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Development of air-coupled ultrasonic probe using air-column and piezoelectric composite

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1. Introduction

The transmission amplitude of ultrasound is important to improve signal-to-noise ratio in air-coupled ultrasonic method. The probes are required both to compensate acoustic impedance mismatch with air and to equip high electromechanical coupling. Although 1-3 piezoelectric ceramic (piezoceramic) and polymer composite is the first solution, the noise occurrence may be problem as the ratio of the polymer increases. Then, authors focused on the fact that the side of the piezoceramic pillars were not constrained by solid material in most proven commercial probe.[1,2] We found that the large flexural vibration of the front plate (FP) played dominant role on the beam formation by lab-made air-column (AC) probe, where dicing kerf in piezoceramic was not filled with the polymer, and developed a frequency design method based on piezoelectric coupling finite element analysis (FEA).[3] However, further experiments have also suggested the importance of the small FP amplitude on the piezoceramic. In this paper, we present the principle of the AC probe, including condition on in-phase excitation, and the status of Lab-made probes.

2. Principle

A feature of conventional AC probe (C-AC probe) is acoustically thick FP for in-phase vibration. Initially, the piezoceramic pillars with high length-to-width ratio was studied for medical applications **[Fig.1(a)]**.[4] Although broadband transmission to water was possible without acoustic matching layer (ML), there was a problem with structural strength. The application to the air-coupled probe was realized by the reinforcement with the honeycomb core and the design of the multilayer MLs with fibrous material on the top surface **[Fig.1(a)']**.[1,2]

Since lab-made AC probe with thin FP less than kerf width generated large amplitude on kerf-intersection region (KIR) by broadband excitation, the probe utilizing fundamental flexural resonance frequency in KIR was proposed (thin-FP AC probe; T-AC probe).[4] Although the phase of FP in KIR must be delayed from that of the piezoceramic element, it is effectively ignored when the element resonance is much higher than the KIP resonance. The frequency design is performed using piezoelectric coupling FEA due to complex boundary conditions on KIR.[4]

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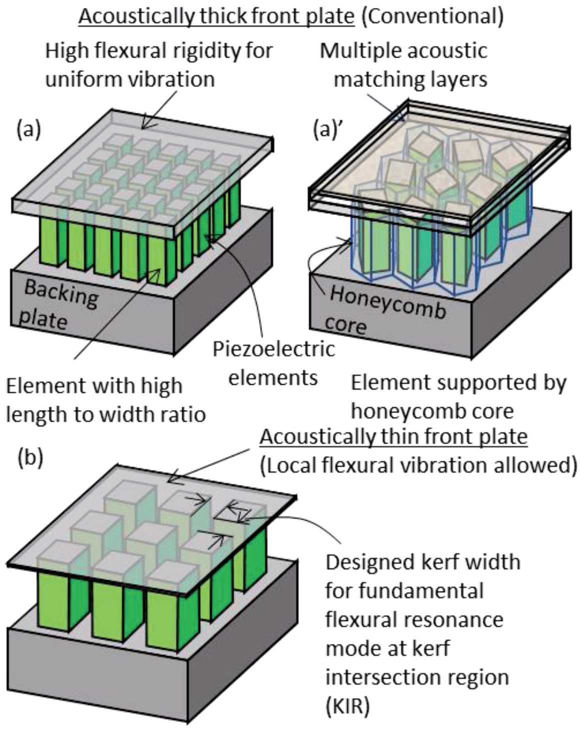

Fig. 1 Schematics of 1-3 AC probes. C-AC probes for (a) water immersion and (b) commercialized air-coupled measurement. (c) T-AC probe.

Figure 2 represents schematics of amplitude distribution on the transmission surface. In-phase large-amplitude local vibration is occured in T-AC probe in addition to uniform vibration in C-AC one.

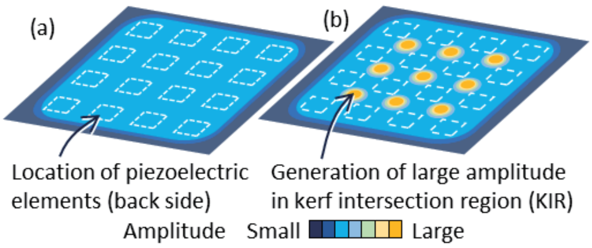

Fig. 2 Schematic illustrations of amplitude distribution on front plate. (a) C-AC and (b) T-AC probes.

3. Experimental method

Figure 3 shows the lab-made AC probe.The FP was bare Al plate **[Fig. 3(a)]**. The dimensions of the elements were the same except for the FP thickness (0.5 mm and 0.1 mm for C-AC and T-AC probes, respectively) to study operating mechanisms **[Fig. 3(b)]**.[4] The kerf width (0.7 mm) was determined as the resonance in KIR became 400 kHz in the FEA.

The resonance frequency was 385 kHz in C-AC probe from the local minimum of the impedance magnitude, but that in T-AC could not be judged. It is estimated to be 600 kHz or more from the FEA. The nominal frequency of commercial C-AC probe was 400 kHz (Ultran, NGC400-S13).

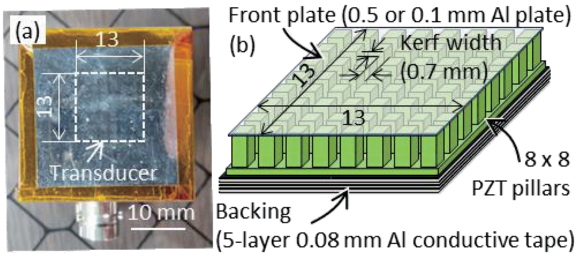

Fig. 3 Lab-made AC probe. (a) transmission surface (bare Al). (b) Dimensions. Front plates with 0.5 mm and 0.1 mm for C-AC and T-AC probes, respectively.

The particle velocity distribution driven by 5 V_{pp} sinusoidal signal was measured by lock-in detection with laser Doppler vibrometer (LDV). The propagation waveform was measured at 50 mm using LDV and polyimide film (5 µm), where each probe was excited by 30 cycles of tone burst signal with the amplitude of 40 V_{pp} and the frequency of every 10 kHz from 200 kHz to 600 kHz.

3. Results

Figure 3 shows the distribution of the particle velocity, where broken square represents active area. The frequency of C-AC and T-AC probes were 385 kHz (element resonance) **[Fig. 3(a)]** and 415 kHz (KIR resonance) **[Fig. 3(b)]**, respectively.

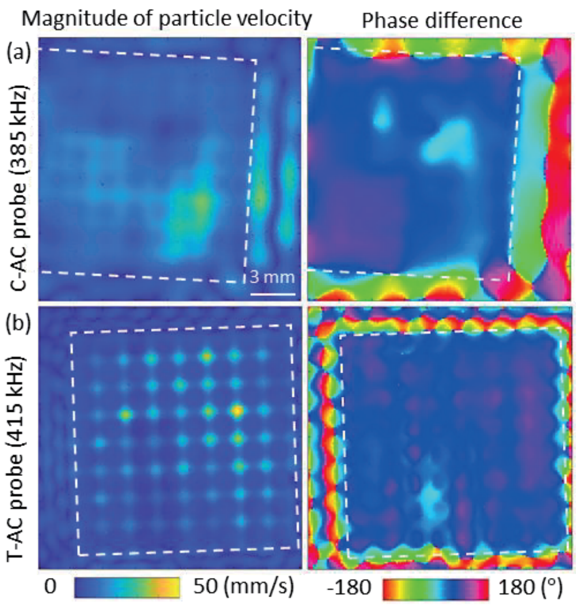

Fig. 4 Distribution of particle velocity magnitude. (a) C-AC probe at 385 kHz. (b) T-AC probe at 415 kHz.

The amplitude increase in KIR was observed in T-AC probe. The average magnitudes of T-AC probe (6.3 mm/s) was smaller than that of C-AC one (11 mm/s). The standard deviation of the phase in T-AC probe (21°) was comparable to that in C-AC one (24°).

Figure 5 shows the frequency dependence of rms magnitude of the particle velocity waveform from 20th cycle to 25th cycle. The peak values of Lab-made probes **[Figs. 5(b) and (c)]** were several times higher than commercial probe**[Fig. 5(a)]**, although the value of the commercial one became the maximum at the nominal frequency. Since the magnitude of surface vibration in T-AC probe was about half as large as that in C-AC one [Fig. 4], the transmission efficiency of KIR was much higher, suggesting key point for further improvement.

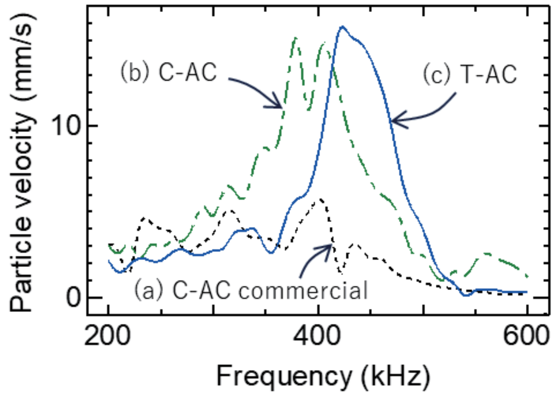

Fig. 5 Frequency dependence of particle velocity magnitude at 50 mm. (a) Commercial C-AC, (b) Lab-made C-AC, and (c) Lab-made T-AC probes, respectively.

4. Conclusions

Effectiveness of T-AC probe was demonstrated for the air-coupled ultrasonic transmitter. With KIR, approaching resonance the frequency to that of the piezoelectric element and expanding area are important strategy for improvement. In future, the principle will be verified through the propagation analysis of the FEA, aiming the design optimization.

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