information for photoacoustic imaging in biomedical fields. Compared with the T-SAFT, the calculation time is significantly shorter. However, future research is necessary to improve the calculation times using different approaches such as employing Graphic Processor Unit (GPU), parallel calculations, or more efficient computer languages to achieve real-time measurements/presentations using this algorithm.
[22] P. Pyzik, A. Ziaja-Sujdak, J. Spytek, M. O'Donnell, I. Pelivanov, L. Ambrozinski, Detection of disbonds in adhesively bonded aluminum plates using laser-generated shear acoustic waves, Photoacoustics 21 (2021) 100226.
[23] J.R. Bernstein, J.B. Spicer, Line source representation for laser-generated ultrasound in aluminum, J. Acoust. Soc. Am. 107 (3) (2000) 1352-1357, http://dx.doi.org/10.1121/1.428422.
[24] V. Krylov, Directivity patterns of laser-generated sound in solids: Effects of optical and thermal parameters, Ultrasonics 69 (2016) 279-284, http://dx.doi.org/10.1016/j.ultras.2016.01.031.
[25] I.A. Veres, T. Berer, P. Burgholzer, Numerical modeling of thermoelastic generation of ultrasound by laser irradiation in the coupled thermoelasticity, Ultrasonics 53 (1) (2013) 141-149, http://dx.doi.org/10.1016/j.ultras.2012.05.001.

Chen-Yin Ni is an Associate Professor at School of Electronic and Optical Engineering, Nanjing University of Science and Technology. He has expertise in applications of laser-generated ultrasound in non-destructive evaluation, laser interaction with materials, research involving optical, thermal materials science and other interdisciplinary areas of knowledge and technology.

Chu Chen is currently an Optical Engineering Graduate from School of Electronic and Optical Engineering, Nanjing University of Science and Technology. CHEN's research work is supervised by Chen-Yin NI and Wei-Wei KAN. Recently, CHEN and her colleagues have devoted themselves to the research of Synthetic Aperture Focusing Technology using laser ultrasonic approaches.

Chen-Yin Ni

Kai-Ning Ying is currently a Biomedical Engineering Graduate from School of Electronic and Optical Engineering, Nanjing University of Science and Technology. He will continue his PhD in School of Science NJUST. Now his research focuses on Photoacoustic Tomography, Laser Ultrasound and Synthetic Aperture Focusing Technology.

Kai-Ning Ying

Lu-Nan Dai is currently as a Ph.D. student major in Optical Engineering in School of Science, Nanjing University of Science and Technology supervised by Chen-Yin NI and Zhong-Hua SHEN. DAI is interested in Laser Ultrasound based NDT&E, especially LU based Synthetic Aperture Focusing Technology.

Lu-Nan Dai

Ling Yuan, Associate Professor at School of Science, Nanjing University of Science and Technology. He acquired his teaching qualification in 2017 and began delivering the course of photoacoustics since then. His current research interest includes acoustic artificial materials, ultrasound imaging and laser ultrasound.

Ling Yuan

Weiwei Kan received his Ph.D. from Nanjing University in 2015. He is currently an Associate Professor at School of Science, Nanjing University of Science and Technology. His current research interest includes acoustic artificial materials, ultrasound imaging and laser ultrasound.

Weiwei Kan

Zhong-Hua Shen is a Professor and Ph.D. supervisor of Nanjing University of Science and Technology. In 1999, she graduated from Nanjing University of Science and Technology with a doctorate degree in optical engineering. Since 2001, she has started working at Nanjing University of Science and Technology. Her research directions are laser ultrasonic non-destructive testing technology and application, laser-substance interaction mechanism and testing. From 2004–2009, she has visited the University of Heidelberg in Germany frequently and has established collaborations with many internationally renowned photoacoustic research groups.

Zhong-Hua Shen