Plate Thickness and Transducer Distance Dual Inversion with Dry Contact Ultrasonic Lamb Wave Transducers

by

J. Pei and B. T. Khuri-Yakub

Edward L. Ginzton Laboratory, Stanford University, Stanford, CA 94305

ABSTRACT

Ultrasonic Lamb wave techniques are widely used in a number of NDE applications. Recent development in dry contact Lamb wave transducers enables one to efficiently excite Lamb waves without the aid of liquid couplant. However, in order to perform thickness measurement in a plate-like structures, the transducer to transducer distance has to be fixed and known to a good accuracy, which places strict mechanical requirements during actual implementation. In this paper, we propose a novel technique that utilizes spectrum analysis on the receiver signal and invert for both the plate thickness and transducer to transducer distance. A pair of pin transducers are used to excite and detect the A_0 mode Lamb wave in a plate and the receiver waveform is captured for a windowed FFT. The signal phase changes with both the plate thickness and the transmitter to receiver distance, but with different sensitivity coefficients. Therefore, with proper calibration, we are able to use an optimization algorithm to perform simultaneous thickness and distance inversion. With the relaxed requirement for known transducer to transducer distance, this technique extends the advantages of the dry contact transducers with added implementation flexibility.

INTRODUCTION

Dry contact Lamb wave transducers have been used for nondestructive evaluation (NDE) of erosion/corrosion for pipes or other plate-like structures[1,2]. Although the benefit of dry contact makes it practical for many applications, accurate transducer to transducer distance is still necessary to perform thickness measurement and precise tomography. In this paper, we propose a method that employs waveform analysis in order to obtain both the plate thickness and transducer to transducer distance simultaneously. When a pair of Lamb wave transducers are used to excite and receive A_0 mode Lamb wave in a plate, any change in plate thickness can be detected by the change in the Lamb wave velocity due to the dispersive nature of the A_0 mode. As a result, the phase delay of the receiver signal changes with both the thickness and transducer distance in a non-linear fashion and thus, we are able to measure the thickness and distance simultaneously by analyzing the phase response of the receiver signal in a reasonably wide frequency range. We demonstrate that with this technique, we are capable of measuring steel plate thickness with an accuracy of 1% without prior knowledge of transducer to transducer distance, and therefore great implementation flexibility can be obtained with such a NDE system.

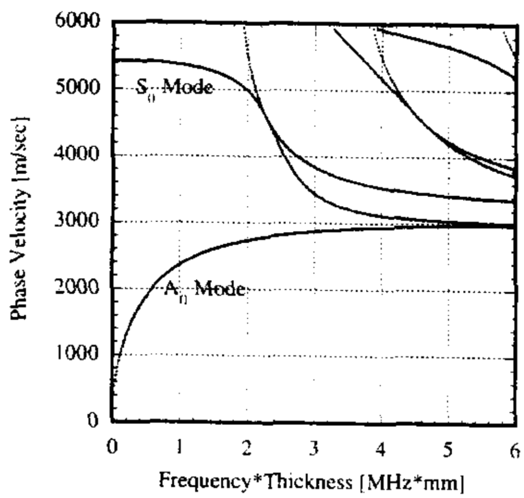


Figure 1. Dispersion relation of the first few modes of Lamb waves in a steel plate.

THEORETICAL BACKGROUND

Plate thickness measurement with A_0 mode Lamb waves has been demonstrated earlier [2]. We are particularly interested in the A_0 mode due to its dispersive nature at low frequencies. As indicated in Fig. 1, at a fixed frequency, the A_0 mode Lamb wave velocity increases with plate thickness. Once the transducer frequency is selected well below the cutoff frequency of any Lamb wave modes other than S_0 and A_0 mode, and due to the asymmetry of the Lamb wave pin transducers[3], most of the excitation displacement

0-7803-4153-8/97/$10.00

field is perpendicular to the plate surface, and A_0 mode becomes the predominantly excited mode. In most of the plate-like structures of our interest, the plate thickness is usually around 10 mm and our transducer

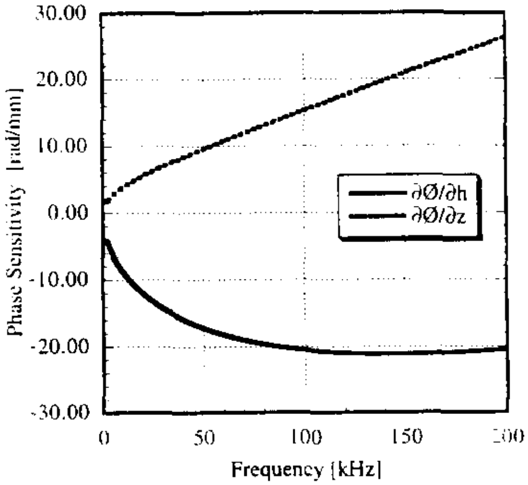


Fig. 2 (a) Phase sensitivity to Lamb wave propagation distance (solid line) and to plate thickness (dashed line).

is chosen to have a resonant frequency around 50 kHz with about 80% bandwidth, which gives us the upper bound of the frequency-thickness product to be below 1 MHz mm, and thus satisfies the low frequency-thickness product condition. As the Lamb wave propagate across a distance z from the transmitting transducer to the receiving transducer, the phase delay associated with such a distance can be written as:

$$\phi = \frac{2\pi f z}{V_p(h)} \qquad (1)$$

where V_p the Lamb wave phase velocity, which is a function of the plate thickness h, and f is the frequency. The phase sensitivity to distance $\frac{\partial \phi}{\partial z}$ and to thickness $\frac{\partial \phi}{\partial h}$ therefore can be calculated from (1). Figure 2 shows the phase sensitivities of A_0 mode Lamb waves on a 10 mm thick steel plate with a propagation distance of 50 mm. As we can observe, the sensitivity to the plate thickness vs. frequency carries a very different shape than that to the propagation distance. This implies that a measured phase curve vs. frequency should yield an unique set of thickness/distance value. Hence, if we can take measurement of phase delay at a range of frequencies, it is possible to perform an inversion since the two sensitivities are not linearly dependent with each other.

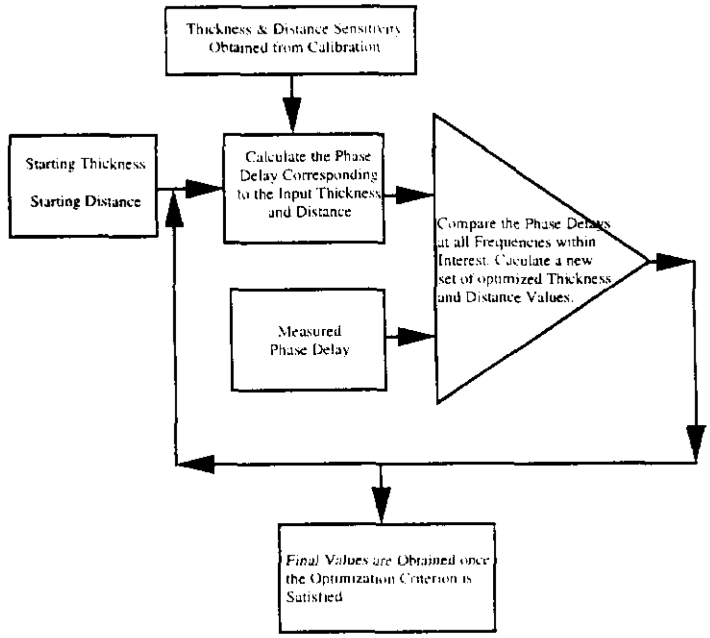


Fig. 3 Flow chart of the optimization program that calculates the plate thickness and transducer pin to pin distance from the receiver signal phase measurement.

A numerical optimization program is developed to calculate the distance and thickness value as shown in Fig. 3. One can assume a starting point for the thickness and distance values. Because of the uniqueness of the solution, it is not necessary to have accurate starting point for the program to converge. The starting value is used to calculate the phase delay with the thickness and distance sensitivity obtained from calibration. This phase delay is then compared with the measured phase delay on a new test plate and both sets of data are fed into the optimization code to minimize the mean square error within the transducer bandwidth. The new thickness and distance value provided by the optimization code is then used as the input of the second iteration. Final values are obtained once the optimization criterion is satisfied.

EXPERIMENTAL SETUP

Fig. 4 shows the experimental setup, which includes two sets of pin transducers mounted individually on two linear ball slides. The Lamb wave transducers are cylindrical shaped 1/4" diameter PZT-5H transducers bonded to alumina buffer pins of the same diameter and whose tips are sharpened to a radius of curvature of 100 microns. A thin sheet of viton is inserted between the pin and the housing to reduce the acoustic coupling. A spring is mounted on the top of the housing so that proper force can be applied when the pin is pushed against test structure. The ball slide that guide the pin moving up and down prevents it from wobbling sideways. One of the housing base plate is mounted on a horizontal translation stage so that the distance between two pins can be adjusted. The entire two-pin structure is then fixed to an computer controlled Z-stage so that the two pins can be raised or lowered automatically during experiment.

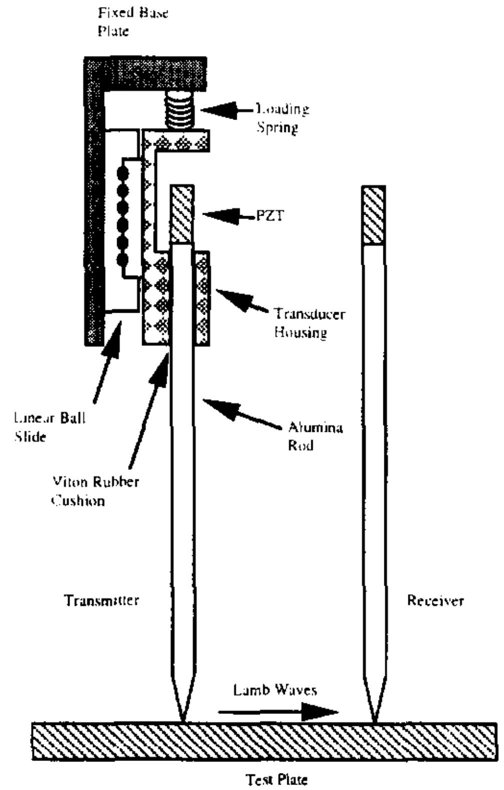
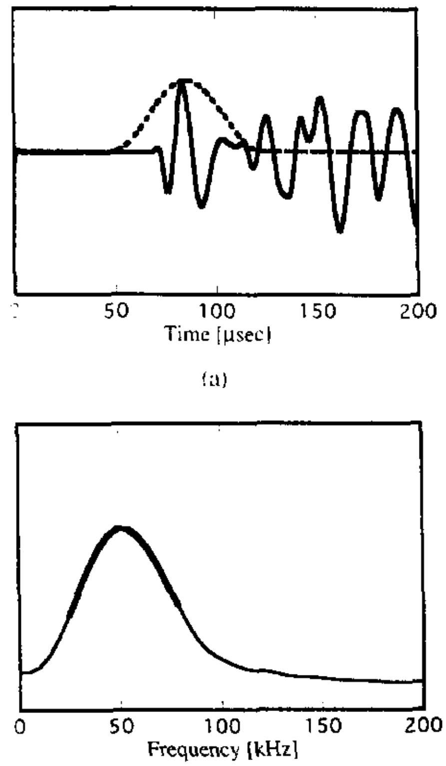


Figure 4. Experimental setup of the Lamb wave pin transducers.

The transmitter pin is driven by a Velonex pulser that produces a pulse height of 2kV and pulse width of 3μsec. A preamplifer utilizing Harris opamp HA5147 with a gain of 30dB is connected next to the receiving transducer since the small signal can degrade significantly when traveling trough a long cable. A secondary amplifier is also used before the signal is conditioned by a 24dB/octave low pass filter with the cutoff frequency set to 100kHz. The SNR from this setup on a 10mm steel plate with pin to pin distance of 50mm is 56dB.

The receiver signal is digitized with a custom designed 40MHz A/D converter (Fig. 4a), whose digitization clock is synchronized with the acoustic trigger, and therefore greatly decreases the trigger jitter that is caused from the digitization process. A forth-power cosine window is applied to the digitized signal to select the first wave packet and the a numerical FFT is used to calculate the signal amplitude and phase. Figure 4b shows the power spectrum and the frequency range used for the thickness/distance calculation. In this selected range, the signal amplitude is greater than 50% of the peak value and thus ensures that good SNR is always associated with the inversion data used.



(b)

Figure 5. The Lamb wave signal transmitted through a 10 mm thick steel plate with a transducer pin to pin distance of 50 mm. (a) Time domain signal with a cosine window (dashed line). (b) Frequency domain signal. The thickened section denote the frequency range with which inversion is performed.

THICKNESS/DISTANCE INVERSION

A proper calibration is needed in order to obtain the phase sensitivity to thickness and pin to pin distance. The calibration is performed a series of plate of different thickness and the phase response is recorded at several pin to pin distances for each plate. The sensitivities is then calculated through the calibration data and used as the phase calculation in the optimization program for all the subsequent measurements.

Armed with the calibrated sensitivities, we perform phase measurements on six test plates machined out of mild steel. Their thicknesses ranges from 8.5 mm up to 11.7 mm. We deliberately vary the transducer pin to pin distance during measurement through the adjustment of the horizontal micrometer. The inverted thickness and distance values are shown in Fig. 6. The solid dots in the figure indicates the thickness and distance values measured from the micrometer and the crosses shows the inverted values from the phase measurement. As we can see, they are in very good agreement.

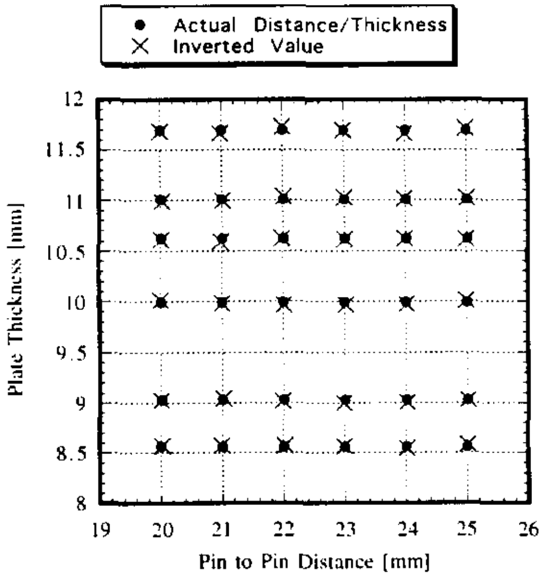


Figure 6. Inverted thickness and distance values and actual values measured with micrometers.

Figure 7 shows the inversion errors for distance and thickness as compared to the micrometer measurement for a number of experiment. The 3σ for the thickness measurement is 0.045 mm and 0.056 mm for distance . The difference in measurement accuracy can be attributed to the sensitivity difference as indicated by Fig. 2 in which the phase change is more sensitive to thickness and thus any measurement error will cause greater variation in the inverted thickness than the inverted distance. However, such measurement accuracies are more than adequate for most of the industrial NDE applications such as erosion/corrosion monitoring.

CONCLUSIONS

We demonstrated that with Lamb wave pin transducers, the plate thickness can be measured without the prior knowledge of the transducer distance. The measurement precision can achieve better than 0.5% for the plate thickness. Furthermore, the inverted transducer distance value with a precision of 0.1% is quite beneficial when transducer array is used for tomographic imaging in which imaging accuracy is directly related to the knowledge of the transducer locations. This technique relaxed the mechanical constraint of distance repeatability and therefore can enhance the flexibility and performance of Lamb wave transducer arrays in many areas of NDE.

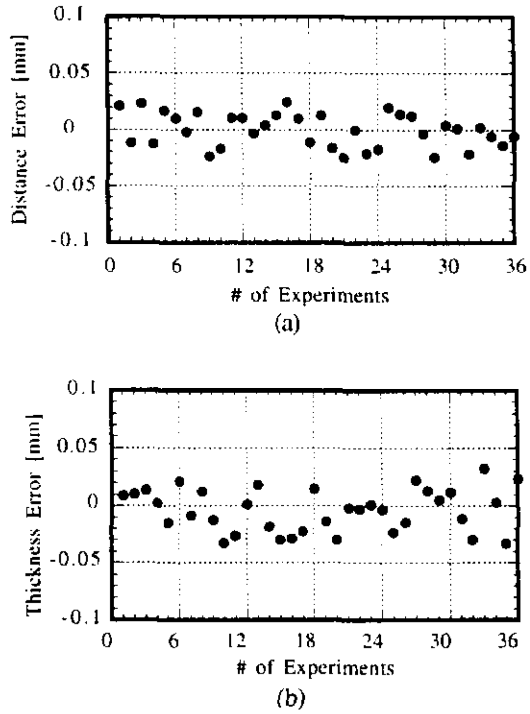


Figure 7. Inverted transducer pin to pin distance (a) and plate thickness (b) error compared with measurement from micrometers.

REFERENCES

[1]. F. L. Degertekin, B. V. Honein and B. T. Khuri-Yakub, "Efficient excitation and detection of Lamb waves for process monitroing and NDE." *Ultrasonics Symposium*, pp 787-90, *Seattle*, Washington, Nov. 1995

[2] J. Pei, M.I.Yousuf, F.L. Degertekin, B.V. Honein,and B. T. Khuri-Yakub "Lamb wave tomography and its application in pipe erosion/corrosion monitoring", pp795-8, Ultrasonics Symnposium, Seattle, Washington, Nov. 1995.

[3]. F. L. Degertekin, B. V. Honein and B. T. Khuri-Yakub, "Analysis of mode conversion transducer for Lamb waves", IEEE trans. on UFFC, 1996