# DEVELOPMENT AND APPLICATION OF CONTACT-TYPE LINE-FOCUS ULTRASONIC PROBE

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## Abstract

A contact-type line-focus ultrasonic probe has been developed. The probe is composed of a quarter cylindrical wedge and a piezoelectric transducer attached to its cylindrical surface. A key feature of the developed probe is that longitudinal wave is incident to the testing object at all angles from 0° to 90° simultaneously. Basic characteristics of the probe have been examined by visualizing ultrasonic wave field and by evaluating the directivity. Some applications of the probe have been also investigated. It has been shown that the probe can transmit and receive Rayleigh and generalized Lamb waves in objects having relatively wide range of mechanical properties. It has been also shown that this probe can be applied to TOFD method.

## 1. Introduction

Non-destructive testing is a key technology in industry nowadays. Ultrasonic testing may be one of the most widely applied among others. However, further improvements of accuracy and reliability are still expected because even up-to-date techniques cannot fulfill all requirements for precise detection or sizing of defects and damages. Many studies are being conducted from various aspects: for example, transmission and reception of ultrasonic waves, numerical processing of detected waveforms.

Development and improvement of ultrasonic probes may be one of the most effective approaches to that purpose. Many kinds of ultrasonic probes have been developed and utilized so far. The authors have proposed contact-type line-focus ultrasonic probe and examined its basic characteristics during the past ten years. This probe can be used in a similar manner to conventional angle beam probes but has several unique features.

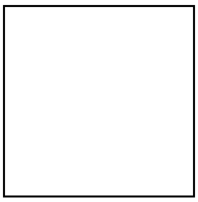


*Figure 1: The first prototype.*

In this paper, the development of contact-type line-focus ultrasonic probe is summarized and several applications of this probe are discussed briefly.

## 2. Basic structure of developed probe

The contact-type line-focus probe is basically composed of a quarter-cylindrical wedge and a piezoelectric transducer attached to its cylindrical surface. When electric pulse is applied to the transducer, longitudinal pulse wave is generated at the cylindrical surface of the wedge, propagates in the wedge cylindrically and focuses into a line at the corner of the wedge at all angles ranging from 0° to 90° against the testing object.

Figure 1 shows the first prototype of the probe [1,2]. The wedge (25 mm in radius and 50 mm in width) is made of polymethyl methacrylate (PMMA). The following sheets and films are stacked on its cylindrical surface: (1) a copper sheet electrode (50 μm), (2) a polyvinylidine fluoride (PVDF) film (40 μm, Kureha Corp.), (3) a copper sheet electrode (50 μm), (4) a rubber sheet (1 mm) and (5) a quarter-cylindrical PMMA shell (2 mm). They are pressed onto the wedge by the outermost PMMA shell with four screws. It was verified that this probe can transmit and receive Rayleigh and Lamb waves in steel and aluminum plates [1,2].

The second prototype was then manufactured by a company (Toray Techno Inc., presently Toray Engineering Co. Ltd.) as shown in Fig. 2 [2,3]. The wedge of this probe is made of PMMA (10 mm in radius and 10 mm in width). A piezoelectric polymer film of P(VDF/TrFE) [4] with electrodes is adhered to the cylindrical surface of the wedge. It was confirmed that the performance of this probe was good enough for transmitting and receiving Rayleigh and Lamb waves [2,3].

Probes of the same type were manufactured and evaluated thereafter. The probe was put in a case of conventional angle beam probe for protection and easy handling, which means that basic usage of the probe is similar to that of conventional angle beam probe. Experimental results shown in the rest of this paper were obtained for this type of probe.

## 3. Visualization of ultrasonic waves

A key feature of the developed probe is that longitudinal wave is to be incident to the testing object at all angles from 0° to 90° simultaneously. The incident wave is refracted at the interface between the wedge and the object. Therefore, it is expected that both longitudinal and shear waves would propagate into the object at all refraction angles from 0° to 90°. In order to verify this, visualization of ultrasonic waves transmitted by this probe was conducted [5,6].

Ultrasonic wave transmitted by the probe into a SUS304 steel block was visualized by a technique developed by Takatsubo *et al.* [7] as shown in Fig. 3. Figures 4 and 5 show the results in which the displacement normal to the observation surface is plotted in gray scale. Propagation of Rayleigh wave is clearly observed on the top surface. On the side surface, though it is somewhat unclear, it has been confirmed that both longitudinal and shear waves propagate cylindrically in all directions from the corner of the wedge.

On the other hand, plain strain numerical analysis of elastic wave propagation was conducted by a finite element code (ABAQUS). The probe was modeled by a quarter circle (10 mm in radius) of PMMA while the specimen was modeled by a semicircle (35 mm in radius) of SUS304. The normal stress and the normal displacement were assumed to be continuous along the probe-specimen interface and no friction was imposed. Generation of longitudinal wave by the piezoelectric film was modeled by imposing a uniform radial displacement (a single cycle of sinusoidal wave with 100 nm-amplitude and 2 MHz-frequency) on the cylindrical surface of the probe. Figure 6 shows the result, where the absolute value of the displacement is plotted in color scale. The time 4 μs in Fig. 6 approximately corresponds to the time 0 μs in Fig. 5. The numerical result matches well with the experimental result. It was found that the probe transmits ultrasonic waves in directions of both positive and negative refraction angles, which had not been expected in advance.

## 4. Evaluation of directivity

Following the results of visualization, directivity of the developed probe was evaluated [5,6]. A semicircular disk (65 mm in radius and 32 mm in thickness) of aluminum alloy was used as specimen as shown in Fig. 7. The corner of the wedge was located at the center of the specimen. An electric pulse (nominally a single cycle of sinusoidal wave with 2-MHz frequency) was applied to the probe by using a waveform generator (Lecroy, LW420) and a gated amplifier (Ritec, GA2500). Longitudinal and shear waves were detected with conventional longitudinal and shear wave probes, respectively. The detected signals were sampled digitally and processed with PC. Wavelet transform with Gabor wavelet [8] was employed in order to evaluate frequency dependence of the directivity.

A simple theoretical analysis was conducted by considering plane longitudinal wave of unit amplitude to be incident to the interface of PMMA and aluminum alloy at various angles. The amplitudes of refracted longitudinal and shear waves were calculated theoretically. It should be noted that the situation considered in this simple analysis is different from actual phenomenon in some respects and hence no result is obtained for negative refraction angles.

Finite element simulation was also conducted to obtain more realistic result. The method of simulation is similar to that in the visualization except that the specimen is made of aluminum alloy. The radial and circumferential displacements were computed at several nodal points that are 18 mm away from the corner of the wedge. The displacement waveforms obtained at each nodal point were processed using wavelet transform.

The directivity was evaluated as shown in Figs. 8 and 9 for longitudinal and shear waves, respectively. The maximum amplitude of the wavelet transform of displacement waveform at each refraction angle is plotted in these figures, where the vertical axis is normalized with the maximum value for all refraction angles. The experimental, theoretical and numerical results coincide fairly well with each other. For longitudinal wave, the amplitude takes its maximum at around 0° to 10° and distributes almost symmetrically for positive and negative refraction angles. On the other hand, the amplitude becomes maximum at refraction angle around 50° to 70° for shear wave. The directivity is slightly dependent on the frequency.

The coincidence between the experimental and numerical results indicates that the probe used in the experiment possesses similar characteristics of the probe assumed in the finite element simulation.

## 5. Guided waves in plates and coatings

Use of guided waves (Lamb and generalized Lamb waves) is advantageous in testing of plates and coatings. However, dispersive nature of such guided waves often causes difficulties in transmitting and receiving them. One of the most popular techniques may be use of angle beam transducer, in which a specific incident angle is required for a given plate or coating with given thickness and material properties according to the Snell's law. In contrast, the contact-type line-focus ultrasonic probe has all incident angles from 0° to 90°. Therefore, a single probe could be utilized for transmitting and receiving guided waves in fairly wide range of plates and coatings.

It has been already verified that the developed probe can successfully transmit and receive guided waves in plates and coatings [2,3]. Examples of received waveforms in a 0.3 mm-thick aluminum alloy plate are shown in Fig. 10 where *d* denote the distance between transmitter and receiver. It has been shown that the dispersion relation of guided waves in plates and coatings can be accurately evaluated by wavelet analysis of received waveforms and, in addition, that the elastic constants of plates or coatings can be estimated by conducting inverse analysis based on dispersion relation. Details of these results were reported in the previous paper [9].

Transmission and reception of Lamb waves by the probe were investigated further by finite element simulation similar to that in visualization mentioned above [10]. The plate analyzed is 1 mm-thick and made of aluminum alloy.

Generation of ultrasonic pulse was modeled by imposing a uniform radial displacement (a single cycle of sinusoidal wave with 100 nm-amplitude and 2-MHz frequency) on the cylindrical surface of the wedge. The result of numerical simulation of Lamb wave excitation is shown in Fig. 11 where distribution of vertical displacement is plotted in color scale. After the longitudinal wave generated by the transducer reaches to the corner of the wedge (4 μs), Lamb wave is transmitted in the plate and travels along the plate (6-8 μs). The principal mode is $A_0$ mode but $S_0$ mode is also observed. Under the condition assumed in this simulation, $A_0$ mode and $S_0$ mode have almost the same velocity.

In the simulation of Lamb wave reception, an artificial wave source (a single cycle of sinusoidal displacement with 2-MHz frequency in both horizontal and vertical directions) was supposed at a point 40 mm away from the corner of the wedge. Figure 12 shows the result, where the Lamb wave propagates along the plate from right to left toward the probe. After $S_0$ mode first reaches the corner of the wedge, refracted wave propagates in the wedge (8-10 μs). Similar phenomenon also observed later for $A_0$ mode (14-16 μs). It should be noted that the refracted wave is not cylindrical but planer as seen clearly at 10 μs. Figure 13 shows the time variation of radial displacement along the cylindrical surface of the wedge. It can be seen, for example, that the first pulse reaches there at about 10 μs at the angle of 90° but later at other angles. This makes the time resolution of the pulse lower unfortunately.

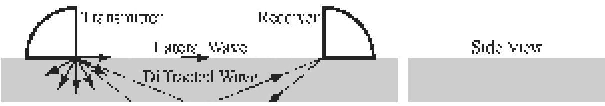
## 6. Application to TOFD

The basic characteristics of the contact-type line-focus probe is expected to be also suitable for the time of flight diffraction (TOFD) technique in which angle beam longitudinal wave probe with relatively wide directivity is usually preferred. Therefore, application of the developed probe to TOFD was attempted [11].

Figure 14 shows experimental setup. The specimen used was a SUS316L plate (30 mm in thickness). A slit (0.3 mm in width) was introduced to the specimen with a metal saw (50 mm in radius). Figure 15 shows a result for maximum slit depth of 10 mm, where top and bottom figures show D-scan image and A-scope waveform, respectively, when the distance between transmitter and receiver is 42 mm. It can be seen that lateral wave, diffracted wave and back-wall echo are clearly observed. Therefore, it has been shown that the developed probe has a potential for application to TOFD.

## 7. Conclusions

Development and applications of contact-type line-focus ultrasonic probe has been summarized in this paper. It has been shown that the developed probe




can be used in a similar manner to conventional angle beam probe but possesses several unique features.

Following the results reported in this paper, improvement of sensitivity is being considered now by using piezoelectric ceramics or piezoelectric composite transducers especially for more precise sizing of defects in TOFD. Also being developed now is an SH-type line-focus probe whose possible application has been reported elsewhere [12].

## 8. References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