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# Measurement of Axisymmetric-Wave Speed in a Pipe by Using Piezoelectric Cylindrical Transducers

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**Abstract**

This paper presents an experimental technique to generate and detect axisymmetric longitudinal waves in a pipe by using piezoelectric cylindrical transducers. Radial pulses transmitted by one transducer have propagated in two opposite directions along the pipe, and other two transducers have received the propagating waves. The difference of the transit times measured for the waves in two paths of known distance difference has yielded the phase speed of the wave propagation. Wave speed has been measured in an empty pipe and in a water-filled pipe.

***Keywords:*** *Elastic wave, Phase speed, Piezoelectric cylindrical transducer*

## I. Introduction

Axisymmetric guided waves have been used to inspect pipelines[1]. Generation and detection of axisymmetric waves have been achieved by using conventional oblique-incident-beam transducers or comb transducers[1], but in this paper axisymmetric waves are transmitted and received by cylindrical transducers[2]. A pair of semi-annular transducers is conveniently installed on the outer wall of a pipe as shown in Figure 1(a).

Ultrasonics provides a convenient, non-intrusive means for the measurement of various properties of liquids confined in pipes and tanks[3]. In a conventional design of an ultrasonic flowmeter, however, as the tube's diameter decreases so does the measurement sensitivity. Moreover, it may be difficult to design sufficiently small transducers for small diameter tubes.

In order to overcome the disadvantages of conventional ultrasonic flowmeters, the use of cylindrical transmitters shown in Figure 1(a) was suggested[4]. As an initial stage it was attempted to measure the effect of an interior fluid due to its mass density on the speed of the elastic waves propagating along a pipe wall. One transducer excited radially the pipe and induced an axisymmetric longitudinal wave propagating along the pipe wall. Another transducer detected the wave at some distance from the first one, and the propagation time was measured. This propagation time was affected by the fluid confined in the pipe. This measurement scheme showed up to 13% error, which is unsatisfactory.

This paper suggests the use of three transducers as shown in Figure 1(b) in order to improve the accuracy of measurement. One transducer transmits radial pulses, which propagates in two opposite directions along the pipe as axisymmetric longitudinal waves. Other two transducers receive the propagating waves at the opposite sides with different distances from the transmitting one. The difference of the transit times measured for the waves in two paths of known distance difference provides the phase speed of the wave propagation. The measurement is performed in an empty pipe and in a water-filled pipe, and the measured wave speed is compared with calculated one.

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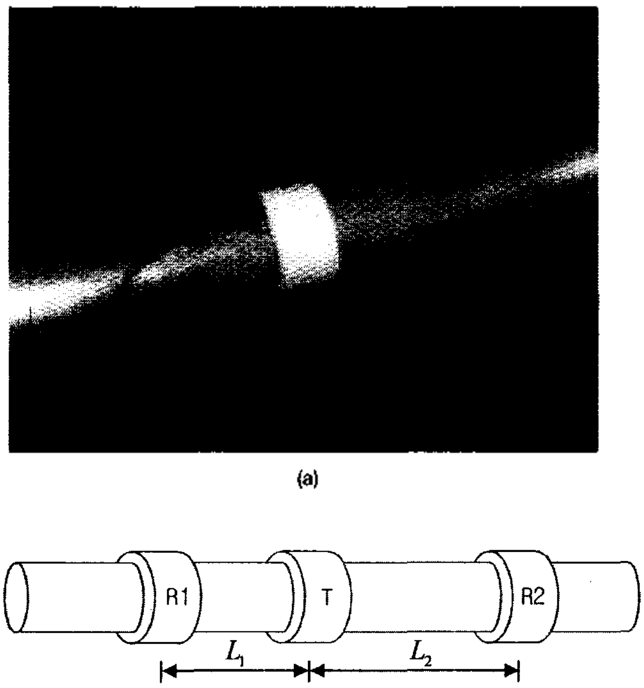
## II. Cylindrical Transducers and Experimental Apparatus

Piezoelectric cylindrical transducers can be used in several applications[2], one of which is the generation of ultrasonic sound field in a pipe for cleaning the interior wall[5]. The transducers were used to generate and detect the elastic waves in a pipe wall[4]. In this paper, three pairs of semi-annular transducers were installed around an aluminum (1100-H14) pipe. The pipe has outer radius 8.0 mm, wall thickness 1.0 mm, and length 1200 mm. The transducers, manufactured by ISTec, were made of PZT (EDO EC-64) and they have thickness 1.0 mm and width 10 mm. Pairs of semi-annular transducers can be easily installed on the outer face of a pipe in the similar way to a device used for bending wave sensing system[6].

In Figure 1(b) the transducer denoted $T$ is the transmitter and the transducers denoted $R1$ and $R2$ are receivers. $R1$ and $R2$ were installed, respectively, at distances $L_1$ and $L_2$ from the transmitter $T$. The distances $L_1$ and $L_2$ were much smaller than the total length of the pipe. Figure 2 depicts schematically the experimental set-up. The set-up consisted of a function generator (Agilent 33120A), a power amplifier (Eliezer HA 400), and a digital oscilloscope (Tektronix TDS3032).




(b)

Figure 1. Arrangement of transducers along a pipe.
(a) photograph of a cylindrical transducer installed around a pipe,
(b) transmitter $T$ and two receivers $R1$ and $R2$.

Electrical pulses produced by the signal generator and amplified by the power amplifier were sent to the transducer $T$. The transmitting transducer $T$ converted the electrical pulses into mechanical vibrations, which in turn induced radial waves that propagated along the pipe wall. The receiving transducers $R1$ and $R2$ detected the elastic waves and converted the mechanical vibrations into electric signals. The transmitted and received signals were sent to the oscilloscope. Figure 3 shows the waveform of the transmitted signal. The center frequency of the signal was 76 kHz.

The path of the wave propagation from $T$ to $R1$ is referred to as Path 1 and the path from $T$ to $R2$ as Path 2. Paths 1 and 2 had different distances. The distance difference $\Delta L$ ($= L_2 - L_1$) of two paths is our concern. The difference of the transit times in two paths is to be measured to yield the phase speed of the wave propagation.

## III. Wave-Speed Measurements

Experiments to measure phase speeds were performed in an empty pipe and in a water-filled pipe. The transducers, however, had a width in the propagation direction and the distance traveled by the wave was not well defined. Therefore, the phase speed determined by dividing the distance between the transmitter and receiver with the time

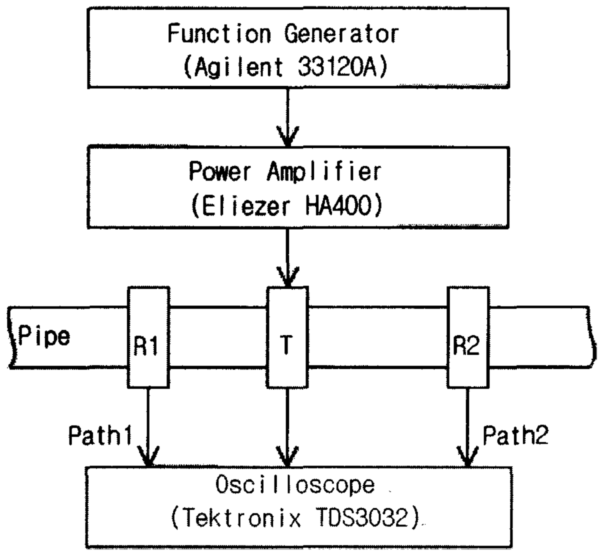



Figure 2. Schematic diagram of the experimental set-up.

Table 1. Comparison between the measured and calculated wave speeds.

| Pipe | time difference $\Delta t$ ($\mu$s) | distance difference $\Delta L$ (mm) | Wave speed, $c$ (m/s) | | Difference (%) |
|---|---|---|---|---|---|
| | | | Measured ($\Delta L/\Delta t$) | Calculated | |
| empty | 22.9 | 111 | 4,847 | 4,806 | 0.8 |
| water-Filled | 22.3 | 111 | 4,977 | 4,861 | 2.0 |

elapsing between transmission and reception was not quite accurate[4].

To overcome this problem, the difference of the two wave paths established by the transmitter and two receivers was considered in the wave speed measurement. The distance of Path 1 of the wave propagation from $T$ to $R1$ is $L_1$ and that of Path 2 from $T$ to $R2$ is $L_2$. $L_2$ is larger than $L_1$, and the distance difference $\Delta L$ is $L_2 - L_1$. For practical purpose, $\Delta L$ can be determined by the difference of the distances between the nearest edges of the transducers. The distance difference $\Delta L$ determined in this way was 111 mm.

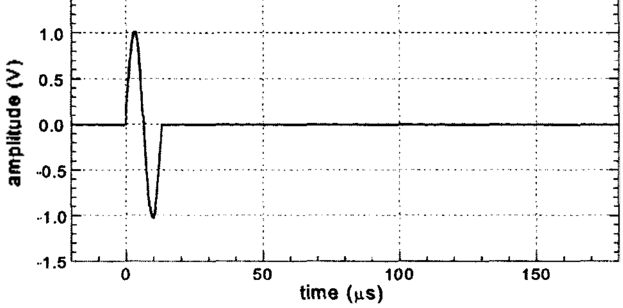



Figure 3. The pulse signal at the transmitting transducer $T$.

The transit time difference $\Delta t$ was measured by comparing the signals of the receiving transducers $R1$ and $R2$ as shown in Figure 4 for an empty pipe and in Figure 5 for a water-filled pipe. Comparison of the transmitted signal in Figure 3 and the received signals in Figures 4 and 5 reveals that the pulse wave was dispersed during the propagation. The time lapses from the beginning of the original pulse in Figure 3 to the beginning of the dispersed pulses in Figures 4 and 5 are the transit times corresponding to the phase velocity.

For the empty pipe, Figures 4(a) and 4(b) depict,

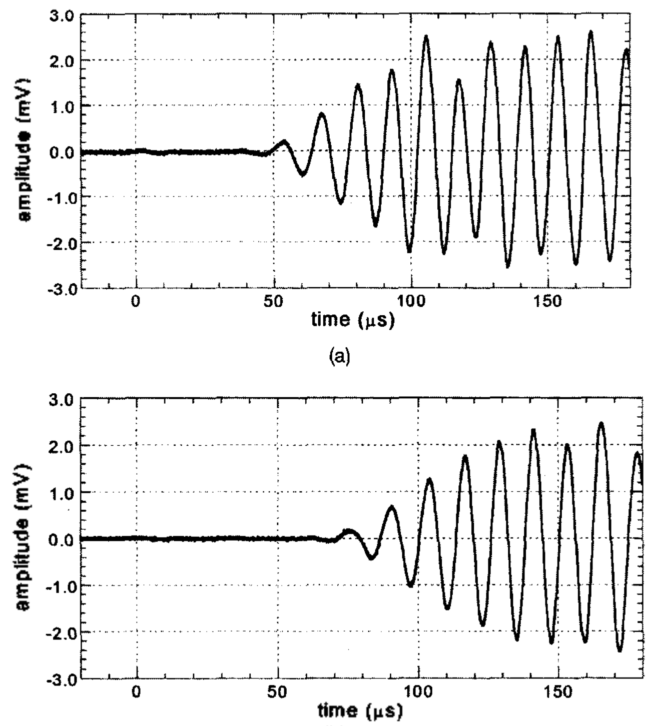



Figure 4. The waveforms of the received signals for the empty pipe. (a) at the receiving transducer $R1$, (b) at the receiving transducer $R2$.

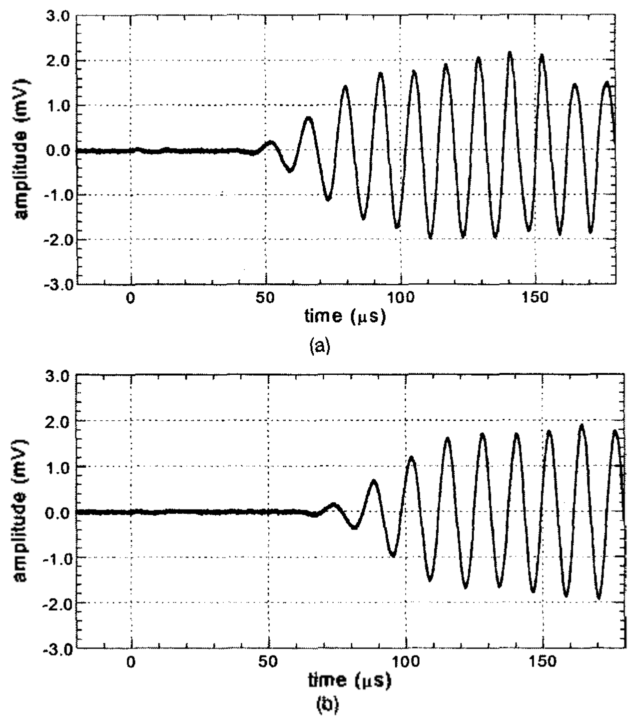



Figure 5. The waveforms of the received signals for the water-filled pipe. (a) at the receiving transducer $R1$, (b) at the receiving transducer $R2$.

respectively, the waveforms of the signals detected by the receivers $R1$ and $R2$. The transit time was measured between the start of the transmitted pulse in Figure 3 and the beginning of the received signals in Figure 4. The transit time $t_1$ for Path 1 measured in Figure 4(a) was 41.7 $\mu$s, and the transit time $t_2$ for Path 2 measured in Figure 4(b) was 64.6 $\mu$s. Therefore, the time difference $\Delta t$ was 22.9 $\mu$s for the empty pipe, and it was listed in Table 1.

For the water-filled pipe, Figures 5(a) and 5(b) depict, respectively, the waveforms of the signals detected by the receivers $R1$ and $R2$. The transit time $t_1$ for Path 1 measured in Figure 5(a) was 40.7 $\mu$s, and the transit time $t_2$ for Path 2 measured in Figure 5(b) was 63.0 $\mu$s. Therefore, the time difference $\Delta t$ was 22.3 $\mu$s for the water-filled pipe, and it was also listed in Table 1.

Dividing the distance difference $\Delta L$ with the measured time difference $\Delta t$ obtains the phase speed of the wave in the pipe. The measured values of the phase speed were summarized in Table 1. These values were compared with calculated ones. Theory of elastic waves in a cylinder was well established[7-9]. This paper cited the calculated values of the wave speed reported earlier in Reference [4], which used a simple equations derived from a thin-shell theory. The comparison of the measured and calculated wave speeds shows errors of 0.8 % for empty pipe and 2.0 % for water-filled pipe. This accuracy is satisfactory.

## IV. Conclusion

Axisymmetric longitudinal waves in a pipe were transmitted and received by using three piezoelectric cylindrical transducers. One transducer transmitted radial pulses, which propagated in two opposite directions along the pipe as axisymmetric longitudinal waves. Other two transducers received the propagating waves at the opposite sides with different distances from the transmitting one. The difference of the transit times measured for the waves in two paths of known distance difference provided the phase speed of the wave propagation.

The measurements were performed in an empty pipe and in a water-filled pipe. The measured wave speeds were compared with calculated ones, and showed satisfactory accuracy with errors of only 0.8 % for the empty pipe and 2.0 % for water-filled pipe.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## [Profile]


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Kyo Kwang Hwang was born in Seoul in 1973. He received the B.S. and M.S. degrees in mechanical engineering from Soongsil University in 2001 and 2003, respectively.

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Jin Oh Kim was born in Seoul in 1958. He received the B.S. and M.S. degrees in mechanical engineering from Seoul National University in 1981 and 1983, respectively, and the Ph.D. degree from the University of Pennsylvania, U.S.A. in 1989.

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