Erosion/corrosion monitoring with dry contact ultrasonic Lamb wave transducers

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ABSTRACT

We propose a novel technique that utilizes point source excitation and detection of Lamb waves through dry, elastic contacts to monitor thickness changes of plate-like structures. A pair of pin transducers are used to excite and detect the A_0 mode Lamb wave in a test plate or a pipe wall and the wave velocity is obtained by time of flight measurement. 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. We demonstrate the power of this approach in ultrasonic pipe erosion/corrosion monitoring and its potential application in aircraft skin defect imaging. We present results of thickness measurements of a test plate with 1% accuracy, and erosion/corrosion monitoring in a section of pipe that was removed from service, as well as imaging of defects in an aluminum thin plate.

INTRODUCTION

Traditional approach to nondestructive evaluation (NDE) of plate-like structures has been based on bulk wave excitation and interface sensing[1]. The major limitation of these techniques is that intimate contact between the transducer and the plate under test is required. In cases where the plate surface is rough or carries curvature different from that of the transducer surface, liquid couplant is usually required to obtain efficient sound coupling. The Curie temperature of the transducer material also limits the environment in which the measurement can be performed. When non-wetting of the test surface is desired, photo acoustics is usually emphasized for its advantage of non-contacting and the ability of rapid scanning. However, due to its excitation inefficiency and low reception sensitivity, this technique requires extensive signal averaging to improve electronic signal to noise ratio[2]. In this paper, we propose a new non-wetting and non-destructive approach for plate thickness measurement and defect detection. It relies on using dry, point contact transducer/buffer pin sets to excite and detect the zeroth order antisymmetric (A_0) Lamb wave mode in plates. Due to the dispersive nature of the A_0 mode Lamb wave, its velocity depends on the thickness of the plate. Hence, a measure of the velocity of the Lamb wave yields a measure of the average plate thickness between the transmitter and the receiver. This technique does not require any couplant, and can be applied in hostile environments to monitor erosion/corrosion processes. There is also no particular requirement for the surface condition of the pipe since only point contacts are established for the measurement. The simplicity of the Lamb wave transducer design enables one to construct transducer scan imaging system or even transducer arrays to realize real time defect imaging.

A_0 MODE LAMB WAVES

Lamb waves propagating in solid plates have been studied extensively[3-5]. Fig.1 shows the theoretical calculation of the phase velocity of the first few Lamb wave modes in a steel plate as a function of the product of frequency and plate thickness. When the A_0 mode Lamb wave is excited, its phase velocity changes as the thickness of the plate changes. Therefore, this dispersive nature can be used to determine the thickness of a plate given the frequency of operation. Fig. 2 shows the phase velocity sensitivity to plate thickness of a 10mm thick steel plate. In order to excite only the A_0 mode, the excitation frequency has to be low enough not to excite any higher order propagating modes. In our work, which is concerned with steel plates and pipes whose thickness is around 10mm, the Lamb wave transducers are chosen to have their resonant frequency at 70 kHz. At this operating point, only the A_0 mode is excited[6] because the method of excitation lacks the symmetry to excite the symmetric A_0 mode, and the operating frequency is well below the cutoff frequency of any higher order mode. At this frequency, the Lamb wave phase velocity changes about 70 meters/second (3%) for every millimeter of thickness change. This high sensitivity is sufficient for our electronics to resolve a thickness change of 0.1mm due to erosion/corrosion.

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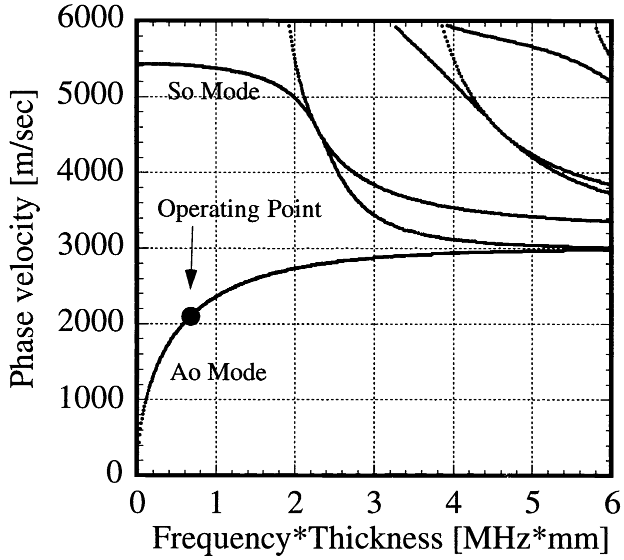


Fig. 1. Theoretical calculation of the dispersion relation of steel plates. Ao mode is chosen in our experiment. The Lamb wave transducers are designed to have a frequency well below the cutoff frequency of higher order modes.

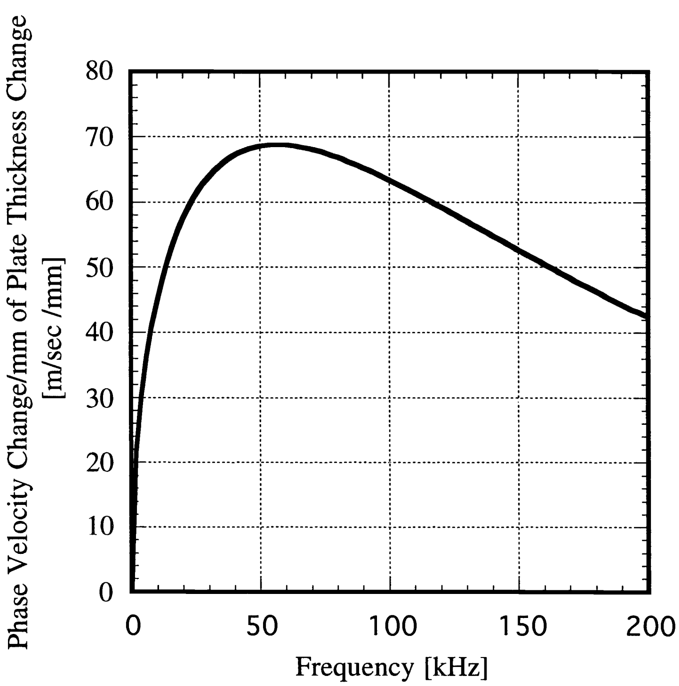


Fig. 2 Theoretical calculation of phase velocity change due to plate thickness variation of Ao mode Lamb waves on a 10mm thick steel plate.

EXPERIMENTAL SETUP

Fig. 3 shows the experimental setup for Lamb wave excitation and reception. The Lamb wave is excited using a piezoelectric transducer bonded to a steel buffer pin. Steel is chosen as the buffer pin material to obtain the best acoustic impedance match between the pin and the steel pipe under inspection. The tip of the pin is rounded to have a radius of curvature of 100 μm. The spherical tip gives a dry point contact to a test plate and the transducer/steel rod assembly is spring loaded to ensure stable contacts every time the steel pin is pushed against plate surface. An identical transducer/steel pin set is used as a receiver to detect the Lamb wave transmitted through the test plate. It is worth noting that different types of pins with different radii of curvature have been used depending on the application and materials involved. Piezoelectric Lead Zirconium Titanate (PZT-5H) is chosen for the transducer material. The PZT-5H is machined to a cylindrical shape with a diameter of 6.35mm and a height of 12.7mm. The resonant frequency of the transducer when bonded to steel is 70 kHz with 50% fractional bandwidth. Fig.4 shows the calculated phase velocity of propagation modes in a steel rod with a diameter of 6.35mm as a function of frequency[7]. The selected 70 kHz resonance ensures that only the lowest order extensional mode is generated in the rod, and hence is the only source of Lamb waves in the test structure.

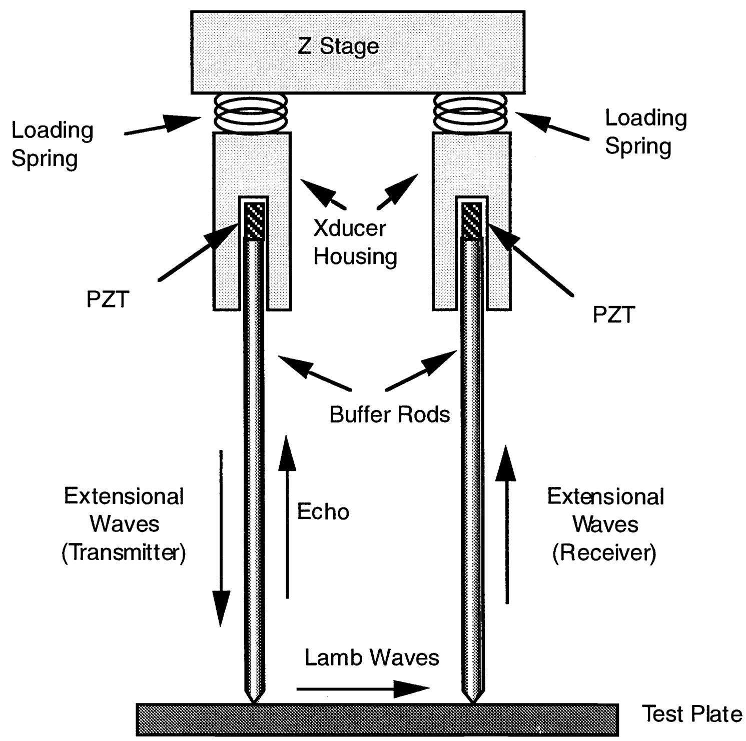


Fig. 3. Experimental setup of plate thickness measurement. Two PZT-5H transducer and steel buffer pin set are used as the Lamb wave transmitter and receiver. Extensional waves are first generated at the transmitter buffer rod and Lamb waves are excited through mode conversion at the transmitter contact to the test plate. The receiver picks up the Lamb wave at the receiver tip and the signal is amplified with a low noise pre-amp. The steel plate under study has thickness around 10mm.

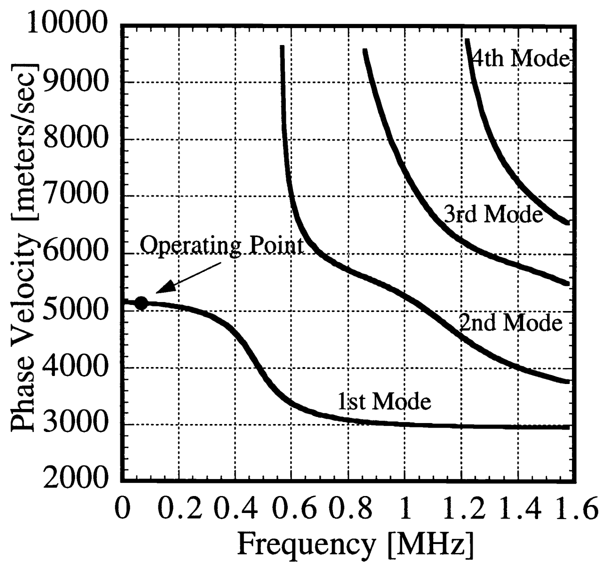


Fig. 4. Theoretical dispersion relation of steel rods with diameter of 6.35mm. The frequency PZT transducer is low enough to excite only the first extensional mode.

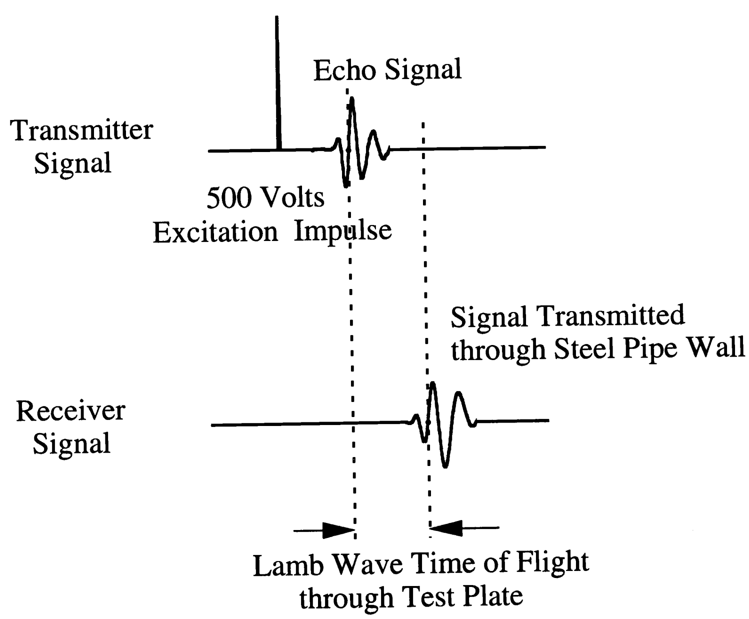


Fig. 5. Timing Diagram for the time of flight measurement. The time delay from the echo signal and transmitted signal is measured. The effect of the two buffer pins is eliminated because the delays of acoustic signals in the transmitter and receiver buffer pins are identical.

A time of flight(TOF) measurement technique is used to obtain the Lamb wave phase velocity in the test plate[5]. The TOF measurement is described in Fig. 5. A short electrical pulse of 500 volts is applied to the transmitter which generates the extensional wave in the steel pin. At the contact interface between pin tip and test structure, part of the extensional mode energy is reflected back to the transmitter and generates an echo electrical pulse, the other part of the energy is coupled into the plate as the A_0 Lamb wave. After propagation through the plate, the Lamb wave is converted back to an extensional mode at the receiver tip and then, to an electrical signal in the receiving transducer. The pin-to-pin time of flight is measured by monitoring the time interval between the transmitter echo and the received signal. The first zero crossing of the echo signal triggers the start of the time delay counter and the first zero crossing of the transmitted signal stops the counter. The time delay measured is the time that takes the Lamb wave to travel through the pipe wall from the transmitter tip to the receiver tip. The effect of the steel pins is eliminated due to the subtraction of the time delay in the pins from both transmitter and receiver.

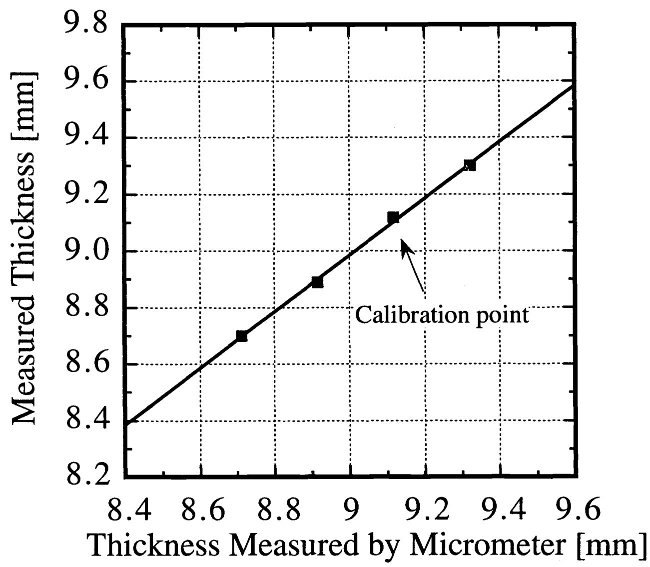


Fig. 6. Calibration measurement is performed on a steel step wedge plate with thickness measured using a micrometer. With known distance between the transmitter and receiver pin tips, one point of the time of flight data is corrected for the electronic delay and fitted to the theoretical dispersion curve. Other thickness points fit the calculated curve within 1% error.

Because the electronic time delays introduced by the amplifiers and filters are also included in the TOF data, a proper calibration is necessary. The calibration is performed on a steel step wedge plate with its thickness varying from 8.25 mm to 9.25 mm. With known distance between the transmitter and receiver pin tips, a TOF data point is taken in a region of the steel plate whose thickness is measured using a micrometer caliper. This data point is fitted to the theoretical dispersion curve and hence the fitting parameters corresponding to the electronic delays are obtained. With the same fitting parameters, the TOF data of other regions are converted to plate thickness accordingly. Fig. 6 shows the measurement of regions with different thickness vs. the measurement done with a micrometer. Note that the fit of the data is better than 1%.

PIPE WALL THICKNESS MEASUREMENT

The system was used to measure erosion/corrosion in a steel pipe elbow that was removed from service. The diameter of the pipe is 35 cm, and the wall thickness is about 1cm. A calibration run was also performed on the steel pipe at a location where the thickness could be independently measured with a micrometer caliper. Wall thickness variations were measured to range from 7.8 mm to 10.1 mm which indicated the presence of extensive corrosion at some locations inside the pipe. This thickness variation was further verified with a traditional pulse echo measurement using a longitudinal wave transducer operating at a frequency of 10 MHz. Fig. 7 shows a comparison of the pipe thickness as measured with both methods. Overall, there is excellent agreement between the two measurements.

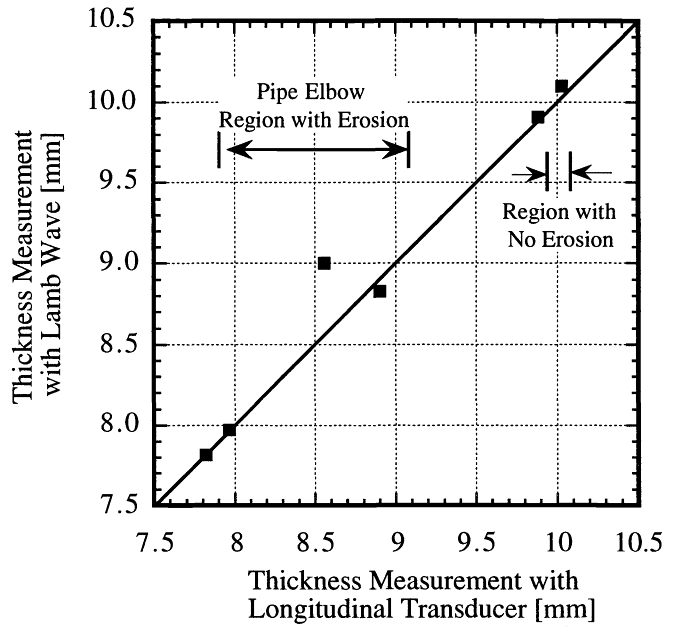
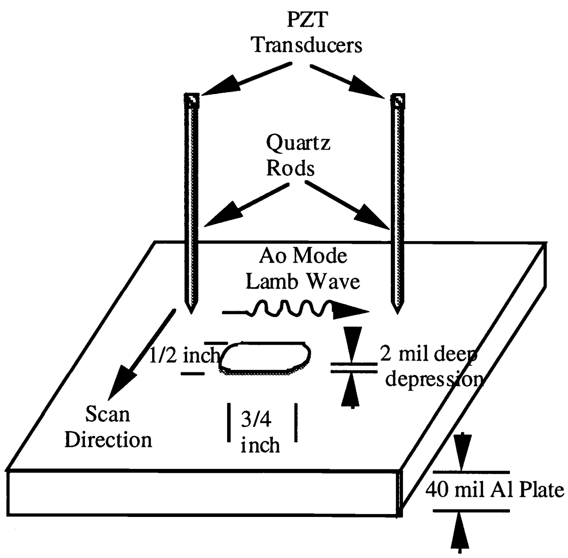


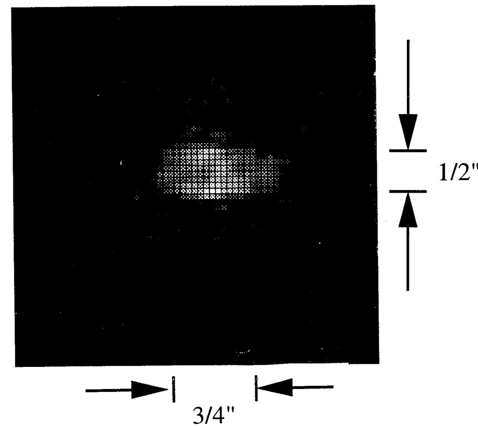
Fig. 7. Thickness measurement performed on a section of steel pipe. Thickness variation measured with Lamb wave technique is plotted against the data obtained from a 10 MHz longitudinal transducer. There is in general very good agreement. The fact that longitudinal transducers can only measure the thickness of a single point and Lamb wave technique gives an average thickness along the acoustic path may contribute to some discrepancy.

SCAN IMAGING SYSTEM

This technique is not limited to the application listed above, indeed, it can also be used for defect detection and imaging in thin plates such as aircraft skins. Fig. 8(a) shows the experimental setup of a scan imaging system used to detect a depression. The thickness of the aluminum plate under inspection is around 1mm. The transducers, therefore, are chosen according to this thickness to have their operating frequency around 200 kHz. Only the A_0 mode Lamb wave can be generated in the plate at this frequency. The PZT-5H piezoelectric material is machined to a cylindrical shape with a diameter of 3mm and a height of 5mm to obtain the 200 kHz resonance. Quartz rods are used as the buffer pins with their tips sharpened to have a radius of curvature of 100μm. The transducers are spring loaded and pressed on the plate surface to form a dry contact. Again, the sharp tips are not sensitive to surface conditions and do not require any liquid couplant.



(a)



(b)

Figure 8. (a) Imaging system for aircraft skin. A 4 mil (0.1mm) depression is milled into the aluminum plate to simulate a defect. 64 time of flight data point is take along the scan path. (b) Reconstructed time of flight image of the depression shown in Fig. 7 using the back-projection algorithm. The field of view is 3.2inches x 3.2 inches (8.1cmx8.1cm) with 64x64 pixels of resolution.

A 0.5mm (2mil) deep rectangular depression is milled into the aluminum plate to simulate a defect. The plate is mounted on an X-Y and rotation stage and the transducers scan over the area with defect. Due to the thinning of the defect area, the time of flight increase as the pins scan across the depression. Filtered back projection[8] tomographic inversion method is used to reconstruct the defect image. 64 points are taken along each scan direction and a total of 60 scans are taken at an interval of every 3°. The reconstructed time of flight image is shown in Fig. 8(b) with a resolution of 64×64 pixels. The depression region is clearly shown in the image.

CONCLUSIONS

We presented a novel method for measuring the thickness and non-destructive evaluation of plate-like structures using the zeroth order antisymmetric Lamb wave. The method employs a Hertzian contact between the buffer pin and the plate. No surface preparation is necessary, and the method can be applied in-situ, in hostile environments such as at high temperature and in the presence of radioactivity, and through insulation. A measurement accuracy of better than 1% was demonstrated experimentally and a scan imaging system is presented. This technique can be applied to a variety of plate like structures for characterizing homogeneous and composite materials. Real time imaging system can be realized with Lamb wave pin transducer arrays.

ACKNOWLEDGMENT

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