

# Guided-Wave Tomographic Imaging of Plate Defects by Laser-Based Ultrasonic Techniques

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**Abstract** Contact-guided-wave tests are impractical for investigating specimens with limited accessibility and rough surfaces or complex geometric features. A non-contact setup with a laser-ultrasonic transmitter and receiver is quite attractive for guided-wave inspection. In the present work, we developed a non-contact guided-wave tomography technique using the laser-ultrasonic technique in a plate. A method for Lamb-wave generation and detection in an aluminum plate with a pulsed laser-ultrasonic transmitter and Michelson-interferometer receiver was developed. The defect shape and area in the images obtained using laser scanning, showed good agreement with the actual defect. The proposed approach can be used as a non-contact online inspection and monitoring technique.

**Keywords:** Guided Wave, Non-Contact Guided Wave, Tomography, Laser Ultrasonics

## 1. Introduction

Ultrasonic guided wave technique has received a great deal of attention as an important tool for nondestructive testing (NDT). This is mainly attributed to the capacity of the waves to travel long distances without substantial attenuation. This advantage of the guided wave approach provides the possibility to inspect inaccessible or hidden areas [1,2]. The waves can propagate over considerable distances without point-by-point scanning, and the wave propagation interacts throughout the entire thickness of the structure, which means that it not only find surface defects, but also internal defects [3-5].

Another remarkable progress in guided wave NDT is its imaging potential in hidden or inaccessible damage zones. One of the most effective ways to quantitatively monitor a structure is to obtain an image either via scanning or tomography. There have been many different tomographic schemes, and some of the

most well-known methods are the time-of-arrival imaging method, the time difference of arrival imaging method, the energy arrival method, and the reconstruction algorithm for the probabilistic inspection of damage (RAPID) method [6,7]. RAPID is apt for efficient implementation with ultrasonic guided wave features. A major advantage of the RAPID algorithm is the simplicity of the data interpretation, in that the wave diffraction is accounted for only on the line of the propagation path with the linear interpolation of the defect location probability distribution based on the distance from the on-line wave propagation path.

Tomographic imaging of plate structures using Lamb waves is often desired when the test area is not directly accessible and must be probed from outside the area. However, most of the related works were done with contact-based techniques such as immersion transducers and conventional piezoelectric sensors [8]. These techniques need constant coupling conditions,

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which are essential for reliability with these techniques. In addition, when the surface of the object is rough or geometrically complicated, the contact-based technique becomes impractical due to limited accessibility. Consequently, the coupling condition can significantly affect the quality of the data in the image reconstruction, leading to poor spatial resolution. Another limitation with contact-based techniques is encountered in harsh inspection environments with high temperature. Online monitoring for moving objects is another challenging task with contact-based techniques. As such, a robust non-contact-based tomography technique has been in high demand.

Laser ultrasonic testing(LUT) is a remote, non-contact ultrasonic testing(UT) method. It uses laser sources to generate and detect high-frequency ultrasound. LUT is fast and effective on rough surfaces. It is ideally suited for many applications that are beyond the capabilities of conventional ultrasonic testing. High-resolution inspection of small parts and fast areal scans of large components or structures are the key advantages of LUT. Laser ultrasonic tomographic systems using the amplitudes of ultrasound for tomographic reconstruction need to take into account the high degree of variability in the generated ultrasound arising from variation in the thermal absorption at different locations on the plate.

The aim of the present work is to develop a non-contact guided-wave tomography technique by a laser ultrasonic method in a plate. A method for Lamb wave generation and detection in an aluminum plate with a pulse laser ultrasonic transmitter and a Michelson interferometer receiver has been developed. An image of a defect shape and area was obtained by laser scanning, and showed good agreement with the actual defect. The proposed approach can be used as a non-contact-based online inspection and monitoring scheme.

## 2. Tomography Algorithm

The probabilistic approach known as the Reconstruction Algorithm for Probabilistic Inspection of Damage consists of signal comparison and image reconstruction. The signal comparison part is based on a damage index known as the signal difference coefficient (SDC), which is a measure of how statistically different the current signal is from a reference or baseline signal. Damage indexes for all transducer pairs are spatially distributed and summed to generate an image of the damaged area [6].

The first step of this algorithm is the computation of the signal difference coefficient between the signal  $x_{ij}(t)$  and the baseline  $y_{ij}(t)$ , which is the drop in the correlation coefficient over a specified time window. The index  $i$  denotes the transmitter, and  $j$  is the receiver. Mathematically, the SDC is represented as follows:

$$SDC_{ij} = 1 - \frac{\int_{t_0}^{t_0+\Delta T} [x_{ij}(t) - \mu][y_{ij}(t) - \mu] dt}{\sqrt{\int_{t_0}^{t_0+\Delta T} [x_{ij}(t) - \mu]^2 dt \int_{t_0}^{t_0+\Delta T} [y_{ij}(t) - \mu]^2 dt}} \quad (1)$$

The time  $t_0$  is the direct arrival time for each transducer pair,  $\mu$  is the mean of the corresponding signal, and  $\Delta t$  is a time window. If the signals are identical, the SDC is zero, and if the signals are completely out of phase, the SDC will achieve its maximum value of 1.

After the SDC value for all sensor pairs are calculated, the RAPID algorithm carries out the image reconstruction. Images are generated by spatially distributing each SDC value on the image plane in an elliptical pattern, where the two foci of the ellipse are the two transducer locations. A parameter  $\gamma$  controls the size of the ellipse, and its amplitude tapers from its maximum value along the line connecting the

ellipse foci to zero on the periphery of the ellipse. The parameter  $\gamma$  is the shape factor that controls the size of the elliptical distribution and is greater than 1.0. The spatial distribution function in which SDC values will distribute in the final step of the algorithm is defined as:

$$S_{ij}(x,y) = \frac{\gamma - R_{ij}(x,y)}{1-\gamma} \text{ for } \gamma > R_{ij}(x,y) \quad (2)$$

$$S_{ij}(x,y) = 0, \text{ otherwise.}$$

$R_{ij}(x,y)$  is the ratio of the sum of distances of the point  $(x,y)$  to the transmitter  $i$  and receiver  $j$  to the distance between the transmitter and receiver, and it is mathematically stated as:

$$R_{ij}(x,y) = \frac{\sqrt{(x_i-x)^2 + (y_i-y)^2} + \sqrt{(x_j-x)^2 + (y_j-y)^2}}{\sqrt{(x_i-x_j)^2 + (y_i-y_j)^2}} \quad (3)$$

However, if the approximate distance of the defect zone on the transmitter-receiver pair is known,  $\gamma$  can be calculated using equation (3). If all of the distances of the defect range are the same on all of the transmitter-receiver pairs, the  $\gamma$  parameter is a uniform number. However, the distances of the defect range are not equal to those of the transmitter-receiver pairs, so the value of  $\gamma$  will vary. The shape factor  $\gamma$  is related to the transmitter-receiver pairs, so equation (2) has to be changed as follows:

$$S_{ij}(x,y) = \frac{\gamma_N - R_{ij}(x,y)}{1-\gamma_N} \text{ for } \gamma_N > R_{ij}(x,y) \quad (4)$$

$$S_{ij}(x,y) = 0, \text{ otherwise.}$$

$N$  is the total number of transmitter-receiver pairs. Finally, the image amplitude at each pixel is the linear summation of the location probabilities from each transmitter-receiver pair  $S_{ij}(x,y)$  with the total number of transmitter-receiver pairs given by  $N$ :

$$P(x,y) = \sum_{i=1}^{N-1} \sum_{j=i+1}^N SDC_{ij} S_{ij}(x,y) \quad (5)$$

### 3. Information of Specimen and Experimental Set-Up

#### 3.1 Samples

The specimens under investigation are aluminum plates. The thickness of the specimen is 1.0 mm, and its area is 150 mm × 300 mm. There are two specimens with different shape of cracks in this study, as shown in Fig. 1, where the laser scanning area is also illustrated. To make sure that the laser-generated signal propagates through the whole area of 65 mm × 65 mm, wave signals were generated from two sides of the specimen. Fig. 2 shows the sensor network. Scanning length is 8 mm along X and Y axis.

#### 3.2 Calibration of Laser Experimental Set-Up

A wavelength of 1064 nm from a fiberized Nd:YAG pulse laser system was used to generate guided waves, while the pulse laser system emits pulses of energy. On the laser

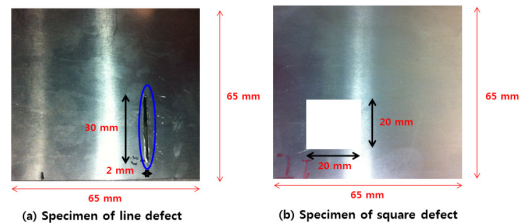


Fig. 1 Schematic of laser scanning area and specimen (a) and (b)

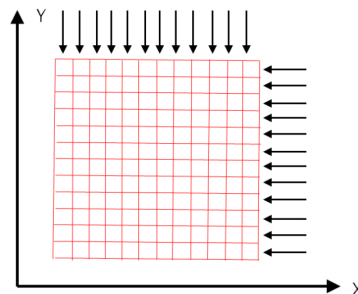


Fig. 2 Schematic of laser scanning direction

side, the slit array is utilized to achieve the linearly arrayed light illumination that acts as the line array source of ultrasonic Lamb waves on the surface of the target. This arrayed-line source type, also referred as the wavelength matching method, is intended to generate a single wavelength of Lamb waves with a narrow bandwidth. The beam of the laser illuminates an arrayed line slit, and the transmitted beam acts as a line source on the plates. The spacing of the array coincides with the wavelength of the specific Lamb wave that will be generated. Therefore, the specific mode of the Lamb wave generated can be selected by simply changing the slit spacing. Selection of the desired mode is performed by drawing a straight line that represents the wavelength on the typical dispersion curves for the phase velocity  $c_p$ , which contains a number of guided wave modes. The relation between the wavelength, frequency  $f$ , phase velocity  $c_p$ , waveguide thickness  $h$ , and slit spacing array  $\Delta s$  is stated as:

$$c_p = f\lambda = f\Delta s = fh \frac{\Delta s}{h} \quad (6)$$

From Eq. (6), the diagonal line with a slope of  $\Delta s/h$  shown in the typical dispersion curve in Fig. 3. The active modes of guided waves are determined at the cross-point of this diagonal line with the dispersion curve. From Fig. 3, it is clear that various modes with different frequencies can be generated simultaneously.

A Michelson interferometer system is used in this work to detect the guided-wave signal propagation in the specimen, as shown in Fig. 4. The surface displacement of the sample due to ultrasonic motion will lead to a change of the optical path difference between the two arms of the interferometer, which leads to a change in the interference fringes. A calibration of the interferometer is required for decoding the surface displacement of the sample from the voltage waveform obtained through the photo-

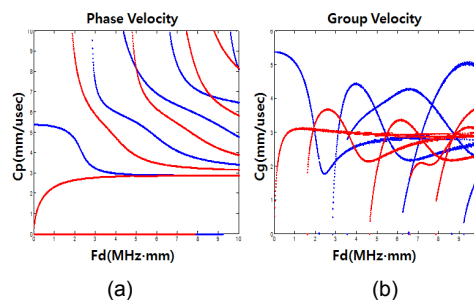


Fig. 3 (a) Phase velocity and (b) group velocity dispersion curve of the specimen

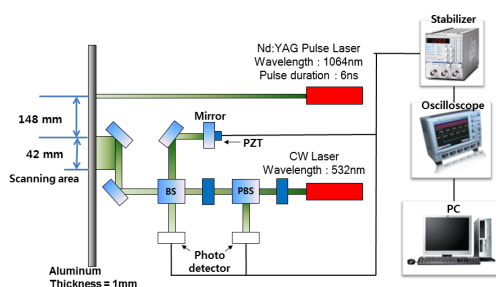


Fig. 4 Experimental setup of laser-based guided-wave technique

detector. By using a photo-detector to convert the time-varying light information into the voltage waveforms, one can calculate the surface displacement. In the present work, a CW Nd:YAG laser (CL-1001 diode-pumped crystal laser, Crystal Laser) with a power of 500 mW and wavelength = 532 nm is used as the optical source. The object uses the surface with smooth tape of the sample to the optical reflections. The reference uses a piezoelectric-controlled mirror with feedback electronics to stabilize against low-frequency noise. To improve the spatial resolution, focusing lenses are used in front of the sample. The photo-detector converts time-varying light information into a voltage waveform, which can be measured and displayed on an oscilloscope.

#### 4. Results and Discussion

A time-velocity analysis was first performed to verify the guided wave modes in the signal

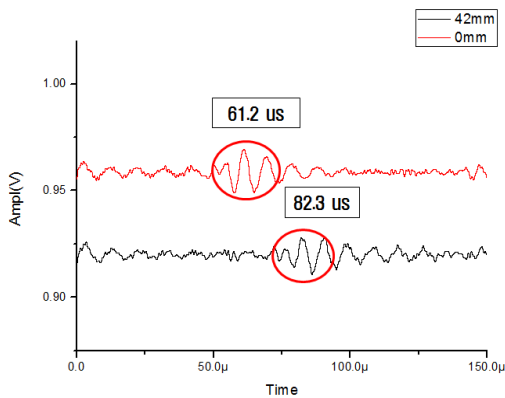


Fig. 5 Group delay measurement to check the guided wave mode

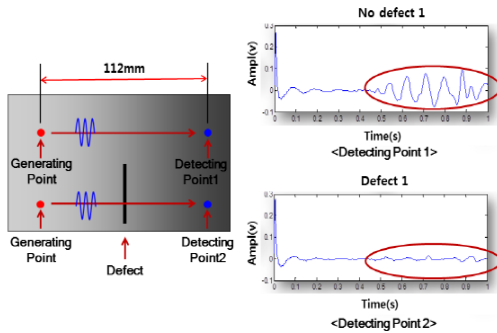


Fig. 6 Example to check the SDC of wave propagation

acquired from the specimen for the non-defect area. The waveform propagation in the specimen with different distances was recorded to check the group velocity of the wave mode, as shown in Fig. 5. The zero-order A0 Lamb mode was generated and detected.

As discussed in section 2, the SDC is the key coefficient for image construction. An example of comparison between the wave signals recorded for the baseline signal (for the defect-free area) and the defect area is shown in Fig. 6. The waveform has one mode present with a good signal-to-noise ratio.

The laser-generated ultrasonic wave signals propagate through the square plate. The wave signal is scanned from two sides of the square as shown in Fig. 7. The SDC calculated based

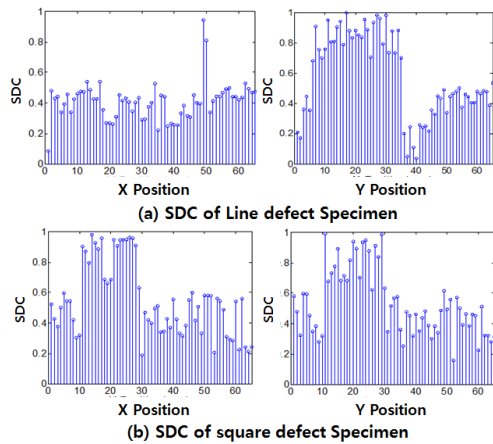


Fig. 7 The SDC values of scanning area for specimen (a) and (b)

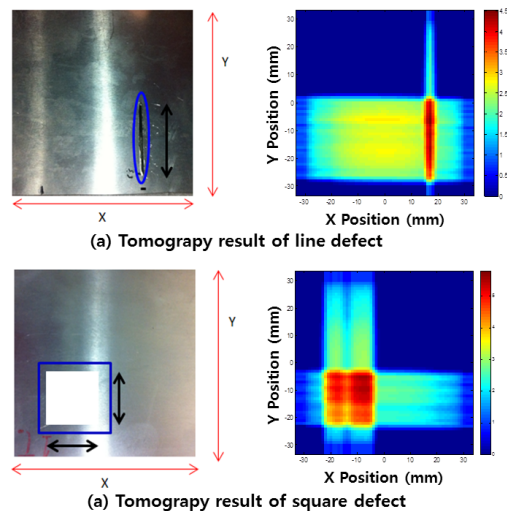


Fig. 8 Imaging reconstruction of specimen (a) and (b) with different shape of defect

on the wave signals scanned from two sides of the square are shown in Fig. 7. It was found that the variations of SDC on the two sides can be used to locate the defect. The shape factors can also be calculated using equations published in earlier work [8]. The image reconstruction result using the laser-based ultrasonic approach is shown in Fig. 8. The image reconstructed by this technique shows similar area and shape to those of the actual defect.

## 5. Conclusion

A non-contact guided-wave tomography technique using a laser ultrasonic method in a plate-like structure was used to find the area and location of a defect. A method for Lamb wave generation and detection in an aluminum plate with a pulse laser ultrasonic transmitter and a Michelson interferometer receiver was developed for guided-wave nondestructive testing. The image of the defect shape and area obtained by laser scanning showed good agreement with the actual defect. The proposed approach can be used as a non-contact-based online inspection and monitoring scheme.

## Acknowledgment

This work was supported by a 2-Year Research Grant of Pusan National University and BK21 (Brain Korea 21) program.

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