Non-contact leaky Lamb wave imaging based on pulsed laser and ultrasound microphone

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***Abstract*— A local wavenumber estimation (LWE) method based on a scanning laser Doppler vibrometer (SLDV) is derived using a frequency–wavenumber domain filtering method. LWE methods based on a standing wave have recently been investigated. This technique utilizes SLDV data in the steady-state excitation of a fixed frequency. Despite its various advantages, the LWE method uses contact actuators to provide sufficient vibrating energy. In this study, we solved the cost and complexity problems of using SLDV by replacing it with an ultrasound microphone. We also measured the shallow defect of an aluminum plate using a noncontact-LWE method. A Nd:YAG laser with wavelength of 532 nm and an ultrasound microphone with a frequency range of 2–200 kHz were both used to detect the shallow defect in the aluminum plate. The LWE image resulting from the pulsed laser has a low signal-to-noise ratio (SNR) and presents wave pattern artifacts because of a low excitation energy. To address this problem, we acquired several data from different laser point positions and constructed LWE images. Because the artifacts in these images are non-correlated, the averaging process removes the artifacts and significantly improves the SNR.**

Keywords—lamb wave, ultrasonic touchscreen, PMN-PT sensor, delay and sum image

I. Introduction

Nondestructive testing (NDE) and structural health monitoring (SHM) are significant components of safety assurance in a variety of industries, including mechanical engineering, civil industries, and aerospace systems. Ultrasound technology is the most commonly used damage-detection technology in NDE and SHM because of its sensitivity to light damage [1-2]. Traditional contact ultrasonic techniques [3] have certain disadvantages. Traditional contact ultrasonic techniques require multiple sensors to identify and localize small defects. In the case of a contact-type technique, it is difficult to obtain a high spatial resolution because the transmission and reception signals operate discontinuously. Moreover, as the number of sensors increases, the cost and workforce increase. It is difficult to apply conventional contact sensors to harsh environments such as radioactive conditions or high temperatures. In addition, the contacted transducer may switch the dynamic characteristics of the target structure. The demand for noncontact ultrasonic techniques has recently increased, and the most widely used technique is the laser ultrasonic approach [4-5]. The non-contact laser ultrasonic method generally makes ultrasonic waves using a pulsed laser and measures the signal using a laser Doppler vibrometer (LDV). However, despite the many advantages regarding its supplementation of the drawbacks of traditional ultrasonic contact techniques, this method also has certain problems. Two of its main problems are the cost and complexity owing to the use of a galvanometer or F-theta lens. In addition, although this method is applicable to damage detection, it has difficulty in accurately measuring certain parameters such as the wavenumber or thickness. To measure the wavenumber or thickness, the use of standing waves was proposed instead of the traveling waves applied in previous studies [6]. The LWE method based on scanning LDVs has also been researched. This technique uses a contact-type actuator to excite the Lamb waves with a specified frequency and applies a frequency–wavenumber domain filtering method. In this study, a noncontact wavenumber estimation method is proposed using a pulsed laser and an ultrasound microphone. We solve the cost and complexity problems by applying ultrasound microphones instead of LDVs. Moreover, we improve the low SNR and wave-patterned artifacts caused by an insufficient excitation wave energy as compared to a CW contact actuator by applying multiple laser point positions.

II. METHOD

A. Principle of non-contact ultrasonic laser

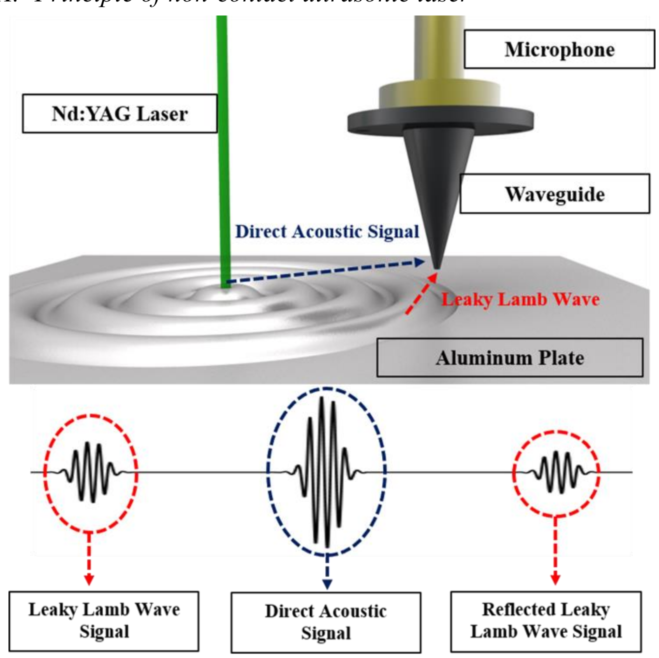

Fig. 1. Measurement using leaky Lamb wave signal.

The principle of generating and measuring a Lamb wave signal is shown in Fig. 1. When a lamb wave propagates in an elastic plate present in the fluid, energy from the propagating lamb wave leaks into the surrounding fluid. These fluid waves are called leaky lamb waves (LLWs). LLWs are affected by the coupling and attenuation with air. To minimize this influence, it is necessary to minimize the distance between the aluminum plate and the ultrasonic microphone. Therefore, a conical waveguide is created, which improves the spatial resolution of the acoustic signal. There are two types of signals that the microphone measures, namely, LLW and direct acoustic signals. The LLW signal, with a higher speed than the acoustic signal, is received first, and the direct acoustic signal is then received by the microphone. After the first LLWs are received, the LLW signals reflected from the edge of the aluminum plate are continuously received. The LLW signals reflected from the edge are analogous to the steady-state response signal and are suitable for a local frequency estimation.

B. *Local wavenumber estimation for using pulsed laser*

The LWE methods generally use an attached actuator [7-9]. The method proposed in this paper is a non-contact approach using a pulsed laser that generates a broadband characteristic signal. Thus, the energy generated by the laser at a single frequency is insufficient compared to the energy generated by the attached actuator. Owing to this effect, the LWE image represents a wave-patterned artifact. To overcome this problem, we use multiple laser point positions. We construct an LWE image for each laser point and calculate the average of the local wavenumber results. The algorithm for constructing each LWE image is as follows. The acquisition of a 3D measurement matrix is the first step of the algorithm. Then, a steady-state response is calculated after a specific single-frequency fast Fourier Transformation (FFT) is applied. The 2D FFT is used to convert the spatial domain of the steady-state response into a wavenumber domain. A narrow wavenumber filter bank is then constructed using a Gaussian-shaped window. An inverse 2D FFT is used to retransform the wavenumber domain into the time domain and envelope it. Finally, the local wavenumber is estimated by finding the maximum wavenumber at each point.

III. Experiment

A. *Whole system setup*

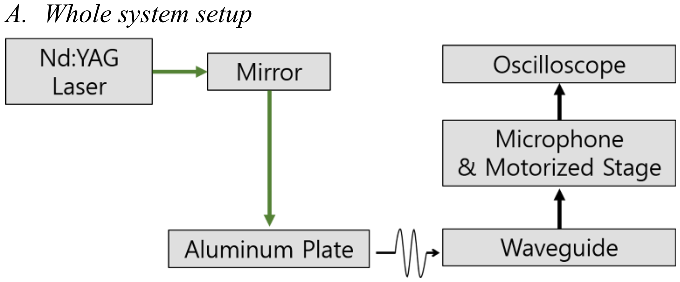

Fig. 2. Experiment setup for noncontact laser ultrasonic defect-detection system

A schematic of the overall experiment is shown in Fig. 2. The light source for the experiment was an Nd: YAG laser (Minilite I, Amplitude, CA, USA) with a wavelength of 532 nm. The mirror was used to reflect the irradiated laser to the aluminum plate. The ultrasonic signal generated was measured using a broadband ultrasonic microphone with a frequency range of 2 to 200 kHz. To overcome the diffraction loss and achieve a better spatial resolution, a conical waveguide was fabricated to receive the LLW signal at the nearest point of the aluminum plate. To accurately measure the LLW signal at specific points, the diameter of the waveguide tip is 1 mm. The waveguide also serves as a link between the microphone and motorized stage. A precise measurement was conducted using a motorized stage, and the data measured using an oscilloscope were stored on a PC.

B. *Specimen and scanning condition*

The specimen used in the experiments was manufactured with a square-shaped milling area on a 1-mm thick aluminum plate (T6061). The milling area is 3 cm in both width and length. The thicknesses of the aluminum plate and the shallow defective area are 1.0 and 0.6 mm, respectively. The experiment was conducted using a laser and microphone placed on top with the milling surface of the specimen facing downward. To detect shallow defects using this method, the microphone scanned the defect-free side of the specimen. This indicates that the method uses Lamb waves and not the progressive acoustic signals to visualize and measure the defects. The experiment was conducted using three different laser points. Area scanning was applied on the 4 cm × 4 cm area with a 0.4 mm spacing for each laser point.

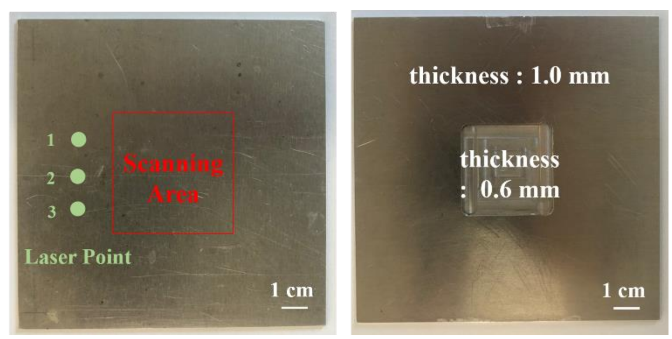

Fig. 3. Front (scanning side) and backside (defected side) of the specimen

IV. Experiment Results

A. *Analysis of measurement data*

As mentioned above, the measured signal consists of an LLW signal and a direct acoustic signal. The acoustic data, which were measured approximately 4 cm away from the laser spot by the ultrasonic microphone, are shown in Fig. 4(a). The Lamb wave is dispersive, which means the velocity differs depending on the frequency. The theoretical A_0 Lamb wave velocity at 140 kHz is approximately 1,100 m/s, and the sound velocity is 340 m/s in air. The first LLW signal arrives at ~260 µs and the direct acoustic signal arrives at ~330 µs. Both types of signals travel through a conical waveguide. The inner side of the waveguide has a 7.5 cm length and both signals take 220 µs owing to a sound velocity of 340 m/s. This means that the velocities of the LLW signal and the direct acoustic signal at 4 cm along the aluminum plate are approximately 1,000 m/s and 360 m/s, respectively. As this result indicates, the LLW signal measured by the ultrasonic microphone is generated by the A_0 Lamb wave, which has the lowest order of the antisymmetric mode.

The progressions of the LLW waveform in the measurement data at 286 μs for each laser point are shown in Fig. 4(b)–(d), respectively. Each image is constructed just before the direct acoustic signal arrives and clearly shows the progress of the LLW signal depending on the location of the laser point. In particular, the progress of the LLW signal is more clearly expressed in the defective area, the wavelength of which is shorter than that of a normal aluminum plate. This is due to the dispersive characteristic of the Lamb wave, which makes the velocity change with the frequency. At a center frequency of 140 kHz, the velocities of the 1 mm aluminum plate and the 0.6 mm aluminum plate are 1,100 and 880 m/s, respectively. Therefore, the wavelengths become 7.9 and 6.3 mm. It was theoretically proved that the wavelength is short in the defective area.

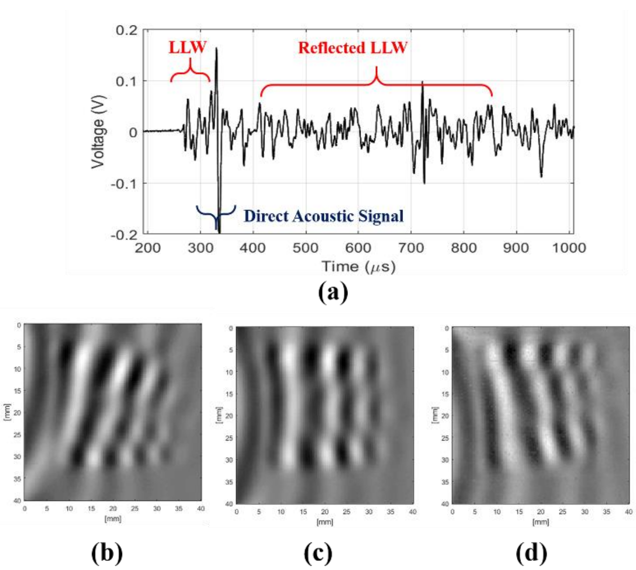

Fig. 4. (a) Acoustic data. Snapshot of propagating LLW by (b) laser point 1, (c) laser point 2, and (d) laser point 3.

B. *Local wavenumber estimation results*

The presence of defects in the snapshot of waveform progression is distinguished, but the initial LLW signal is inadequate for calculating the exact defective area and wavenumber. Because conventional LWE methods generally use contact-type actuators to generate a steady state through continuous-wave excitation at a fixed specific frequency, the LWE method for pulse laser excitation is applied using the reflected LLW signal that arrives after the acoustic signal rather than the initial LLW signal. The state of the reflected LLW signal is similar to a steady state, but owing to an attenuation, the signal is not as large as that of the contact actuator. The steady-state responses calculated from the reflected LLW signal are shown in Fig. 5 (a)–(c). Based on this, the LWE image constructed using the algorithm described above is shown in Fig. 5 (d)–(f). Each LWE image shows square defects but wave-patterned artifacts. These artifacts occur because the magnitude of the reflected LLW signal is insufficient and is created through inaccurate points estimated from an imprecise local wavenumber.

To solve this problem, we construct an LWE image for each of three laser points. Wave-pattern artifacts are uncorrelated with each other. The average LWE image is reconstructed using the average value of the LWE image constructed according to the laser points, as shown in Fig. 6. The estimated local wavenumber of the aluminum plate and the shallow defective area are 147.16 ± 1.05 (1σ) and 186.30 ± 1.55 (1σ) 1/m, respectively. The theoretical wavenumbers at 140 kHz of 1.0 and 0.6 mm thick aluminum plates are 127.27 and 162.82 1/m. The average value has an error of 13.52% and 12.61% when compared to the theoretical value, respectively. These errors occur because the Lamb wave generated by the laser is a broadband wave compared to the contact actuator with the specific frequency despite passing through the narrowband frequency filter.

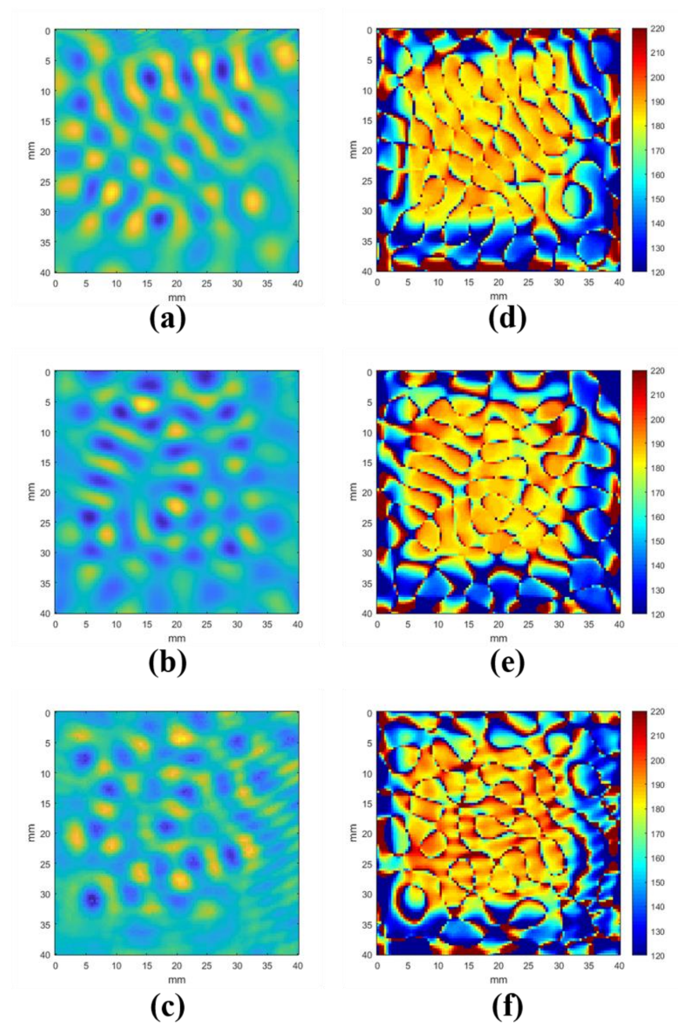

Fig. 5. Steady-state response using (a) laser point 1, (b) laser point 2, and (c) laser point 3. Resulting image of local wavenumber estimation using (d) laser point 1, (e) laser point 2, and (f) laser point 3.

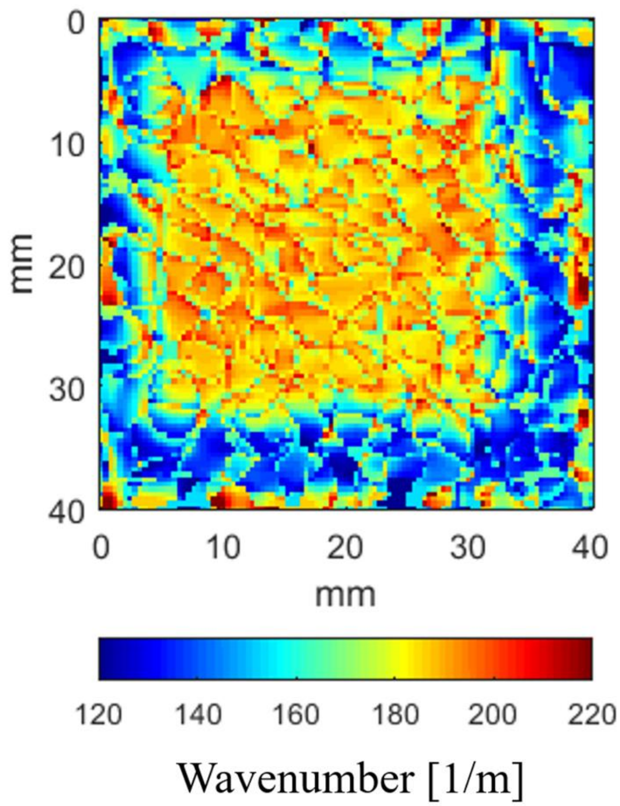

Fig. 6. Average local wavenumber estimation image using each local image according to a laser point.

CONCLUSION

This study proposed a non-contact laser ultrasonic method for detecting shallow defects of thin aluminum plates. Replacing LDV with ultrasonic microphones solves the problems of high cost and complexity in traditional laser ultrasonic methods using LDV. In addition, the non-contact LWE method was applied using a reflected LLW signal. Compared with a CW contact actuator, an insufficient excitation energy creates low SNR problems. To solve this problem, we obtained multiple images according to multiple laser points and applied their average. The LWE result was calculated using the average of the results acquired for each laser point and incurred an error of approximately 13.52% and 12.61% compared to the theoretical wavenumber. Increasing the number of laser points, or using the broadband characteristic of the signal generated by pulsed lasers, improved results can be achieved.

ACKNOWLEDGMENT

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