Laser Ultrasonic Imaging Based on Synthetic Aperture Focusing Technique Algorithm

Sundara Subramanian Karuppasamy, Che Hua Yang

***Abstract*—**In this work, the laser ultrasound technique has been used for analyzing and imaging the inner defects in metal blocks. To detect the defects in blocks, traditionally the researchers used piezoelectric transducers for the generation and reception of ultrasonic signals. These transducers can be configured into the sparse and phased array. But these two configurations have their drawbacks including the requirement of many transducers, time-consuming calculations, limited bandwidth, and provide confined image resolution. Here, we focus on the non-contact method for generating and receiving the ultrasound to examine the inner defects in aluminum blocks. A Q-switched pulsed laser has been used for the generation and the reception is done by using Laser Doppler Vibrometer (LDV). Based on the Doppler effect, LDV provides a rapid and high spatial resolution way for sensing ultrasonic waves. From the LDV, a series of scanning points are selected which serves as the phased array elements. The side-drilled hole of 10 mm diameter with a depth of 25 mm has been introduced and the defect is interrogated by the linear array of scanning points obtained from the LDV. With the aid of the Synthetic Aperture Focusing Technique (SAFT) algorithm, based on the time-shifting principle the inspected images are generated from the A-scan data acquired from the 1-D linear phased array elements. Thus the defect can be precisely detected with good resolution.

***Keywords*—**Laser ultrasonics, linear phased array, nondestructive testing, synthetic aperture focusing technique, ultrasonic imaging.

I. Introduction

STRUCTURAL Health Monitoring (SHM) plays a vital role in examining the defects in aerospace, nuclear, and concrete structures [1]-[3]. For Nondestructive Evaluation (NDE) of metal blocks, ultrasonic waves are more preferred to interrogate the inner defects in these blocks [4], [5]. The most common method used for the generation and reception of ultrasonic waves is piezoelectric transducers. Ultrasonic transducer arrays with various configurations are employed in detecting the defects since they provide maximum flexibility and higher performance than conventional monolithic transducers [6]. These configurations can be either sparse or phased array. For sparse array, the major drawbacks are if the specimen is large, it is difficult to mount the transducers over a large area [7], the direct arrivals and coherent structural reflection reduce the contrast of the image unless there was a baseline comparison of signals [8]. These drawbacks were overcome by the phased array. In the case of the phased array, whether it is 1D - linear array [9], [10] or 2D - rectangular array [11], circular array [12], we need to consider the pitch between transducers, the ratio of pitch to wavelength, and steering angle for efficient beamforming [13]. Both configurations need more transducers, time-consuming calculations and also, they provide limited bandwidth.

In this work, a non-contact method is employed for the generation and reception of ultrasonic waves. A Q-switched pulsed laser is used for generating the ultrasonic waves and the reception is done by using the LDV. An artificial defect of 10 mm diameter hole with a depth of 25 mm is introduced in the center of the aluminum block and further interrogations of this defect were carried out by selecting a linear array of scanning points from the LDV. To generate inspection images with the acquired signals from the scanning points, a SAFT algorithm is developed with the help of MATLAB software. By utilizing this algorithm, the defect can be detected with good resolution.

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II. Materials and Methods

A. Sample

Aluminum is extensively used in building aerospace, industrial, and naval structures due to its outstanding properties [14], [15]. To ensure the reliability of those structures, we need to examine them with the aid of NDT before the failure occurs. Here, an aluminum block (6082 T651 aluminum alloy) with the properties listed in Table I is used as the inspecting material and a 10 mm diameter hole with 25 mm depth is introduced as in Fig. 1. The defect is located at 7.5 mm from the top surface.

TABLE I
PROPERTIES

Parameter	Value	Unit
Length	60	mm
Breadth	60	mm
Thickness	25	mm
Young's modulus	71	GPa
Density	2.71	g/cm^3
Poisson's ratio	0.33	-

B. Laser Vibrometer Array System

This array system provides a rapid, high-spatial resolution and a non-contact method for ultrasonic waves sensing and visualization. Based on the Doppler effect, this system can measure the displacement/velocity wavefield of ultrasonic waves over the scanning area. From the scanning area, a series of scanning points can be selected, serving as the phased array sensing elements as in Fig. 2. These selected scanning points can be made up into various configurations such as 1D-linear array, 2D-rectangular, and circular ring array [16], [17]. The major advantages of this array system are:

(i) It is a non-contact minimally invasive array.
(ii) It can achieve higher spatial density array distribution compared to other phased arrays which are usually limited by their sensor profile.
(iii) It can be easily defined into various array configurations without additional sensor installations for different purposes such as parametric studies and array distribution optimization.

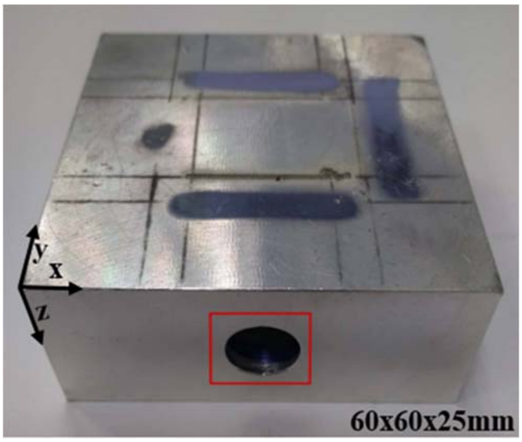


Fig. 1 Sample representing the 10 mm diameter hole

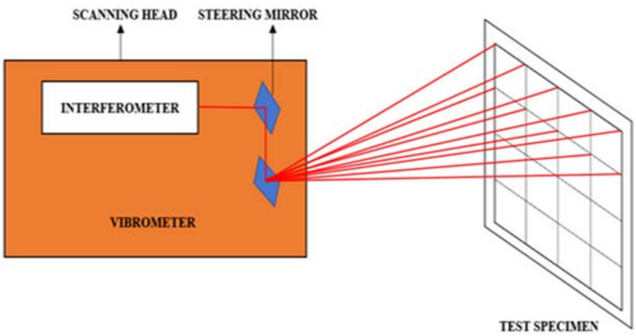


Fig. 2 Laser Vibrometer Array System

III. SAFT Algorithm

From the data acquired from the sensor elements, the ultrasonic imaging technique helps detect and locate the defect in industrial parts. In ultrasonic imaging, the main priorities were given to the lateral resolution of the image and signal to noise ratio of the signals. The algorithms used for generating the images are aimed at increasing the lateral resolution of the image with a good signal to noise ratio. The SAFT technique follows the principle of pulse-echo mode for the sensor elements in an array [18]-[21]. First, the material to be inspected is divided into grids that represent the pixels in the image. Each element is said to transmit and receive the ultrasonic signals and this procedure is repeated for all the sensor elements as in Fig. 3. The data received by element i placed in u_i are represented by $y(t,u_i)$. For N number of elements, the coherent summation is calculated using (1):

$$o(x,z) = \sum_{n=1}^{N} y\left(\frac{2D}{v}, u_i\right) \tag{1}$$

where $D = \sqrt{(x-u_i)^2 + z^2}$, the distance between the element and the pixel, v = wave velocity, and d = pitch between the transducers.

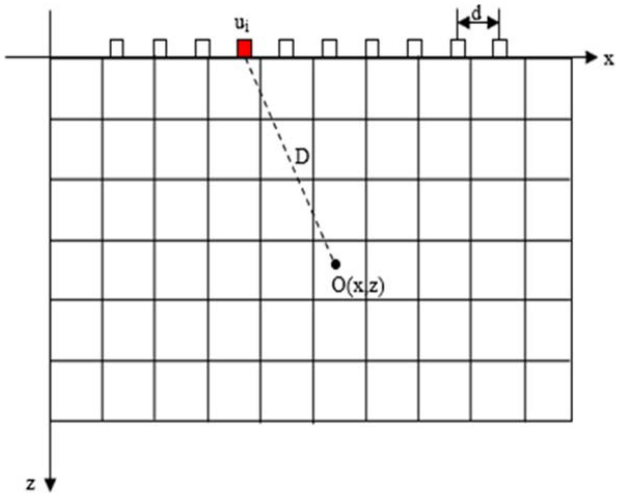


Fig. 3 SAFT imaging algorithm

IV. Experimentation

A. Experimental Setup

The schematic representation of the experimental setup is shown in Fig. 4. A Q-switched Nd:YAG laser (Quantel Brilliant B model) having a wavelength of 532 nm, pulse duration of 5 ns, and pulse energy of 400 mJ is employed for the excitation of the ultrasonic signal. A sample to be inspected is placed in the sample holder of the stepper motor. The LDV with sensor head (Polytec OFV 511 and OFV 2700 model) was used for sensing the signals. The signals received by the LDV were recorded on the computer by utilizing the program made using LabVIEW software. These A-scan data containing the defect signal were used as the input to the SAFT algorithm to generate the inspection images.

B. Array Configuration

A linear phased array has been used to interrogate the defect and for generating the inspection images. This 1D array with 41 elements was created by scanning the laser beam and the LDV simultaneously with an equal pitch of 0.5 mm as in Fig. 5. The specimen is mirror polished to a finite distance for the effective use of LDV. The distance between the generation and detection point is said to be 5 mm to avoid the plasma generated during the generation process. From each generation point, the ultrasound is generated and received by its corresponding detection point. Thus, the 41 A-scan data were collected from the 41 scanning points, serving as the input for the SAFT algorithm.

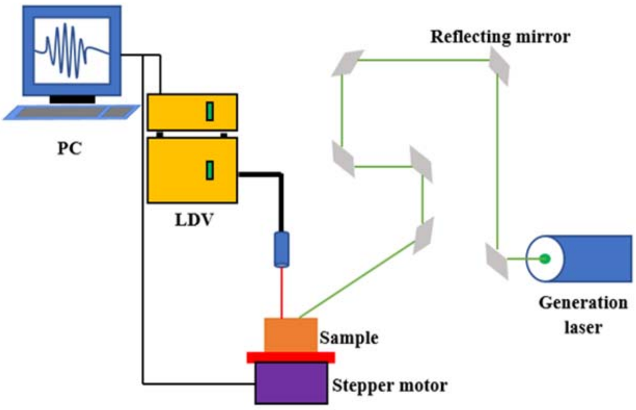


Fig. 4 Schematic representation of the experimental setup

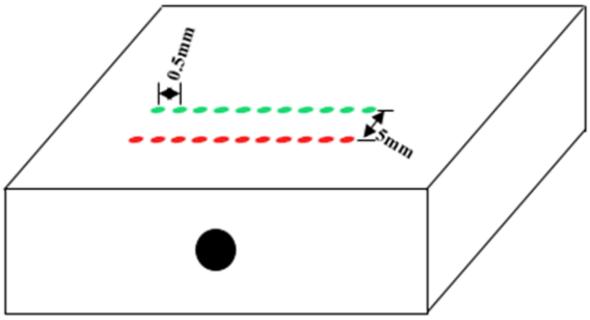


Fig. 5 Linear phased array configuration where green dots represent the generation point from the laser and the red dots represent the reception point from the LDV

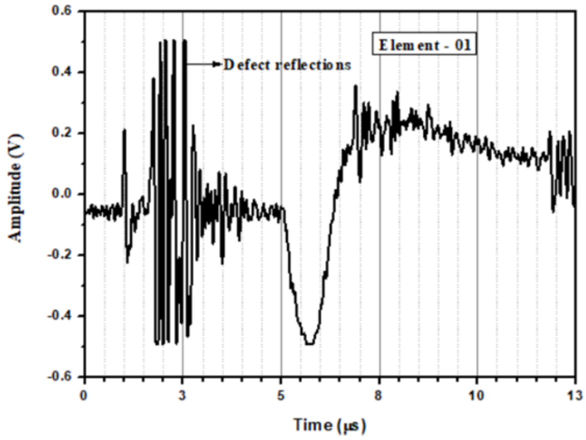
V. RESULTS AND DISCUSSION

A. Data Collection

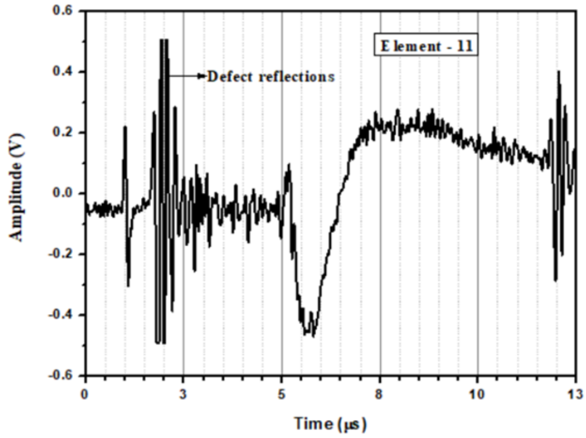
By adjusting the cycle rate and flash delay parameters of the laser, the desired laser spot is focused on the sample via the reflecting mirrors. The sample is placed on the specimen holder of the stepper motor. By moving the stepper motor with a step length of 0.5 mm, a 1D linear array of generation points has been obtained. The ultrasonic waves are generated at each generation point and received at its corresponding detection point. As a result, 41 A-scan data were obtained from the 41 elements linear phased array. The A-scan data obtained from 1^{st}, 11^{th}, 31^{st}, and 41^{st} elements are shown in Figs. 6 (a)-(d).

B. Inspected Images

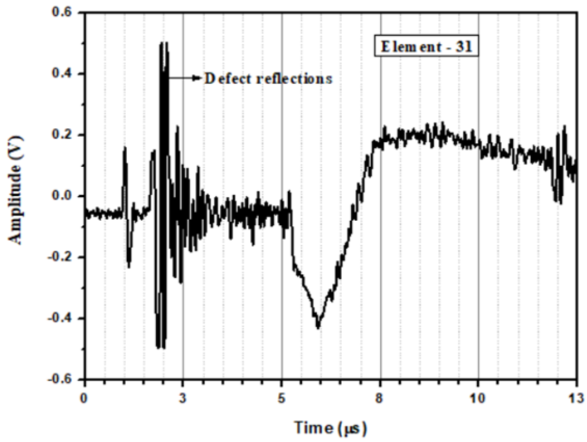
The obtained A-scan data from the linear array are stored in excel file format, serves as the input for the SAFT algorithm. A set of two RGB images with different resolutions are generated by using the SAFT algorithm. Fig. 7 shows the generated image having 121x101 pixels at a resolution of 0.5 mm/pixel and 0.25 mm/pixel on the x and y-axis respectively. The x and y-axis of this image represent the x and z-axis of the specimen. Since the generation and the detection point is separated by 5 mm, the near surface reflection occurs around the 20^{th} pixel (20x0.25 = 5 mm) along the y-axis of the image. This reflection is due to the influence of Rayleigh waves. The defect occurs around 31^{st} pixel multiplied by its resolution gives 7.75 mm which matches with the defect location in the specimen.



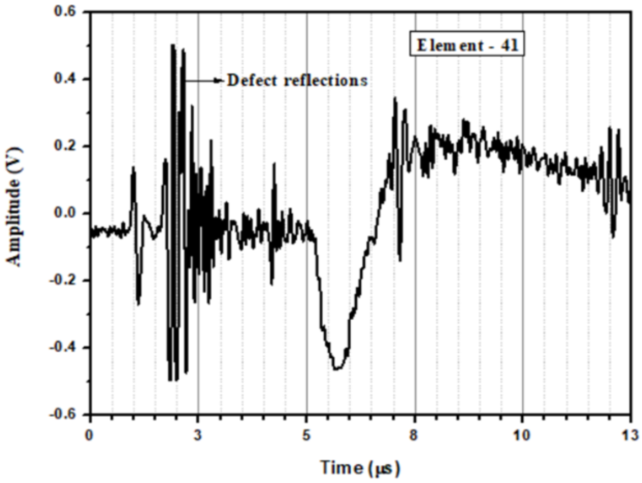
(a) 1^{st} element



(b) 11^{th} element



(c) 31^{st} element



(d) 41st element

Fig. 6 A-scan data received from the linear phased array elements

To clearly visualize the defect with good resolution, another RGB image is obtained by increasing the number of pixels and decreasing the pixel resolution. Fig. 8 represents the inspected image with the pixel resolution of 0.08 mm/pixel along the x-axis and 0.05 mm/pixel along the y-axis and the total number of pixels in the image is 751x501 pixels. Here, the defect is clearly visualized when compared to Fig. 7 and the defect occurs around 153rd pixel (153x0.05 = 7.65 mm), matches with the actual defect location.

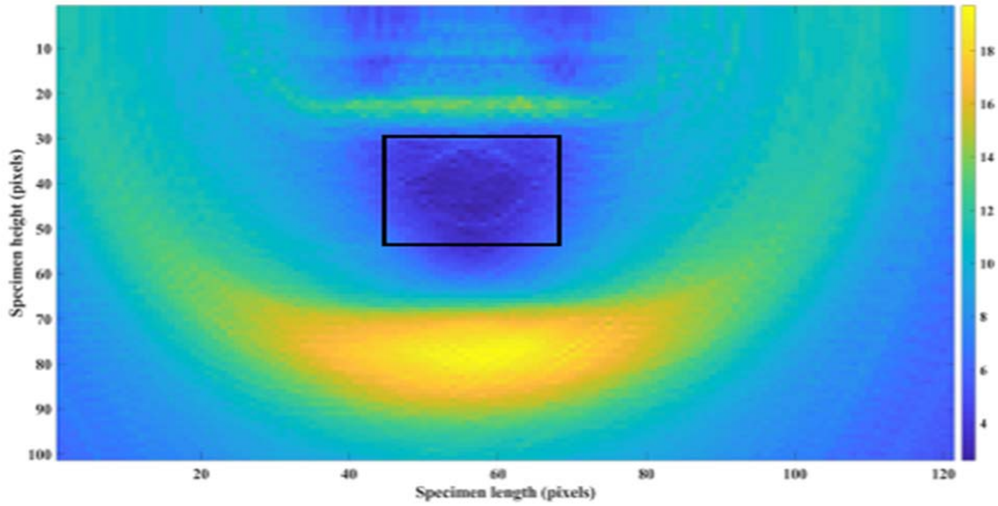


Fig. 7 Inspected image representing the defect with the resolution of 0.5 mm/pixel on the x-axis and 0.25 mm/pixel on the y-axis

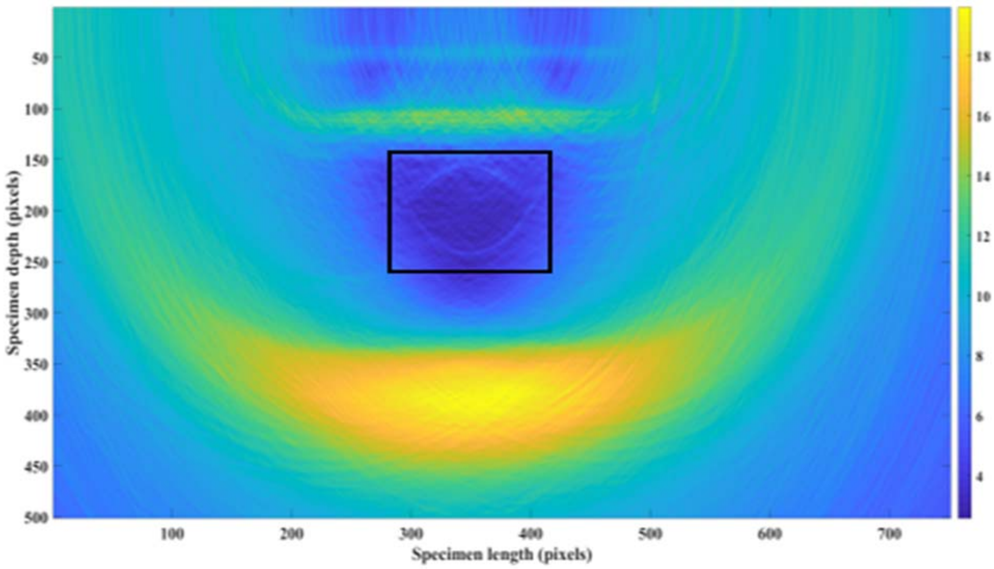


Fig. 8 Inspected image representing the defect with the resolution of 0.08 mm/pixel on the x-axis and 0.05 mm/pixel on the y-axis

VI. Conclusion

This work employs a non-contact way of analyzing the inner defects in aluminum blocks. This non-contact method uses the pulsed laser for generation and the LDV for the reception of ultrasonic waves. A 10 mm diameter hole with 25 mm depth is introduced in the center of the aluminum block and a 41 elements linear phased array is used to examine this hole. The SAFT algorithm has been applied to the data obtained from this array. Thus, the inspection images are generated by using this algorithm and the defect is detected and clearly visualized at different image resolutions.

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