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Generation Laser Scanning Method for Visualizing Ultrasonic Waves Propagating on a 3-D Object

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Abstract
For visualizing ultrasonic propagation, we have developed a generation laser scanning method. This method has the following features that make it superior to the conventional visualization methods such as the photo-elasticity method and the reception probe scanning method. (1) It enables us to visualize ultrasonic waves propagating on a complexly shaped object. (2) It makes high-speed imaging possible and enables us to remotely measure images of ultrasonic waves. Using this laser ultrasonic imaging technique, we tried to visualize ultrasonic waves scattered from artificial defects such as corrosion on an inner surface of a pipe elbow and cracks on the backside surface in metal plates. From the measured dynamic images, we could observe the defect echoes as they scatter radially, like water rings, on the surface of the specimen. These results indicate that this method can be utilized for nondestructive inspection of materials.
Keywords: Laser ultrasound, Visualization, Imaging, Nondestructive inspection, defect.

1. Introduction

Ultrasonic inspections have so far been primarily dependent on what are known as "listening technologies" that observe and analyze signal waveforms. However, ultrasonic waves propagating on an actual structure generate complex propagating waveforms due to interference between the many different waves generated by multipath reflections, modal conversions, etc. Such propagating waveforms are so complex that their signals are occasionally misinterpreted even by experts. We consider that if ultrasonic propagation can be easily visualized at the propagation site by using "seeing technologies" rather than "listening technologies", then it would be easy for experts to visualize the way in which ultrasonic waves propagate, which in turn can assist in reducing misidentifications and/or overlooking defects.

Although several methods [1-3] visualizing ultrasonic propagation have been proposed, no method is suitable for complexly-shaped objects. Recently, we developed a method [4-7] that generates thermal-excitation ultrasonic waves on a specimen through pulsed laser scanning and detects the propagating signals via a reception transducer attached at a fixed point. Images of ultrasonic waves propagated from a fixed point are created using the reciprocity principle of sound propagation. The advantage of this method is that the pulsed laser can be directed to any point virtually ignoring the incidence angle and focal length of the laser. The laser beam also provides non-contact scanning, with which we can visualize any object—no matter how complicated its shape. Using this laser ultrasonic imaging technique, we tried to visualize ultrasonic waves scattered from artificial defects such as corrosion on an inner surface of a metal tube and cracks on the rear surface in metal plates. In the measured dynamic images, we can see defect echoes as they scatter radially, like water rings, on the surface of the specimen. These results indicate that this method can be used for nondestructive inspection of materials.

2. Generation laser scanning method for visualizing US propagation

Figure 1 schematically illustrates the generation laser scanning system. In this system, ultrasound signals are generated from the thermal strain induced by a pulsed laser. The laser beam is scanned by a dual angle rotation mirror. The generated ultrasounds are received by ultrasonic transducers attached to the specimen. We can obtain a visualized image of ultrasonic waves propagating from the reception transducer on the assumption that reciprocity of wave propagation is valid between laser transmission and PZT reception. As depicted in Fig. 2, when ultrasonic waves are detected propagating through a defect between two points using a pair of transmission-reception transducers, the same waveforms are detected if the transmission-reception transducers were switched. This reciprocity concept illustrated in Fig. 3 (a) indicates that ultrasonic measurement with transmission-laser and reception-PZT (Fig.3 (b)), is equivalent to that with transmission-PZT and reception-laser assuming that the reception characteristics of the laser probe are the same as the transmission characteristics of the generation laser. Accordingly, the train of waveforms detected by the reception-PZT transducer at a fixed position when a generation laser is scanned will be the same as the train of waveforms detected by scanning the reception laser when ultrasonic waves are generated with the transmission-PZT at a fixed position.

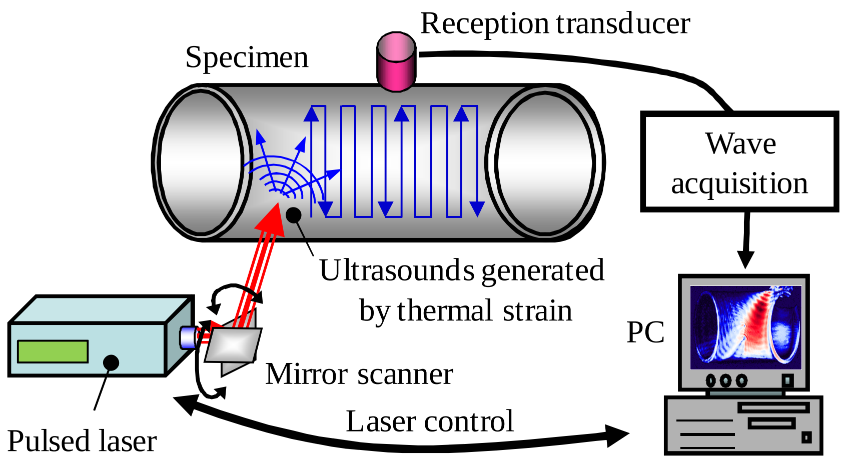


Figure 1. Schematic of the generation laser scanning method

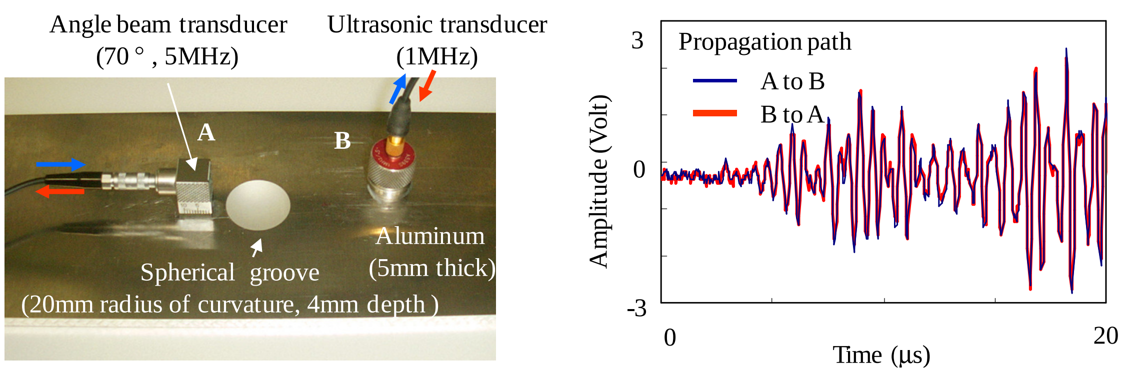


Figure 2. Reciprocity of wave propagation between transmission and reception PZT transducers.

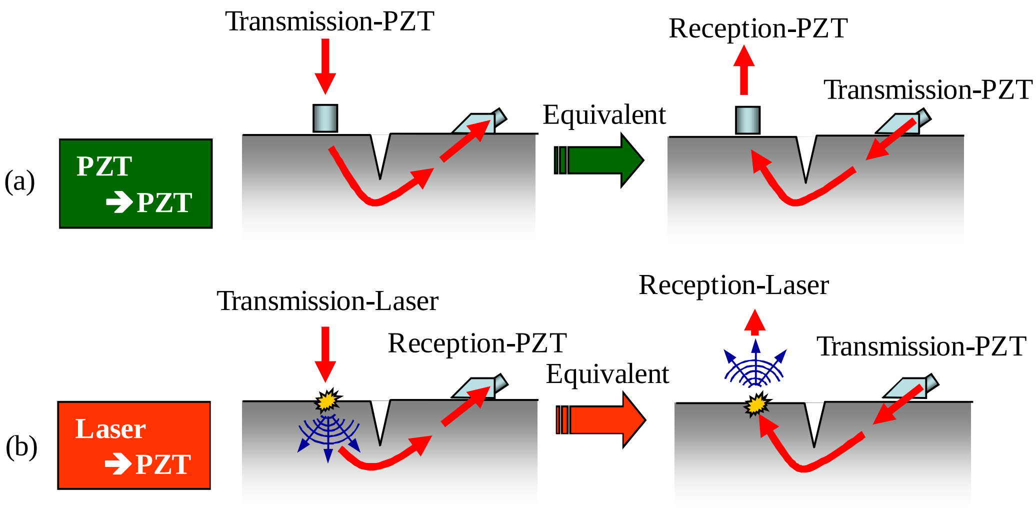


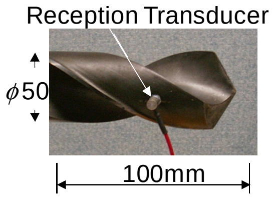
Figure 3. Reciprocity of wave propagation between generation laser and reception transducer

Therefore, dynamic images of ultrasonic propagation from a fixed point may be created by making a time series contour map of the displacement of the detected waves. This method does not require arranging the focal length and incidence angle of the laser beam, so we can visualize ultrasonic propagation for any complexly-shaped object in a short time by using mirror scanning.

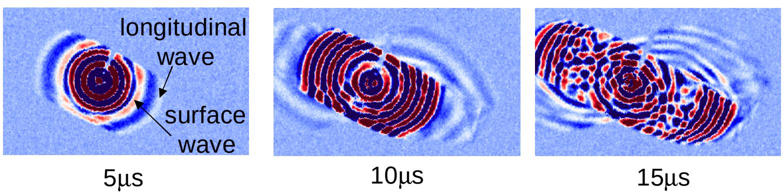
3. Visualization of ultrasonic waves propagating around various objects with defects

3.1 Propagation on a drill blade

Fig. 4 presents an example of visualization of an ultrasonic wave propagating on a drill surface to demonstrate that this technique is applicable to three-dimensional complexly shaped objects. As shown in Fig. 4 (a), a PZT transducer (sensitivity diameter of 4 mm, nominal resonant frequency of 300 kHz) is mounted on the surface of the drill, and a 100 mm × 50 mm area was scanned by laser at intervals of approximately 0.5 mm (beam rotation pitch: 0.025°) to obtain images of the propagation of ultrasonic waves. The laser beam is approximately 1 m in length, and the sampling interval of the detected waveforms is 0.2 µs. The number of sampling points is 500. Figure 4 (b) presents visualized images for each 5 µs of propagation time. Although computer simulation of ultrasonic waves propagating on an object of complex-spiral form would seem difficult, visualization may be accomplished within a short time using the proposed method.



(a) Photograph of a drill

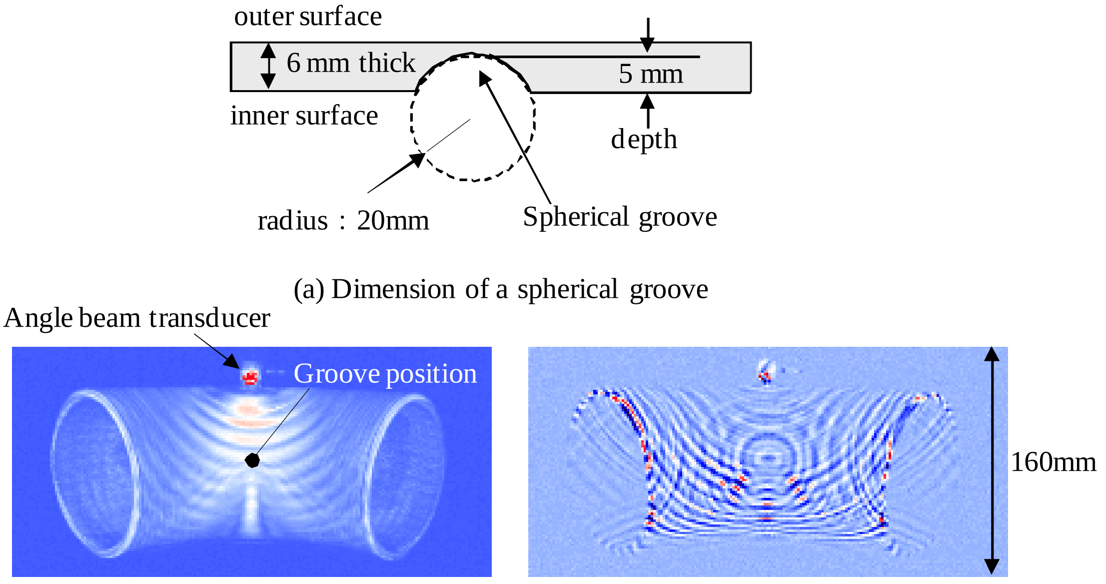


(b) Visualized images

Figure 4. Visualization of an ultrasonic wave propagating on a drill blade.

3.2 Propagation on an elbow-pipe with an artificial corrosion in the rear surface

A stainless steel elbow-pipe joint with an outer diameter of 105 mm and thickness of 6mm was provided. As illustrated in Fig. 5 (a), the spherical groove simulating corrosion in the rear surface was machined by electric discharge machining. An angle beam transducer (45°) with a resonance frequency of 500 kHz was mounted on the outer surface. The laser beam was scanned at 416 × 200 points with a scan pitch of 0.8 mm. Figure 5 (b) depicted the maximum amplitude image of the detected ultrasound signals. We can see the amplitude change at the position of the inner spherical groove. The scattered wave from the spherical groove can be observed from the visualized image of the ultrasonic propagation in Fig 5 (c).



(a) Dimension of a spherical groove

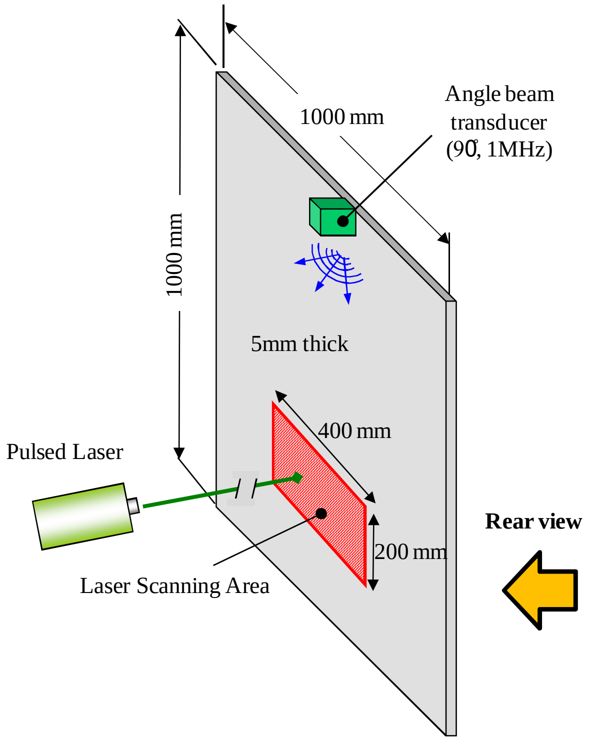
(b) Maximum amplitude image

(c) Propagation image

Figure 5. Ultrasonic propagation image of a stainless steel elbow pipe

3.3 Propagation on an aluminium plate with rear slits

We visualized the wavefield of an aluminum plate with rear slits. Fig. 6 shows the experiment setup. Rear slits with different lengths and depths were machined by electric discharge machining. An angle beam transducer (90°, 1 MHz) was mounted on the surface 800 mm from the slits. The laser beam was scanned at 400 × 200 points with a scan pitch of 1 mm. Fig. 7 presents the visualized wavefield. We can recognize waves scattered from the rear slits. In order to enhance the image of the scattered waves, we performed simple data processing. The principle of the data processing is based on the assumption that near-by waveforms are almost the same. As a result, if we synchronize and subtract the near-by waveforms, then the forward-travelling wave is erased and only the backward echo should be left. Fig. 8 shows the propagation image after data processing in which the scattered waves from rear slits were emphasized. In this Fig, we cannot see the scattered waves from slit-1 or slit2. The reason is not only that the slit is small and the propagation distance is long but also that, since the ultrasonic transducer has directivity, the amplitudes of the ultrasounds arriving at both sides of the slits is small. The maximum amplitude image after data processing is depicted in Fig. 9, in which we can easily detect the scattered waves from the slits with a size over 2 mm.



Slit size

Slit No.	length (mm)	depth (mm)	width (mm)
1.	1	1	0.3
2.	2	1	0.3
3.	4	1	0.3
4.	8	1	0.3
5.	8	2	0.3
6.	4	2	0.3
7.	2	2	0.3

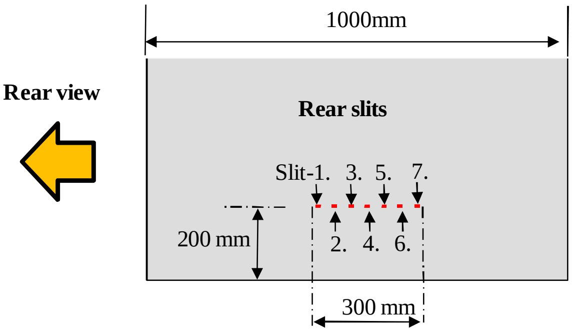


Figure 6. Experimental setup for visualizing ultrasonic waves propagating on an aluminum plate with some slits on its rear surface

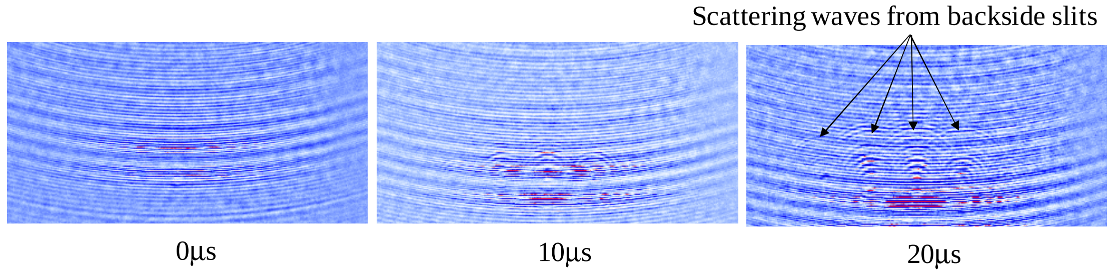


Figure 7. Ultrasonic propagation image of an aluminum plate with rear slits

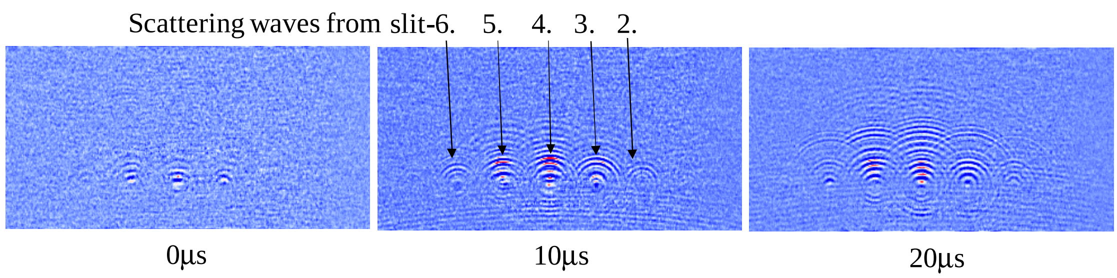
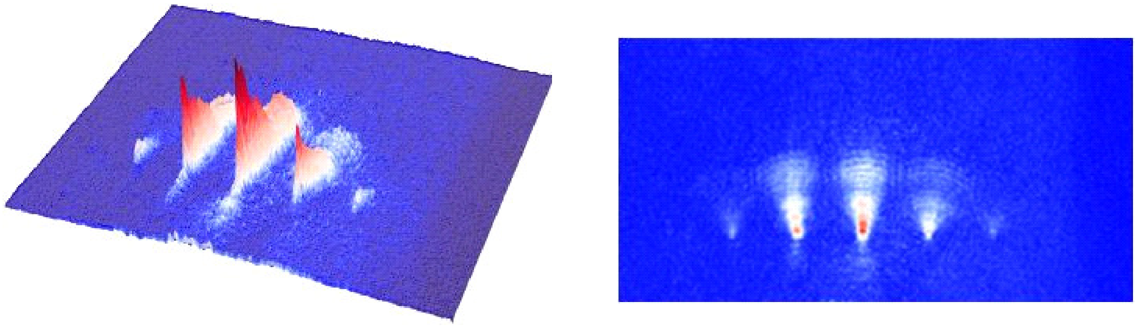


Figure 8. Ultrasonic propagation image of an aluminum plate with rear slits after data processing

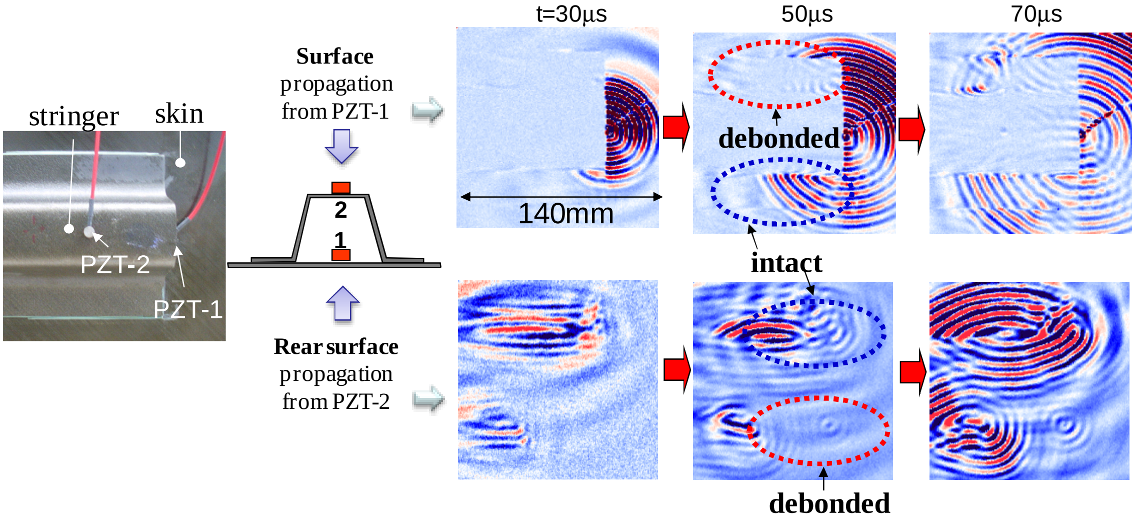


(a) 3-D image (b) 2-D image

Figure 9. Maximum amplitude image of scattered waves from rear slits after data processing

3.4 Propagation on a CFRP skin-stringer structure with a flange disband

We also tried to visualize ultrasonic waves propagating on a CFRP skin-stringer structure. Figure 10 (a) depicts the skin-stringer specimen of an airplane wing. Both the skin and stringer were made of 3mm-thick CFRP quasi-isotropic laminated plate. The bonded corner section between them was debonded using a chisel and hammer (indicated by the red circle in the figure), and the difference in ultrasonic propagation between the intact section and debonded section was visualized. High-sensitivity PZT transducers (nominal frequency 300 kHz) were mounted at two positions, i.e., the surface of the stringer and on the skin, as depicted in Fig. 10 (a). The image of ultrasonic propagation on the rear surface (bottom of Fig. 10 (b)) is inverted from the image of ultrasonic propagation on the surface shown at the top. These ultrasonic propagation images should be vertically symmetric if there is no debonding. However, the visualized images are obviously asymmetric, so debonded sections in the skin-stringer structure can be detected just by detecting this asymmetry. The amplitudes of ultrasonic waves passing through the debonded section are considerably lower than those in the intact section because the air layer produced by debonding makes it difficult for ultrasonic waves to propagate.



(a) Positions of PZT transducers (b) Visualize images

Figure 10. Ultrasonic propagation around debonding area of the CFRP skin-stringer structure.

These results indicate that this visualization technique is useful for the non-destructive inspection of structures.

4. Conclusions

We have developed a measurement system that generates thermal-excitation ultrasonic signals on a specimen through pulsed laser scanning, and detects the propagation signals via a reception transducer attached at a fixed point. The ultrasonic signals propagated from the fixed point are visualized as a dynamic image using the reciprocity principle of sound propagation. The advantage of this method is that the pulsed laser can be directed to any point virtually ignoring the incidence angle and focal length of the laser. This method will facilitate the inspection of pipe elbows, welded joints, narrow areas and other parts that have conventionally been hard to inspect. We will be happy if this technique can contribute to establishing inspection techniques that visualize defects and yield an easy-to-understand, reliable inspection method that enables the precise identification of defects.

Acknowledgements

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