Imaging slit in metal plate using aerial ultrasound source scanning and nonlinear harmonic method

Ayumu Osumi*, Kenta Yamada and Youichi Ito

Faculty of Science and Technology, Nihon University,
1–8–14, Kanda-Surugadai, Chiyoda-ku, Tokyo, 101–8308 Japan

(Received 1 April 2020, Accepted for publication 21 July 2020)

Abstract: We previously proposed a stable high-speed visualization measurement method that combines nonlinear harmonics with aerial ultrasonic wave source scanning. In this paper, a more efficient method is proposed to visualize a slit flaw in a metal plate. The results show that visualization of the propagation of ultrasonic waves was possible by wave source scanning. Harmonic propagation was also visible. The slit in the metal plate was visualized with the same accuracy as that of the previous laser probe scanning method.

Keywords: Aerial ultrasonic wave, Non-destructive method, Wave source scanning method, Nonlinear harmonic method

PACS number: 43.35.Zc, 43.35.Pt, 43.25.+y [doi:10.1250/ast.41.885]

1. INTRODUCTION

The nondestructive inspection of metal materials (particularly large structures such as factory equipment, aircraft parts, train cars, and automobiles) is very important for social safety. Among various nondestructive inspection methods, ultrasonic flaw detection allows easy inspection inside materials, and is used for both medical diagnosis and inspection of industrial materials such as steel products, concrete, and resins. In particular, the ultrasonic pulse echo method measures wall thickness and defect position based on the delay in arrival time and an amplitude change of the reciprocating echo in the material. This method is both reliable and widely used. However, the propagation characteristics of ultrasonic waves depend on the type of sensor, the bonding state and position, and the material and shape of the target. In particular, in a region that has a complicated shape, reflected waves, diffracted waves, and mode-converted waves propagate while interfering [1]. Therefore, it is difficult for even an inspection expert to identify a defect echo.

However, a method is available that visualizes the ultrasonic wave propagation and thereby allows for easy detection of defects [2]. With such visualization, there is less chance of overlooking or misidentifying defects, leading to higher inspection reliability. One of the techniques for visualizing the ultrasonic wave propagation is laser probe scanning that measures the surface displacement of an inspected object and visualizes the ultrasonic wave propagation in a solid by scanning a laser Doppler vibrometer (LDV). Osumi et al. [3] proposed a method that combines laser probe scanning and nonlinear harmonics using high-intensity aerial ultrasonic waves, and they succeeded in visualizing the propagation of ultrasonic waves including many harmonics. Also, from the visualization animation of high-frequency ultrasonic waves (approximately 200 kHz), they succeeded in detecting an approximately 3-mm-wide slit in a thin metal plate.

In the present paper, the nonlinear harmonic method (NHM) involves nondestructive inspection by exciting multi-frequency ultrasonic waves using harmonics generated by the nonlinearity of high-intensity aerial ultrasonic waves [4–6]. The advantage of this method is that it is possible to visualize the propagation of ultrasonic waves simultaneously at multiple frequencies, thereby avoiding the need to select an optimal frequency for visualization depending on the defect size and depth. This substantially reduces the time spent searching for the optimal frequency and improves the inspection efficiency.

However, in the conventional method, it is necessary to scan the inspection target using the LDV laser so the surface properties may affect the measurement results. This restriction causes the following problems.

First, when the surface properties decrease the light-receiving sensitivity, the measurement results are affected by disturbance noise. Second, to suppress the disturbance

*e-mail: osumi.ayumu@nihon-u.ac.jp

885
noise, it is necessary to subject the measurement results to signal averaging and image processing. Third, the signal averaging increases the measurement time. These problems make on-site measurement extremely difficult.

To solve the above problems, a method was proposed that involves scanning a wave source based on the reciprocity theorem of acoustic fields. In this method, a laser is used as a wave source: the LDV on the receiving side is fixed, and the laser for ultrasonic excitation on the transmitting side is scanned [7–12]. The advantage of this method is that the receiver is fixed at a position where the surface properties are stable. This means that the disturbance noise has minimal influence and no signal processing is required, thereby reducing the measurement time. In general, a contact-type receiver is more sensitive than an LDV, so the effectiveness likely depends on the experimental environment.

In the present work, we investigate a method that uses the NHM combined with wave source scanning; the aim is practical application of a stable high-speed measurement method that is resistant to disturbances. The inspection target is a thin metal plate. In this paper, we verify the realization of (i) wave source scanning using aerial ultrasonic waves, (ii) ultrasonic wave propagation including harmonics by wave source scanning, and (iii) visualization of a slit in a metal plate by wave source scanning using aerial ultrasonic waves.

2. MEASUREMENT PRINCIPLE

Most of a sound wave that reaches a solid from the air is reflected because of the large difference in acoustic impedance between the air and the solid. However, up to 0.1% of the irradiated sound wave penetrates the solid [13]. The incident sound wave is mode-converted into longitudinal and transverse waves at the boundary surface, and some of these waves propagate as Rayleigh waves. At this time, if the radiated sound wave is a high-intensity aerial ultrasonic wave, then harmonic components generated by nonlinearity also propagate as Rayleigh waves. However, as described above, since the amplitude of the sound wave that penetrates into the solid is extremely low, it is considered that there are almost no harmonics generated due to the nonlinearity of the material.

In the case of a thin plate, Lamb waves are generated according to the Rayleigh–Lamb equation [14,15]. Lamb waves are divided into S (symmetric) and A (antisymmetric) modes depending on the propagation mode, and each mode experiences frequency-dependent velocity dispersion. Generally, the best excitation efficiency is obtained by irradiating from the air at a critical angle \( \theta \) that is calculated as

\[
\theta = \sin^{-1} \frac{C_{\text{air}}}{C_p}
\]

where \( C_p \) is the phase velocity of the Lamb waves and \( C_{\text{air}} \) is the sound velocity in air. However, because our proposed method involves a focused sound wave, the latter is incident without using the critical angle. When the focused sound wave is irradiated vertically onto the thin plate, the latter vibrates so as to bend. Therefore, the mode that occurs is mainly the A mode. The A-mode phase velocity satisfies

\[
\tan \left( \frac{k_1 d}{2} \right) = -\frac{4k_0^2 k_1 k_2}{(k_0^2 - k_2^2)^2}, \quad k_0 = \frac{\omega}{C_p}
\]

\[
k_1 = \sqrt{(\omega/C_L)^2 - k_0^2}, \quad k_2 = \sqrt{(\omega/C_T)^2 - k_0^2}
\]

where \( d \) is the plate thickness, \( C_L \) is a longitudinal wave velocity, \( C_T \) is a transverse wave velocity, and \( \omega \) is the angular frequency.

In the present experiments, the NHM used the frequency band of 40–200 kHz, in which only the lowest A0 mode is generated from Eq. (2). Figure 1 shows the theoretically calculated phase speed of the A0 mode up to 200 kHz.

The calculation was performed by substituting into Eq. (2) the material constants of the metal plate (aluminum) used in the experiments (thickness: 3 mm; longitudinal wave speed: 6,300 m/s; transverse wave speed: 3,100 m/s). Figure 1 shows that in the frequency band used in the experiments, the phase velocity of the A0 mode increases monotonically.

Next, the wave source scanning method is described. Figure 2 shows a schematic view of the reciprocity theorem of acoustic fields used in this method.

If two sensors with the same characteristics are placed at points A and B in Fig. 2, then the waveform when the ultrasonic wave propagating from point A is received at...
point B is the same as that when the ultrasonic wave propagating from point B is received at point A. The visualization principle of the source scanning method is based on the premise that the reciprocity of the acoustic field is established.

Given the reversibility of ultrasonic wave propagation, the following two measured waveform sequences are the same: (i) the one detected by a fixed piezoelectric sensor subjected to ultrasonic waves generated at each position by scanning airborne ultrasonic waves (Fig. 3(a)); and (ii) the one detected by a piezoelectric sensor that is scanned and subjected to ultrasonic waves generated from only one point (the fixed position of piezoelectric sensor (i)) by airborne ultrasonic irradiation (Fig. 3(b)).

Note that the above discussion holds even if the transmitter and the receiver are replaced with lasers [7–12]. From the above, a waveform sequence similar to that of laser probe scanning is obtained by wave source scanning. When the amplitude distribution at each time of the obtained waveform sequence is visualized on a color scale and displayed continuously in the order of the measurement time, an image of the ultrasonic wave propagation in the measurement region is obtained. In actual experiments, the propagation images are not exactly the same because of differences in the transmitter and receiver, the measurement system, and the source diameter. However, the present experiments were conducted assuming that the acoustic field reciprocity theorem holds.

3. EXPERIMENTAL METHOD AND PROCEDURE

Figures 4(a) and 4(b) show the experimental devices. Figure 4(a) shows conventional laser probe scanning schematically, Fig. 4(b) does the same for the proposed wave source scanning.

These devices comprised an aerial ultrasonic sound source, an LDV (LV1620; Ono Sokki, Tokyo, Japan), a receiving piezoelectric element (PICO; Physical Acoustics, Princeton Jct, NJ), a data logger (PXIe-5172; National Instruments, Austin, TX), other peripheral devices, and a PC to control them. This sound source was a point-focused sound source [16–18] with a spherical arrangement of 335 aerial ultrasonic transducers (UT1007-Z325R; SPL, Kowloon, Hong Kong; driving frequency: 40 kHz) and a focal length of 150 mm. The LDV was used to measure the vibration velocity at each position by the conventional method.

One of the main purposes of the wave source scanning method was to realize wave source scanning...
using aerial ultrasonic waves. Therefore, a receiving piezoelectric element more sensitive than the LDV was used. To avoid the influence of the side rope of the radiated sound wave, an acoustic guide (acryl plate: thickness 3 mm; acryl pipe: diameter 6 mm, length 30 mm) [19] was installed at the sound-wave focal point and the sound wave propagated through the sound guide, thereby realizing point irradiation with a diameter of 6 mm to the inspection object.

Figure 5 shows the acoustic field after passing through the guide and measured by a 1/8-inch microphone (40DP; GRAS Sound & Vibration, Holte, Denmark). The average sound pressure in the high-sound-pressure region in Fig. 4 reached approximately 4000 Pa at an input voltage of 24 V applied to the sound source. The distance between the sound guide and the test object was approximately 1 mm. The acoustic guide and the sound source had an integrated structure. This sound source was mounted on a precision three-dimensional stage and could move two-dimensionally. The experimental procedure was as follows. In the case of the conventional method, the transmitted ultrasonic waves were scanned two-dimensionally and measured in the measurement area using the LDV mounted on a three-dimensional precision stage. In the case of the wave source scanning method, the ultrasonic wave excited two-dimensionally by scanning the sound source at each position in the measurement area was received by the receiving piezoelectric element at the receiving point. Subsequently, the signal processing of the received waveform in the experiment was performed as follows. The received waveform contained harmonic components that were integer multiples of the fundamental frequency by irradiating the high-intensity aerial ultrasonic wave. Therefore, each frequency component was extracted by a band-pass filter. The extracted temporal waveform of each frequency component was stored together with the position information in the data logger. When the measurements at all positions were completed, the instantaneous vibration amplitude distribution at each time was created by synchronizing the received waveforms. An ultrasonic wave propagation image was obtained from an animation in which these vibration distributions were reproduced continuously.

The samples used in the experiments were thin aluminum plates. We prepared a sound sample and a sample containing a slit. The dimensions of each sample were 500 mm x 340 mm x 3 mm. Figure 6 shows the appearance of the sample containing a slit, which was located near the center of the metal plate. The dimensions of the slit were 50 mm x 3 mm x 0.5 mm. Furthermore, a wave source scanning area (LDV measurement area) and a receiver (wave source) were arranged as shown in Fig. 6. The measurement area (the wave source scanning area and the LDV scanning area) was 80 mm x 100 mm. The sound source was excited by a 10-burst cycle with a frequency of 40 kHz and an input voltage of 24 V. The experimental conditions were a sampling frequency of 2 MHz and a sampling time of 1 ms.

4. RESULT AND DISCUSSION

4.1. Visualization of Ultrasonic Wave Propagation by Aerial Ultrasonic Wave Source Scanning Method

The visualization of Lamb-wave propagation and harmonic-component propagation was investigated by the aerial ultrasonic wave source scanning method. The experiment was performed on a sound sample of the same size as the thin metal plate shown in Fig. 6 and containing no slit. The scanning interval was 2 mm for both the conventional method and the wave source scanning method. Figures 7 and 8 show the results of visualizing the Lamb-wave propagation at 750 μs. Figures 7(a)–7(c) show the results measured by the conventional method at each frequency (fundamental frequency: 40 kHz, second harmonic: 80 kHz, third harmonic: 120 kHz), and Figs. 8(a)–8(c) show the results measured by the wave source scanning method at the same frequencies.

The results obtained by both methods were almost the same at each frequency. That is, the visualization of the ultrasonic wave propagation was also successful in the measurement results of the wave source scanning method.
The phase velocities calculated using the wave front interval of the propagation image as the wavelength were approximately 1,040 m/s, 1,400 m/s, and 1,660 m/s at the respective frequencies. Because these phase velocities fit well to the curve of the velocity dispersion characteristic in Fig. 1, it was confirmed that the propagating Lamb wave was in the A0 mode. From the above, the visualization of Lamb wave propagation and the realization of harmonic propagation were confirmed by the aerial ultrasonic wave source scanning method.

4.2. Visualization of Slit in Metal Plate

The experimental sample contained a slit (Fig. 6), but because the width of the slit was 3 mm, it could only be visualized if at least the fifth harmonic was used, as previously demonstrated [3]. Therefore, in the wave source scanning method, the fifth harmonic was used to visualize the slit in the metal plate. Figures 9 and 10 show the visualization results for Lamb-wave propagation obtained by the wave source scanning method and the conventional method, respectively. In Figs. 9 and 10, the times in parts (a)–(f) are the elapsed times after applying the input voltage to the sound source.

First, we consider the visualization results. Those in Fig. 9 confirm that the incident sound wave on the slit was partially reflected at the boundary area and partially transmitted. In addition, the Lamb waves transmitted to the slit area were reflected at the ends, thereby confirming that a standing wave was generated on the slit area. The slit area was visualized from the propagation animation as described above. Next, we compare the visualization results by each method shown in Figs. 9 and 10. It was confirmed that the visualization results of the slit area by the wave source scanning method can be visualized more accurately than that of the conventional method.

5. CONCLUSION

In this study, we investigated stable and high-speed visualization measurement for thin metal by combining the NHM with aerial ultrasonic wave source scanning. As a result, it was possible to visualize the propagation of ultrasonic waves by the wave source scanning method. Harmonic propagation was also visible. Also, a slit in a metal plate could be visualized with the same accuracy as that of laser probe scanning without performing averaging or image processing. The results indicate the usefulness of this new technique for visualizing ultrasonic wave propagation using aerial ultrasonic waves.

ACKNOWLEDGEMENTS

This work was partially supported by JSPS KAKENHI (19K04931).
REFERENCES

[1] P. Fromme, “Lamb wave (A0 mode) scattering directionality at defects,” *AIP Conf. Proc.*, **1806**, 030002 (2017).

[2] J. Takatsubo, M. Imade, Q. Fan and S. Yamamoto, “Visualization of elastic waves by digital laser ultrasonics,” *Trans. Jpn. Soc. Mech. Eng. Ser. C*, **65**(639), 4299–4304 (1999) (in Japanese).

[3] A. Osumi, K. Yamada, Y. Asada and Y. Ito, “Harmonic imaging of a defect in a flat plate using a guided wave generated by a high-intensity aerial ultrasonic wave,” *Jpn. J. Appl. Phys.*, **58**, SGGB14 (2019).

[4] A. Osumi, K. Doi and Y. Ito, “Fundamental study of detecting internal defect in building materials using high-intensity aerial ultrasonic waves with finite amplitude,” *Jpn. J. Appl. Phys.*, **50**, 07HE30 (2011).

[5] A. Osumi, H. Kobayashi and Y. Ito, “Basic study of detecting defects in solid materials using high-intensity aerial ultrasonic waves,” *Jpn. J. Appl. Phys.*, **51**, 07GE04 (2012).

[6] A. Osumi, M. Ogita, K. Okitsu and Y. Ito, “Detection of crack in a shallow layer of mortar by using a harmonic component of very high intensity aerial ultrasonic waves,” *Jpn. J. Appl. Phys.*, **56**, 07JC12 (2017).

[7] J. Takatsubo, B. Wang, H. Tsuda and N. Toyama, “Generation laser scanning method for the visualization of ultrasounds propagating on a 3-D object with an arbitrary shape,” *J. Solid Mech. Mater. Eng.*, **1**, 1405–1411 (2007).

[8] T. Hayashi, M. Murase and T. Kitayama, “Frequency dependence of images in scanning laser source technique for a plate,” *Ultrasonics*, **52**, 636–642 (2012).

[9] M. N. Salim, T. Hayashi, M. Murase, T. Ito and S. Kamiya, “Fast remaining thickness measurement using a laser source scanning technique,” *Mater. Trans.*, **53**, 610–616 (2012).

[10] T. Hayashi and M. Fukuyama, “Vibration energy analysis of a plate for defect imaging with a scanning laser source technique,” *J. Acoust. Soc. Am.*, **140**, 2427–2436 (2016).

[11] S. Nakao and T. Hayashi, “Non-contact imaging for delamination using diffuse field concept,” *Jpn. J. Appl. Phys.*, **58**, SGGB07 (2019).

[12] T. Hayashi, “Imaging defects in a plate with complex geometries,” *Appl. Phys. Lett.*, **108**, 081901 (2016).

[13] D. E. Chimenti, “Review of air-coupled ultrasonic materials characterization,” *Ultrasonics*, **54**, 1804–1816 (2014).

[14] I. A. Victorov, *Rayleigh and Lamb Waves* (Plenum, New York, 1967), Chap. III, pp. 123–144.

[15] J. L. Rose, *Ultrasonic Waves in Solid Media* (Cambridge University Press, New York, 1999), Appendix E, pp. 400–438.

[16] A. Osumi, T. Saito and Y. Ito, “Improved method of imaging defect in noncontact and nondestructive technique by high-intensity aerial burst ultrasonic wave and optical equipment,” *Jpn. J. Appl. Phys.*, **54**, 07HC07 (2015).

[17] T. Kamakura, H. Nomura and G. T. Clementz, “Linear and nonlinear ultrasound fields formed by planar sources with random pressure distributions,” *Acoust. Sci. & Tech.*, **36**, 208–215 (2015).

[18] M. Akiyama and T. Kamakura, “Elliptically curved acoustic lens for emitting strongly focused finite-amplitude beams: Application of the spheroidal beam equation model to the theoretical prediction,” *Acoust. Sci. & Tech.*, **26**, 279–284 (2005).

[19] N. Suzuki, A. Osumi and Y. Ito, “Transmission of high-intensity ultrasonic waves by using sound wave transmission straight rigid tube,” 2017 IEEE Int. Ultrason. Symp., P3-B1-7 (2017).