A Novel Double-Layered Piezoelectric Transducer for Detecting Second Harmonic Ultrasonic Pulse Waves

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A novel detection system for second harmonic ultrasonic pulse waves is constructed by modifying the double-layered piezoelectric transducer (DLPT). The new DLPT composed of two PbTiO₃ thickness-mode piezoceramic concave disks is employed: one is a conventional concave transducer and the other is a ring type concave transducer. Since the switch for the electrical connection used in the conventional DLPT system is not required, a simple system for detecting second harmonic ultrasonic pulse waves can be constructed. Furthermore, for real time detection of second harmonic ultrasonic pulse waves, pulse inversion averaging (PIA) is carried out. As a result, the enhanced second harmonic ultrasonic pulse waves are displayed on an oscilloscope in real time. A drilled hole in an aluminum plate is then imaged to demonstrate the effectiveness of this system.

Key Words : Ultrasonic, Second harmonic pulse wave, Double-layered piezoelectric transducer, Real time, Pulse echo, Nonlinear ultrasonic imaging

1 INTRODUCTION

Ultrasonic waves have been widely used in the non-destructive evaluation (NDE) of several materials including metals. For detecting open cracks, a pulse-echo method has been employed. However, dislocation, closed cracks and plastic deformation cannot be easily detected by a conventional pulse-echo method. Recently, second harmonic ultrasonic waves have been studied as new tools for testing materials [1-6]. Second harmonic ultrasonic waves are generated by nonlinear vibrations of dislocation and closed cracks has been considered as the resonance with finite-amplitude ultrasonic waves traveling through the testing materials. In second harmonic imaging, the advantages of images have a high lateral resolution, low sidelobe, and low influence for multiple reflections of ultrasonic pulse waves compared with those obtained by conventional imaging have recently been presented [7]. The detection of small or slightly closed cracks, which generated second harmonic ultrasonic waves much smaller than fundamental ones will become very important in NDE. Second harmonic pulse waves generated from plastic-deformed metal rods reported by authors have been approximately -60 dB smaller than fundamental ones. [1] Namely, the dynamic range of 60 dB or more is required for detecting small second harmonic waves.

Several transducers for harmonic wave detection have been developed and several transducers with resonance frequencies of both the fundamental and second harmonic component, as well as a LiNbO₃ plate with a ferroelectric inversion layer fabricated by heat treatment have been reported [8]. Transducers arranged coaxially [9] or stacked [10] on their acoustic radiated surfaces for transmitting the fundamental pulse wave or receiving the harmonic

pulse wave, respectively, have also been reported.

A method of generating short ultrasonic pulse waves using a double-layered piezoelectric transducer (DLPT) has been reported by the authors [1, 11]. The DLPT in an electrically parallel connection has the advantage of transmitting the fundamental pulse waves with a higher sensitivity to the fundamental frequency compared with a conventional single transducer. Moreover, the DLPT in an electrically series connection has a higher sensitivity to the second harmonic frequency component. In our previous DLPT system [6], switching the electrical connection in parallel or series for a DLPT allows the effective transmitting of the fundamental pulse waves and the receiving of second harmonic pulse waves. However, the switching during ultrasonic traveling time (approximately 50 μs in water of round-trip distance 80 mm) requires the low chattering switch and their complex switch control system. Although these switch and system can be easily constructed in the laboratory, a simple system is required in the application. A novel second harmonic pulse waves detecting system having the dynamic range of 60 dB or more without a switch is required.

In this paper, a novel system for detecting second harmonic ultrasonic pulse waves using a bonded ring type double-layered piezoelectric transducer is described. Furthermore, the pulse inversion averaging (PIA) method [11] for extracting the second harmonic pulse waves is applied to obtain the second harmonic pulse waves in real time. Finally, a drilled hole in an aluminum plate is imaged to demonstrate the effectiveness of this system.

2 TRANSDUCER

The novel double-layered piezoelectric transducer (DLPT) is

Figure 1 A novel transducer for second harmonic pulse waves detection.

Figure 2 Frequency-admittance characteristics of a novel transducer. (a): Transmission part. (b): Reception part. Solid lines denote the absolute values of admittance and dotted lines denote the phases of admittance.

composed of two PbTiO₃ thickness mode piezoceramic concave disks (frequency constants = 2230 m-Hz, thicknesses = 1.1 mm, aperture diameters = 20 mm, and focal lengths = 40 and 41.1 mm, respectively) (Fuji Ceramics, M-6), one is the conventional type and the other is ring type transducer as shown in Figure 1. The inside and outside electrodes of the bonded side in the concave transducer are fabricated as the output and input terminals, respectively. In this study, the resonance frequency (f_0) of these transducers is 2 MHz. This frequency is included in the frequency bandwidths (1-10 MHz) frequently used in the NDT and the ultrasonic imaging. These transducers are stacked and bonded to each other in the opposite direction to the polarization using electroconductive silver paint as shown in Figure 1. The ultrasonic transmission component is the outside part of the transducers (the DLPT part), which is electrically connected in parallel. The ultrasonic reception component is the inside part of the concave transducer. The frequency-admittance characteristics of the transmission and the reception component are shown in Figure 2(a) and 2(b). The resonance frequency of the transmission part can be changed from 2 MHz to 1 MHz by parallel connection. Parallel connection of the DLPT has the advantage of transmitting fundamental pulse waves (1 MHz) with a higher sensitivity at the fundamental frequency than for a single transducer [12]. The resonance frequency of the reception part remains at 2 MHz, and enables the sensitive reception of the second harmonic pulse waves.

An electrical switch and control system for switching the receiving circuit are not required in this transducer. Second harmonic detection can thus be accomplished by a simpler system compared to our previous system.

In the next section, a novel transducer for detecting the second harmonic pulse waves is evaluated experimentally.

3 EXPERIMENTAL

3.1 Method

A driving voltage signal for the DLPT was generated by an arbitrary waveform generator. Figure 3 shows the driving voltage waveform for the PIA method [11]. The driving voltage waveform was designed as a burst of 20 cycles of the 1 MHz sinewaves (burst duration time: 20 μ s), and the period T [s] to the next inverted driving signal was determined to be 0.5 ms, which was much longer than the round trip time (about 50 μ s) of ultrasonic wave. Trigger signal was generated by pulse generator which was phase-locked on the arbitrary waveform generator was set to T [s] to synchronize with the trigger of oscilloscope.

The experimental system for the second harmonic pulse waves using the novel DLPT transducer is shown in Figure 4. The driving signal generated by the arbitrary waveform generator was amplified up to 150 V by a high-frequency power amplifier (with input and output impedances both at 50 Ω), and was electrically

Figure 3 Oscillating signal for generating DLPT.

matched to the transducer (with an impedance at resonance frequency of $100\ \Omega$) by an electrical impedance matching circuit.

Ultrasonic pulses (1 MHz) were transmitted in water, which were then reflected by the reflector set 40 mm away from the transducer. While ultrasonic pulse waves propagated in the water, second harmonic pulse waves (2 MHz) were generated by the elastic nonlinear effect in water. The received pulse waves were averaged by an oscilloscope, and only the second harmonic pulse waves were extracted by the PIA method. Finally, the extracted

pulse waves were fed to a personal computer via a general purpose interface bus.

3.2 Results and Discussion

Figure 5(a) shows the received ultrasonic pulse waves using the conventional single transducer, and the spectrum of Figure 5(a) is shown in Figure 5(b). In Figure 5(b), the second harmonic component is approximately 50 dB smaller than the fundamental component because the conventional single transducer has low sensitivity at 2 MHz. Figure 5(c) shows the waveform received by our system using the novel DLPT transducer. The spectrum of Figure 5(c) is shown in Figure 5(d). The difference between the fundamental and second harmonic amplitudes decreased to approximately 10 dB because the reception part of the transducer has a high sensitivity at 2 MHz. Figure 5(e) shows the waveform obtained by the PIA method, and the spectrum of Figure 5(e) is shown in Figure 5(f).

In Figures 5(b) and 5(d), the relative amplitudes of the second harmonic component improved by approximately 20 dB. Furthermore, after the pulse inversion averaging method is applied, the fundamental amplitude decreases by approximately 40 dB compared to that in Figure 5(d), as shown in Figure 5(f). Therefore, the amplitude of our system improved by relatively 60 dB compared to the case of a conventional single transducer. The dynamic range of 60 dB in a novel system without the switch has been accomplished.

As observed in Figure 5(e), the second harmonic pulse wave was extracted and displayed on the oscilloscope in real time.

3.3 Sample Imaging

To confirm the performance of this novel system, the imaging of a drilled hole was carried out. The measured object with the imaged area shaded is shown in Figure 6.

A hole with a diameter of 3.0 mm was drilled in an aluminum plate. In the experiment, the amplitudes of particular frequencies (1 MHz and 2 MHz) in the spectra were detected by the

Figure 4 Experimental set-up.

Figure 5 Experimental results of ultrasonic pulse waveform and spectrum. (a) Waveform in conventional pulse echo system. (b) Spectrum of (a). (c) Waveform in a novel transducer without pulse inversion averaging. (d) Spectrum of (c). (e) Waveform in a novel transducer with pulse inversion averaging. (f) Spectrum of (e).

FFT function in the oscilloscope in real time. For automatic measurement, a stage controller and x-y stage were used.

Imaging results using the fundamental (1 MHz) and second harmonic (2 MHz) components are shown in Figures 7(a) and 7(b), respectively, where gray scales are normalized by maximum amplitudes of fundamental and second harmonic components in Figure 5(b) and 5(f), respectively. In Figure 7(b), pulse inversion averaging is carried out. The existence of the hole was determined using our second harmonic detection system and was confirmed more clearly than that of the fundamental component.

Lateral resolution is expressed as

$$\Delta r = \lambda \frac{F}{D} \quad (1)$$

where λ is wave length, F is focal length and D is aperture diameters, respectively. [7] Wave length is expressed as

$$\lambda = \frac{c}{f} \quad (2)$$

where c is velocity of water and f is frequency. Wave lengths of 1 MHz and 2 MHz in water (≈ 1500 m/s) are 1.5 mm and 0.75 mm, respectively. In the DLPT part, the calculated lateral resolution Δr_1

Figure 6 An aluminum plate drilled hole and measured area.

Figure 7 Results of object imaging. (a) Fundamental pulse waves using conventional system. (b) second harmonic pulse waves using our system. Gray scales are normalized by maximum amplitudes of fundamental and second harmonic components in Figure 5(b) and 5(f), respectively.

equals 3 mm because of $F=40$ mm and $D=20$ mm. On the other hand, in the reception part, the calculated lateral resolution Δr_2 equals 2.7 mm because of $F=40$ mm and $D=11$ mm. Calculated lateral resolutions of the DLPT part and the reception part were almost equal. However, second harmonic image (2 MHz) was clear compared with fundamental one (1 MHz), because second harmonic pulse waves have the advantage of low sidelobe compared with fundamental ones. Consequently, usefulness of the novel transducer in harmonic imaging was confirmed.

4 CONCLUSIONS

A novel transducer of a double-layered piezoelectric transducer (DLPT) for detecting second harmonic pulse waves was constructed. The sensitivity of the received second harmonic pulse wave was improved by approximately 20 dB compared to the conventional single transducer. The real time extraction of the second harmonic pulse waveform using the pulse inversion averaging method was demonstrated, and the fundamental component was decreased by 40 dB. The second harmonic component was emphasized and showed a relative improvement of 60 dB compared to conventional pulse echo systems. To confirm the usefulness of the system, a drilled hole was imaged. As a result, compared with the fundamental component system, higher resolution imaging has been accomplished.

These results indicate that our system effectively addresses the extraction of second harmonic pulse waves. We intend to apply this to harmonic imaging for medical diagnostic or nondestructive testing using our transducer system. However, in this study, the axial resolution of the novel transducer was not discussed. In the future, the analytical and experimental discussion of the matching layers and the backing medium to improve the axial resolution will be required.

References

- [1] M. Fukuda, M. Nishihira and K. Imano, "Real Time Detection of Second-Harmonic Components Generated from Plastic-Deformed Metal Rod Using Double-Layered Piezoelectric Transducer," *Jpn. J. Appl. Phys.*, Vol.46, No.7B, pp.4529-4531, (2007).
- [2] K. Imano and A. Muto, "Detection of Second Harmonic Wave from the Closed Crack Using Finite Amplitude Ultrasonic Wave," *Sozai Busseigaku Zasshi*, Vol.20, No.1, pp.12-18, (2007) [in Japanese].
- [3] A. Hikata and C. Elbaum, "Generation of Ultrasonic Second and Third Harmonic Due to Dislocations. I," *Phys. Rev.*, Vol.144, No.2, pp.469-477, (1966).
- [4] K. Kawashima, M. Murase, Y. Ohara, R. Yamada, M. Matsushima, M. Uematsu, F. Fujita and T. Miya, "A Nonlinear Ultrasonic Imaging System for Detecting Minute Damage and Defects of nm Gaps in Industrial Materials," *Hihakai Kensa*, Vol.54, No.9, pp.509-514, (2005) [in Japanese].
- [5] Y. Ohara, H. Endo, T. Mihara and K. Yamanaka, "Ultrasonic Measurement of closed Stress Corrosion Crack Depth Using Subharmonic Phased Array," *Jpn. J. Appl. Phys.*, Vol.48, No.7, pp.07GD01-1-6, (2009).
- [6] T. Ohtani, H. Ogi and M. Hirao, "Noncontact Evaluation of Surface-Wave Nonlinearity for Creep Damage in Cr-Mo-V Steel," *Jpn. J. Appl. Phys.*, Vol.48, No.7, pp.07GD02-1-6, (2009).
- [7] M. Ito and T. Mochizuki, *Cho-onpa Shindan Souchi*, (Corona

- Pub., Tokyo, 2002) p.179 [in Japanese].
- [8] K. Nakamura, K. Fukazawa, K. Yamada and S. Saito, "Broadband Ultrasonic Transducers Using a LiNbO_3 Plate with a Ferroelectric Inversion Layer," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol.50, No.11, pp.1558-1562, (2003).
- [9] H. Adachi, K. Wakabayashi, M. Nishio, H. Mizuno and T. Kamakura, "Fabrication of Ultrasonic Transducers with KNbO_3 Piezoelectric Single Crystal for Detecting Harmonic Signals," *Jpn. J. Appl. Phys.*, Vol.40, No.9B, pp.5698-5702, (2001).
- [10] I. Akiyama, A. Ohya and S. Saito, "Speckle Noise Reduction by Superposing Many Higher Harmonic Images," *Jpn. J. Appl. Phys.*, Vol.44, No.6B, pp.4631-4636, (2005).
- [11] M. Fukuda, M. Nishihira and K. Imano, "Real Time Extraction System Using Double-Layered Piezoelectric Transducer for Second-Harmonic Ultrasonic Pulse Waves," *Jpn. J. Appl. Phys.*, Vol.45, No.5B, pp.4556-4559, (2006).
- [12] H. Yamada and M. Onoe, "Double Frequency Ultrasonic Search Unit," *Hihakai Kensa*, Vol.20, No.11, pp.605-608, (1971) [in Japanese].