Use of energy trapping type piezoelectric transducer to suppress lateral vibration in the transducer

Kazuhiko Imano\textsuperscript{a)"

Abstract Vibration characteristics of two types of piezoelectric transducers with whole-surface electrode and a partially electrode were driven in the thickness direction in air and water acoustic loading on the acoustic radiation surface. Partial electrode transducers had an acoustic loading on the side surface, which is called “siding”. Use of partial electrode transducer allowed the lateral vibration on the acoustic radiation surface to be flattened, and thickness vibration becomes almost uniform. Schlieren observation and wavenumber analysis indicate that lateral waves were identified as Lamb waves. An A1 mode Lamb wave is given as a sample to verify the usefulness of this method.

key words: piezoelectric transducer, thickness vibration, lateral vibration, partial electrode transducer, siding, Lamb wave, A1 mode Lamb wave

Classification: Circuits and modules for electronic instrumentation

1. Introduction

Piezoelectric transducers have been used for the transmitting and receiving ultrasonic waves in various non-destructive tests and diagnoses, and are used for a range of instrumentation and medical imaging\textsuperscript{1). Many of the piezoelectric transducer, for example a circular type transducer, are used in the thickness expansion mode, and the sound waves from thickness driven transducers are believed to be plane waves. However, since the transducer is an elastic body, other wave components propagate in the lateral direction (in-plane) and interfere the thickness direction mode of the transducer. For this reason, vibration of the transducer is not like piston source and vibration velocity is distributed on the surface of transducer\textsuperscript{2-5). As a result, the sound field is not always generated as represented by Rayleigh integral\textsuperscript{6-12). Usually, the piezoelectric transducer has the backing material to suppress the ringing vibration which gives an acoustic load on the back of transducer to improve pulse characteristics\textsuperscript{13-16). Another method of suppressing ringing vibration is to mount a matching layer on the front surface of the transducer\textsuperscript{17,19). However, both method are of limited effectiveness in suppressing lateral vibration propagating from the edge toward the center of transducer\textsuperscript{17-20). Moreover, the wave propagating properties of the lateral waves are not fully understood. Although, Ueha et al. estimated these waves to be A-mode Lamb wave, a detailed analysis has not been performed\textsuperscript{15,19). In addition, there has been no research on suppression of this wave. In this work, the effect of suppression by “siding”\textsuperscript{21) was demonstrated experimentally and an analysis of the mode of lateral waves was attempted from the analysis for wavenumber spectrum.

2. Experiments

2.1 Transducer with siding

When thickness mode vibration is excited to the piezo material, lateral vibration generated due to the elastic coupling with the thickness vibration will also be excited. In addition, if an exciting voltage is applied to the piezoelectric transducer, a lateral wave concurrently with the vibration in the thickness direction is also generated electrically. Source of lateral vibration exist at the circumference of the transducer. There are thus two factors that contribute to the occurrence of lateral waves, which propagate from the edge to the center of the transducer and they spreads the opposite process and repeats this process on the surface of transducers. At the center of the transducer, only thickness vibration is observed until lateral wave arrives. Thereafter, lateral waves are multi-reflected in the plane of the transducer to form the multiple waves\textsuperscript{15,20). In order to suppress the lateral vibration, two types of transducer were used: a whole electrode type and a partially electrode type. Fig.1 shows the pictures of the whole electrode type of transducer (a) and the circular partial electrode type of 30×40 mm rectangular piezoelectric plate (b). The whole electrode type is conventionally used transducer. In the partial electrode type transducer, partial electrodes are fabricated to both sides of one rectangular piezoelectric plate which is the electrode part and the outside made of the same ceramic.

\textsuperscript{a)\textsc{Imano@gipc.akita-u.ac.jp}}
material as shown in Fig. 1(d). That is, the outer portion of the electrode operates as the acoustic load and the same acoustic load and the same acoustic impedance as the internal part under electrodes (Fig. 1(d)). Thus, the outer part of the electrode exerts a lateral load, we have called this condition “siding”. This structure is acoustically continuous with no bonding part between transducer and siding material. Moreover, this transducer is simple in structure and easy to manufacture. The piezoelectric transducers used in the experiment were made of lead-titanate-based ceramic $\text{PbTiO}_3$ having an electrode diameter of 20 mm $\phi$, a thickness of 2 mm, a resonance frequency of 1 MHz, an electromechanical coupling coefficient in the thickness direction of 0.54, and in the lateral direction of less than 0.03 (Fuji Ceramics: M-6), respectively. The material of this transducer has an electromechanical coupling coefficient in the lateral direction is almost 0. There is only elastic coupling due to expansion and contraction in the thickness direction, and lateral vibration due to the excitation by electrical coupling does not occur (22,23).

2.2 Admittance response of transducers
Fig. 2 shows the electrical admittance responses of the whole electrode type (without siding) (a) and the partial electrode type (with siding) (c) in air which is the acoustic load on the radiation surfaces of transducers. Fig. 2 (b) (without siding) and (d) (with siding) show the admittance characteristics when water is loaded onto the acoustic radiation surface (thickness direction). The peak admittance around 1 MHz of transducers (a) and (c) are almost equal. Furthermore, the motional admittance response of partial electrode type (d) is not reduced compared with whole electrode type (b). Because the motional admittance are proportional to the vibration velocity of the acoustic radiation surface of the transducer, these figures confirm that siding is almost no effect to the thickness vibration efficiency. In the following experiments the front acoustic radiation surface is loaded with water assuming that it radiate sound in water and the back side surface of the transducer is air. The velocity of surface of transducer was observed in the diameter direction with a laser Doppler vibrometer (Graphitec: AT3100 & AT027). Measurement method and system were the same as in ref. 21. Optical method is useful for this experiments (24-28).

2.3 Measurements of vibration velocity distribution
Figs. 3 (a) and (b) show the vibration distribution of the acoustic radiation surface for the whole electrode type without siding and for the partial electrode type with siding, respectively. The distribution pattern varied as the sound wave propagation in water. Measurements were made every 0.1 mm in the diameter direction through the center. These figures show the vibration velocity after 10 $\mu$s from exciting the transducer. The results in Fig. 3 (a) shows that when siding is not applied, lateral waves that appear to be Lamb waves are seen on the acoustic radiation surface. The lateral vibrations superimpose the
thickness vibration, and the entire waveform moves up and down in the vertical direction. In contrast to this, in Fig. 3 (b), these wave almost disappear and the vibration distribution becomes almost flat. Since acoustic energy is almost trapped under the electrodes in partial electrode transducer, there are few reflection from the edge of rectangular plate.

2.4 Schlieren observation of sound field

Fig. 4 shows Schlieren photograph of the underwater sound field when the transducer was driven with 1 MHz, burst sine waves of 80 cycles of 100 Vp-p to evaluate the sound field in water. The photographs show that the 1 MHz ultrasonic wave radiated upward from the lower transducer. As can be seen in Fig. 4 (a), waves other than the waves generated from the thickness vibration are radiated to the outside of the radiating face. These results suggest that the lateral vibration is one cause of unnecessary radiation and is consistent with the previous experimental result of the authors. Conversely, in the partially electrode transducer shown in Fig. 4 (b), unnecessary radiation was drastically reduced, and the ultrasonic beam is narrowed at the head of the wave front. This seems to be mainly due to the energy trapping effect. This property may be advantageous for improving spatial resolution in the non-destructive evaluation. Even an ideal piston sound source generates side lobes, but these are small in the case of the partial electrode transducer. Since the side lobe is one factor that determines the directivity of the transducer, it is important to consider the directivity of a partial electrode transducer in designing the ultrasonic probe.

2.5 Wavenumber analysis

For the lateral vibration such as Fig. 3 (a), a wavenumber analysis was performed to identify the mode of the Lamb wave existing on the acoustic radiation surface, as shown in Fig. 5 (a). In the figure, vertical and horizontal axes show the amplitude and wavenumber (1/λ), respectively. The figures shows that not a single mode, but multiple Lamb wave modes will be exist on the acoustic radiation surface. Fig. 5 (b) is one sample of Lamb wave dispersion curve which corresponds to the peak wave number (1/λ) in Fig. 5(a). In this case, we can determine this large wavenumber ( 1/λ = 426.6 mm ) component as A1. Since λ=1/426.6 = 2.344 mm from Fig.5 (a), Lamb wave velocity can be determine from f・λ=1MHz・2.344 mm=2344 m/s. This velocity corresponds to A1 mode Lamb wave as shown in Fig. 5(b). Other modes were similarly obtained from wave number analysis. For the every lateral waves, siding is effective because siding is the same material for the transducer and therefore acoustic impedance always becomes equal and acoustic matching condition is always achieved for all Lamb waves. Since wavenumber spectrum varies with time, it is considered that the Lamb waves do not exist as a single standing wave.

3. Conclusion

This paper proposes a new method called “siding” applied to the side surface of a piezoelectric transducer as a method of flattening the vibration velocity distribution on the acoustic radiation surface. The experiments showed that this method flattened the vibration velocity distribution on the radiation surface,
resulting in almost pure thickness vibration. Future work will include closer examination of the mode of the Lamb wave existing on the acoustic radiation surface of the piezoelectric transducer though experiment and analysis. I would like to improve the performance of the ultrasonic probe using these results.

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