Flaw Inspection of Aluminum Pipes by Non-Contact Visualization of Circumferential Guided Waves using Laser Ultrasound Generation and an Air-Coupled Sensor

K Urabe¹, J Takatsubo², N Toyama¹, T Yamamoto¹ and H Tsuda¹

¹ National Institute of Advanced Science and Technology, 1-1-1 Umezono, Tsukuba 305-8568, Japan
² Tsukuba Technology Co., Ltd., Plaza214, 2-1-6 Sengen, Tsukuba 305-0047, Japan

E-mail: urabe-k@aist.go.jp

Abstract. Our group had previously proposed a generation laser scanning system for visualizing ultrasound propagation on an object as an animate image, which provided visible and quick flaw inspection. Recently, we improved this system to make it completely non-contact by employing an air-coupled ultrasound transducer as a receiver instead of a contact transducer, and demonstrated the successful visualization of Lamb waves propagating on aluminum and carbon fiber reinforced plastic plates, as well as the detection of flaws. In this research, we applied this system to the non-contact visualization of circumferential guided waves on aluminum pipes. It was shown that circumferential guided waves propagating in opposite directions could be visualized separately, and that a flaw such as a slit or thinning on the inside surface of the pipe could be successfully detected even when it existed outside the scanning area.

1. Introduction

Our group had previously proposed a generation laser scanning system for visualizing ultrasound propagation on an object as an animate image, for the purpose of realizing “simple,” “quick,” “easy to understand,” and “non-contact” ultrasound non-destructive inspections [1][2]. Recently, we improved this system to make it completely non-contact by employing an air-coupled ultrasound transducer as a receiver, instead of the conventionally used contact piezoelectric transducer [3][4]. Using this non-contact ultrasound visualization system, we demonstrated the successful visualization of Lamb waves propagating on plate-shaped specimens. From the visualized images, flaws such as delamination or lack of fiber in carbon fiber reinforced plastics and slits or thinning on the backside of aluminum plates could be detected.

In this research, we investigated an application of this system to the non-contact visualization of circumferential guided waves, which are guided waves propagating in the circumferential direction, on pipes, with the aim of inspecting for flaws on the inner side of the pipes. The possibility of inspecting the entire circumference is an advantage of the non-destructive inspection of a pipe using circumferential guided waves [5]. The possibility of using a higher frequency compared to guided waves propagating in the axial direction, which would provide a higher sensitivity to small defects, has also been pointed out as an advantage [5]. Several studies have been conducted on the non-contact generation and detection of circumferential guided waves and improvements in the received signal amplitude, with the purpose of non-contact inspections for the thinning of pipes [6][7].

Published under licence by IOP Publishing Ltd
2. Experimental setup

The experimental setup is shown in figure 1. A pulsed laser beam was irradiated from the side of the pipe, and a wide-band ultrasound signal was generated at the irradiated point of the pipe by thermal strain. From the generated ultrasound, circumferential guided waves were received by the air-coupled transducer, which was placed above the pipe. The irradiated point was scanned with a fixed pitch in the circumferential direction on the pipe using a mirror scanner, and the pipe was moved in the axial direction with a fixed pitch. Thus, a two-dimensional area of the pipe was scanned by the laser beam. The received signal for each irradiated point was amplified, filtered, and recorded by the computer. Subsequently, the received ultrasound signals were rearranged to form a two-dimensional contour map of the received amplitudes corresponding to the irradiated (generated) points, for each time. When showing the maps represented as color or brilliance images continuously in order of time, the sequence appeared to show an animation of the ultrasound propagation, generated by the air-coupled transducer and propagating in the circumferential direction in the scanned area, because of the reversibility of the ultrasound propagation [1][2]. For a pipe specimen, the receiving angle could be adjusted to the critical angle of the guided wave by adjusting the receiving position above the pipe, as shown in figure 2, so as to obtain a high amplitude for the received signal and to select the mode and propagating direction of the wave to be received [6]. The use of a line-focus-type transducer has been proposed to maintain a constant receiving angle for the transducer and thus obtain a higher level for the received signal [7]. To receive the circumferential guided wave at the critical angle, the transducer was better to be flat along the axial direction of the pipe, rather than a point-focus-type one where the receiving angle varies in the axial direction and directivity for the guided wave was lower [3]. Therefore, we used a line-focus-type transducer (Japan Probe Co., Type 0.4 or 0.8K20×20N R90, for 400 or 800 kHz band respectively) with a size of 20 × 20 mm and a 90-mm radius of curvature, and adjusted its position above the pipe (the horizontal and vertical directions shown in figure 2) so as to obtain the maximum amplitude for the received signal. Other experimental conditions are indicated in figure 1, and also in the figure captions in the next section. The gain of the receiver was regulated so that the maximum signal level was ±2.0 V after amplification, and the total gain (dB) is noted in the figure captions of the visualized images. A smaller value for the total gain means a larger level for the received signal. The frequency of the visualized ultrasound was 340 kHz or 700 kHz, where the highest sensitivity was obtained for each transducer. As specimens, aluminum alloy pipes with a diameter of 100 mm, thickness of 5 mm, length of 1 m, and artificial flaws on the inside surface were used.

![Figure 1. Experimental setup.](image)

![Figure 2. Adjustment of receiving position (receiving angle) and direction of guided wave to be visualized.](image)
3. Results and discussion

Figure 3 shows propagation images of the circumferential guided waves on an aluminum pipe with 3-mm-deep spherical thinning on the inside surface at 340 kHz. The air-coupled transducer was set at 6.0 mm to the right side from just above the pipe axis in figure 3(a), whereas it was set at 6.6 mm to the left side in figure 3(b). Therefore, the propagating directions of the visualized waves were opposite to each other. The time (μs) on each image indicates the time that had passed since the irradiation of the laser beam, which equivalently corresponds, on the image, to the passage of time from the generation of the ultrasound wave at the transducer. As shown in the left and the middle images of figure 3(a), the thinning caused a phase delay when the wave passed it. After some interval, the 2nd round wave appeared as shown in the right image, where the effect of the thinning that was passed in the 1st round appears. Hence, as can be seen in figure 3(b), even if the thinning was not in the scanned (visualized) area, it could be detected as a phase change in the wave in the image, as long as it existed in the propagation area for the circumferential guided wave. The receiving angle values given in each figure caption were derived from the position of the transducer (see figure 2), and they were generally close to the critical angle of Lamb wave of A₀ mode for a 5-mm-thick aluminum plate [3].

![Figure 3](image)

**Figure 3.** Propagation images of circumferential guided waves on aluminum pipe with spherical thinning on inner side. The shape and size of thinning are illustrated in the right figure. Scanning pitch = 0.5 (vertical) \times 1 (horizontal) mm.

(a) Position of the thinning is indicated by the dotted line. Receiving angle = 6.9°. Gain = 102 dB. Lift-off = 11.5 mm.

(b) The thinning exists out of the scanned area (opposite side). Receiving angle = 7.6°. Gain = 106 dB. Lift-off = 13.0 mm.

![Figure 4](image)

**Figure 4.** Propagation images, after eliminating forward travelling wave, of circumferential guided waves on an aluminum pipe with slit (4 mm long, 1 mm deep, and 0.3 mm wide) on inner side. Scanning pitch = 0.5 (vertical) \times 1 (horizontal) mm.

(a) Position of the slit (center) is indicated by the arrow. Receiving angle = 6.2°. Gain = 96 dB. Lift-off = 21.5 mm.

(b) The slit exists outside the scanned area (bottom). Receiving angle = 6.7°. Gain = 100 dB. Lift-off = 21.0 mm.
Figure 4 shows images at 700 kHz for a pipe with a 4-mm-long and 1-mm-deep slit on the inside surface. The images are those after eliminating the forward travelling wave using the synchronizing differential method [8], so as to emphasize the reflected or scattered wave caused by the slit. In addition to the slit in the scanned area (figure 4(a)), a slit that existed outside the scanned area (figure 4(b)) was clearly detected. Figure 5 shows propagation images when a 4-mm-long and 2-mm-deep slit was parallel to the propagating direction of the wave. Although it is unclear compared with a slit that was perpendicular to the propagating direction, the wave reflected from the slit was observed.

4. Conclusion
We have shown the non-contact visualization of circumferential guided waves propagating on an aluminum pipe, using generation laser scanning and an air-coupled transducer as a receiver. The propagating direction of the wave to be visualized could easily be selected by adjusting the position of the air-coupled transducer. The propagation of the circumferential wave was successfully visualized as clear images, and flaws such as thinning or a slit on the inside surface of the pipe could easily be detected as a phase change, scattering, or reflection of the propagating wave from the image, even when the flaw was outside the scanned area. The elimination of the forward travelling wave was effective for detecting a slit.

Further research and developments is necessary to apply this system to other materials with various thicknesses and structures with more complicated shapes. Appropriate frequency and mode of the visualized wave, and the conditions for the laser irradiation are important factors that must be further investigated. Studies on the reduction of the measurement time and image processing techniques to emphasize the signals from defects are now in progress.

Acknowledgements
This work was supported by JSPS KAKENHI Grant Number 22560687.

References
[1] Takatsubo J, Wang B, Tsuda H and Toyama N 2007 Journal of Solid Mechanics and Materials Engineering 1 1405
[2] Yashiro S, Takatsubo J, Miyauchi H and Toyama N 2008 NDT & E International 41 137
[3] Urabe K, Takatsubo J, Toyama N, Tsuda H and Nagai H 2012 Journal of the Japan Society for Composite Materials 38 183 (in Japanese)
[4] Urabe K, Takatsubo J, Toyama N, Tsuda H, Wang B and Nagai H 2012 Journal of the Japanese Society for Non-destructive Inspection 61 537 (in Japanese)
[5] Nishino H, Yokoyama R, Kondo H and Yoshida K 2007 Japanese Journal of Applied Physics 46 4568
[6] Nishino H, Asano T, Taniguchi Y, Yoshida K, Ogawa H, Takahashi M and Ogura Y 2011 Japanese Journal of Applied Physics 50 07HC10
[7] Nishino H, Yoshida K, Asano T, Taniguchi Y, Ogawa H, Takahashi M and Ogura Y 2011 E-Journal of Advanced Maintenance 2 181
[8] Takatsubo J, Miyauchi H, Urabe K, Tsuda H, Toyama N and Wang B 2009 Transactions of the Japan Society of Mechanical Engineers A75 211 (in Japanese)