Laser Ultrasonic Technique for Visualizing Ultrasonic Waves Propagating on 3-D Object

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Abstract

If it were possible to perform ultrasonic inspections while observing the propagation of ultrasonic waves as dynamic images, the identification of defect echoes would become easier, and inspection, quicker. Furthermore, fewer defects would be overlooked or improperly identified, leading to higher-reliability inspections. For visualizing ultrasonic propagation, we have developed a generation laser scanning method with a pulsed laser. 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: Ultrasound, Laser, Visualization, Imaging, Defect

1. Introduction

In the field of ultrasonic flaw detection, it is common to inspect defects by observation and analysis of detected waveforms. However, in areas with complex shapes, reflected waves, diffracted waves, and mode-converted waves interfere with each other, making it difficult for even an expert inspector to accurately distinguish the echoes from a defect. If it were possible to perform ultrasonic inspections while observing the propagation of ultrasonic waves as dynamic images, the identification of defect echoes would become easier, making inspections quicker. Furthermore, fewer defects would be overlooked or improperly identified, leading to higher-reliability inspections. Although some method [1-3] visualizing ultrasonic propagation have been proposed, no method is suitable for complexly-shaped objects. Recently, we developed a method [4] 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 pipe elbow and cracks on the rear surface in metal plates. In the measured dynamic images, we could observe 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.

2. Generation Laser Scanning Method

Figure 1 schematically illustrates the generation laser scanning method. In this method, ultrasound signals are generated from the thermal strain induced by a pulsed

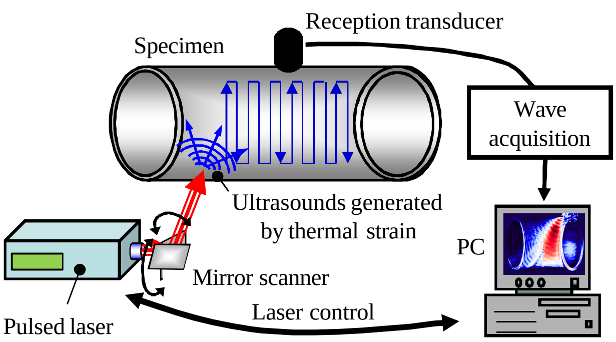


Figure 1. Schematic of the generation laser scanning method

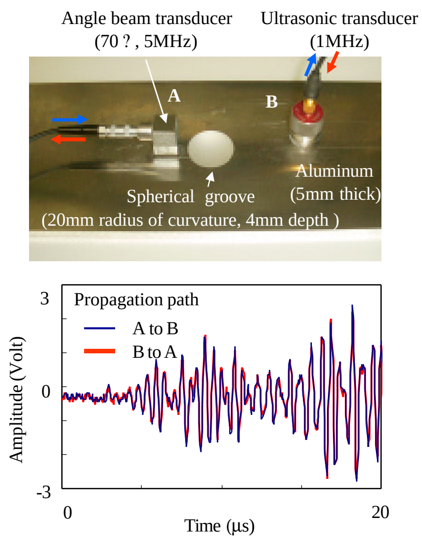


Figure 2. Reciprocity of wave propagation between transmission and reception PZT transducers.

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

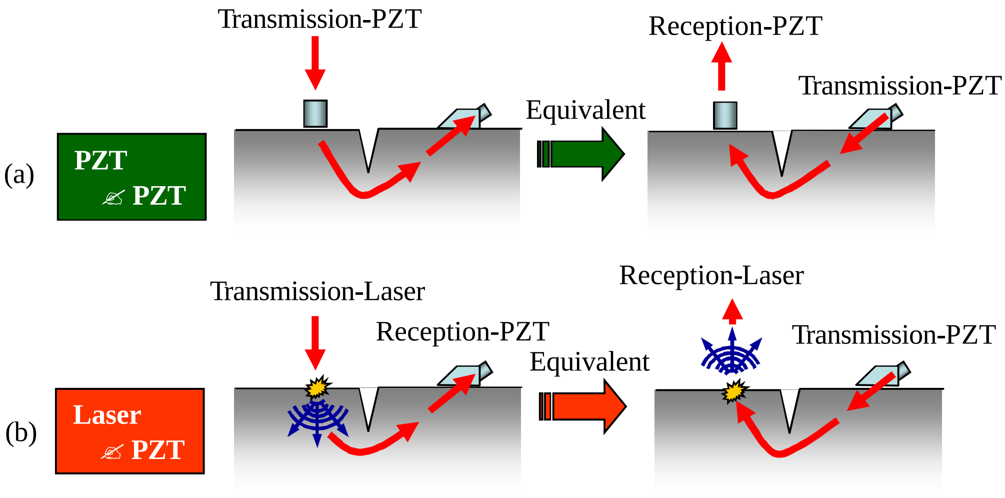


Figure 3. Reciprocity of wave propagation between generation laser and reception transducer

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 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 PZT sensor with the irradiating laser beam in a fixed position. 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. Effect of measurement conditions on the visualized image

3.1 Effect of beam incidence angle

We examined the effect of the laser incidence angle on the amplitude of generated ultrasound signals. As depicted in Fig. 4, laser beams were irradiated at the center of an aluminum plate with different incidence angles ?, and the generated ultrasound signals were detected by an angle beam transducer (90 ?, 1 MHz) mounted 100 mm from the laser shot point while varying position angle ?. Figure 4 presents the relationship between the laser incidence angle and the amplitude of the generated ultrasound signals. This result indicates that if a laser beam is scanned at an incidence angle less than 30 ?, ultrasound signals are generated with almost the same amplitude.

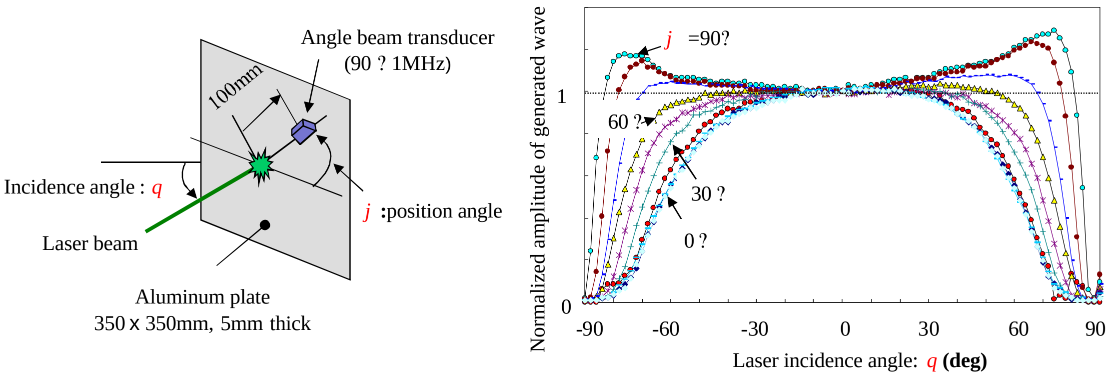


Figure 4. Effect of beam incidence angle on the amplitude of generated ultrasonic wave

3.2 Effect of laser scan pitches

Figure 5 presents the relationship between the laser scan pitch and the visualized images of ultrasound propagating around a 4-mm-long pass-through slit on an aluminum plate 350 mm ? 350 mm square and 2 mm thick. When the laser was scanned with a pitch above 2 mm, the obtained images were not focused, suggesting that it is necessary to select a scan pitch sufficiently less than the wavelength of the generated ultrasound signal (in Fig.5, the wave length of the surface wave was around 3mm).

3.3 Effect of laser scanning speed

We also examined the relationship between the laser scanning speed and the visualized image. Figure 6 (a) depicts waveforms detected at point A in Fig. 6 (b) with scanning speeds of 100 Hz and 1000 Hz. As can be seen from Fig. 6 (a), the detected wave with 1000 Hz scanning was noisy because of the reverberation due to high repetition of the generation of ultrasound signals. This reverberation causes the spotted pattern in the background of the visualized image.

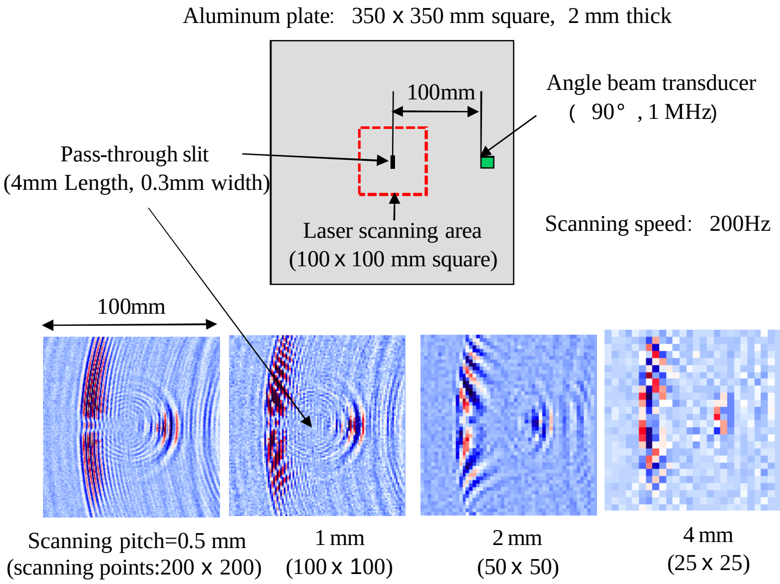
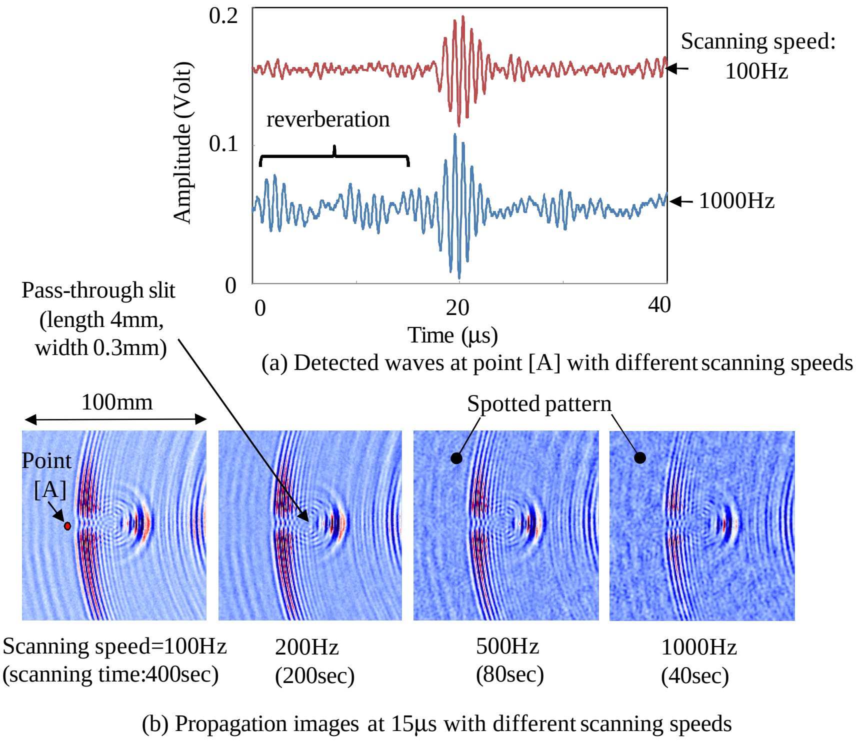
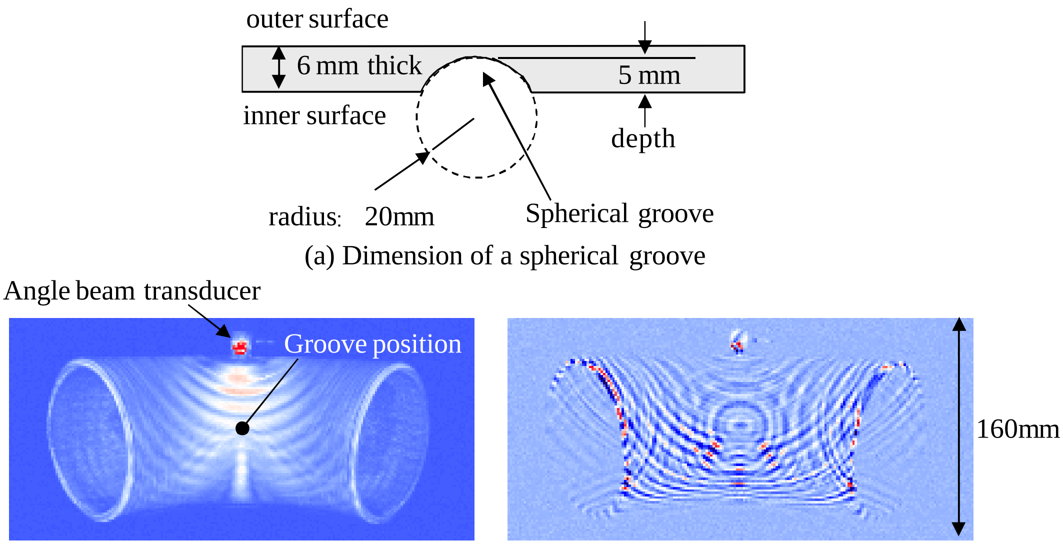


Figure 5. Relationship between scanning pitch and visualized image



4. Visualization of ultrasonic waves propagating around various defects

Figure 6. Relationship between scanning speed and visualized image



(a) Dimension of a spherical groove

(b) Maximum amplitude image

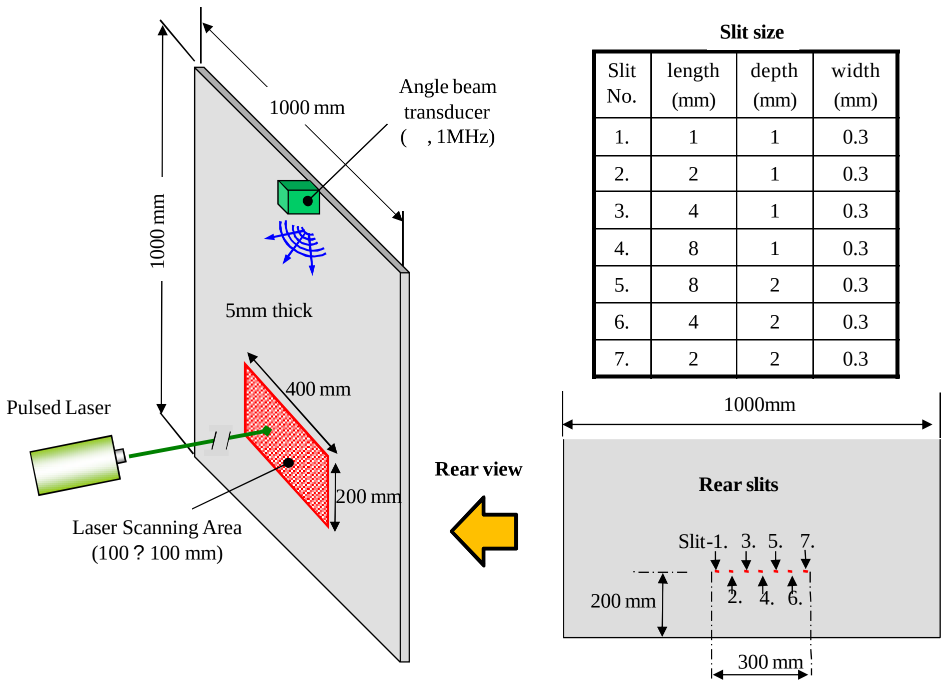
(c) Propagation image

Figure 7. Ultrasonic propagation image of a stainless steel elbow pipe

A stainless steel elbow-pipe joint with an outer diameter of 150 mm and thickness of 6mm was considered to demonstrate the capability of this wavefield propagation imaging system for a curved surface. As illustrated in Fig. 7 (a), the spherical groove simulating corrosion in the inner 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 7 (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 7 (c).

We also visualized the wavefield of an aluminum plate with rear slits. Figure 8 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. Figure 9 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-traveling wave is erased and only the backward echo should be left. Figure 10 shows the propagation image after data processing in which the scattered waves from rear slits were emphasized. In this figure, 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 become small. The maximum amplitude image after data processing is depicted in Fig. 11, in which we can easily detect the scattered waves from the slits with a size over 2 mm. These results indicate that this visualization technique is useful for the nondestructive inspection of structures.

Figure 8. Experimental setup for visualizing ultrasonic waves propagating on an aluminum plate with some slits on its rear surface



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

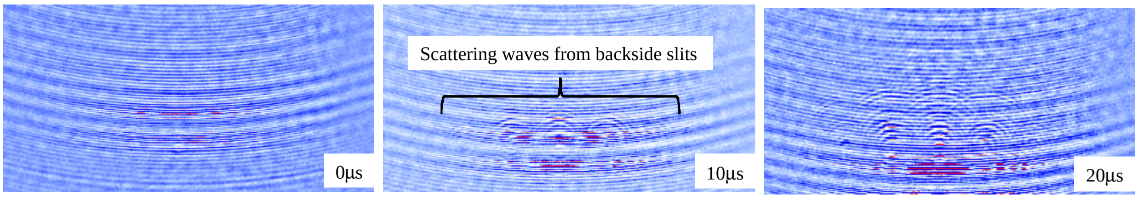


Figure 9. Ultrasonic propagation image of an aluminum plate with rear slits

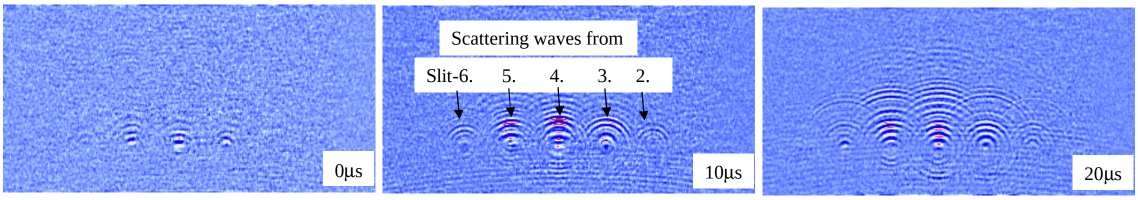
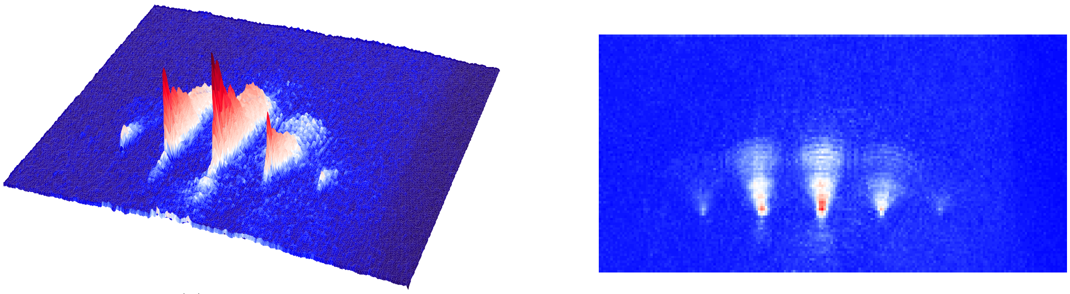


Figure 10. Ultrasonic propagation image of an aluminum plate with rear slits after data processing



(a) 3-D image

(b) 2-D image

Figure 11. Maximum amplitude image of scattered waves from rear slits after data processing

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, even in a minor way, to establishing inspection techniques that visualize defects and yield an easy-to-understand, reliable inspection method that enables the precise identification of defects.

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