LAMB WAVE TOMOGRAPHY AND ITS APPLICATION IN PIPE EROSION/CORROSION MONITORING

by

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ABSTRACT

Ultrasonic Lamb wave techniques are widely used in a number of NDE applications. To excite Lamb waves, mode conversion of bulk waves or photo acoustic excitation are often used. Both of these approaches suffer from the need for liquid couplant or ablation of materials to reach good signal to noise ratio. In this paper, we propose a novel technique that utilizes point source excitation and detection of Lamb waves through dry, elastic contacts to monitor velocity changes. 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 measurements of plate thickness, and erosion/corrosion in a section of pipe that was removed from service, as well as imaging of defects in an aluminum thin plate.

MOTIVATION FOR ULTRASONIC LAMB WAVE THICKNESS MEASUREMENT

Ultrasonic measurement of the thickness of plates is most often done by measuring the time of flight of bulk waves in the material[1]. This technique usually requires a liquid couplant between the transducer and the plate, and is especially difficult when the plate has surface curvature or roughness. Traditional techniques are of limited use in hostile environments because of limitations on the fluid couplant and the piezoelectric transducer material. Plate thickness can also be measured with photo acoustic excitation of Lamb waves[2,3]. However, ablation of the test material is often needed to reach good signal to noise ratio in order to perform accurate measurements[4]. In this paper, we present a new technique that 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 Ao 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 or corrosion processes. There is also no particular requirement for the surface condition of the test structure 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.

LAMB WAVE PROPAGATION AND A_0 MODE DISPERSION

Lamb waves are elastic perturbations propagating in solid plates with free boundaries. 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[5].

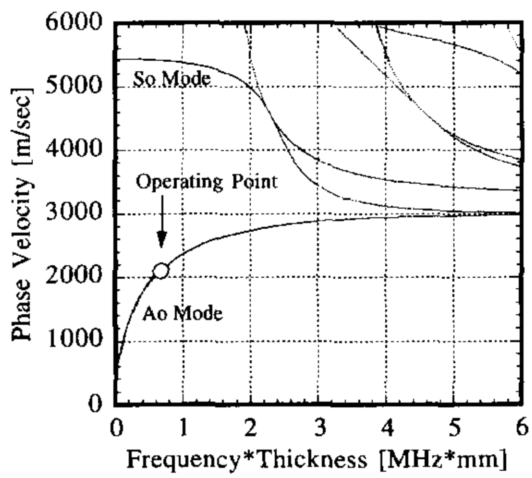

Figure 1. Theoretical calculation of the dispersion relation of steel plates. Ao mode is chosen in our experiment. The Lamb wave transducers are designed to have a frequency well below the cutoff frequency of higher order modes.

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. In order to excite only A_0 mode, the excitation frequency has to be low enough not to excite any higher 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 70kHz. At this operating point, only the A_0 mode is excited because the method of excitation lacks the symmetry to excite the symmetric S_0 mode, and the operating frequency is well below the cutoff frequency of any higher order mode. Another feature of this operating point is that the phase velocity of the Ao Lamb wave in the plate changes about 100 meters/second (5%) for every millimeter of thickness change. This high sensitivity to thickness is sufficient for our electronics to resolve a change of 0.1mm due to erosion/corrosion.

The experimental setup for pipe erosion/corrosion monitoring is shown in Fig. 2. 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

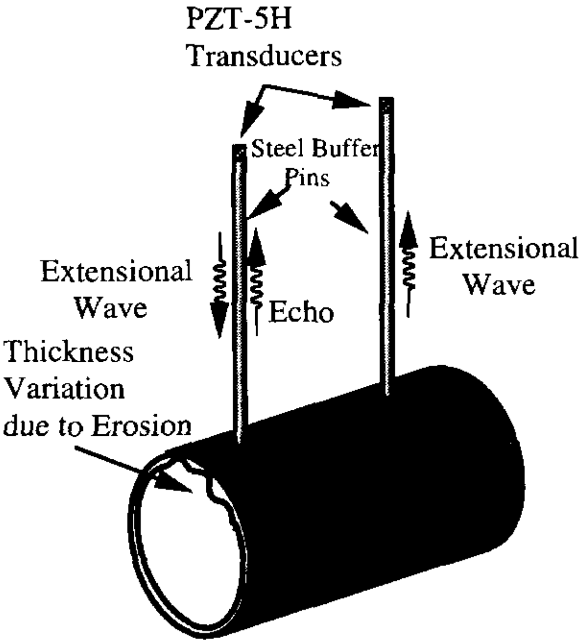

Figure 2. Experimental setup of pipe wall thickness measurement. Two PZT-5H transducer and steel buffer pin sets are used as the Lamb wave transmitter and receiver. The steel pipe under study has a diameter of 35cm and wall thickness around 10mm.

pin is rounded to have a radius of curvature of 100 µm. The spherical tip gives a dry Hertzian contact to the pipe and the transducer/steel rod assembly is spring loaded to ensure stable contacts every time the steel pin is pushed against pipe wall surface. An identical transducer/steel pin set is used as a receiver to detect the Lamb wave transmitted through the pipe wall. 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. This selected frequency ensures that only the lowest order extensional mode is generated in the rod[6], and hence is the only source of Lamb waves in the test structure.

A time of flight(TOF) measurement technique is used to obtain the Lamb wave phase velocity in the pipe wall. The TOF measurement is described in Fig. 3. 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 pipe wall as the A_0 Lamb wave. After propagation through the pipe wall, 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 transmitted echo and the received signal. The first zero crossing of

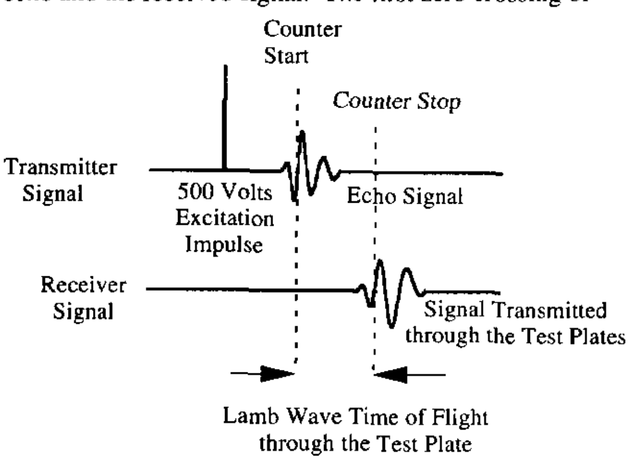

Figure 3. Timing Diagram for the time of flight measurement. The time delay from the echo signal and transmitted signal is measured. The effect of the two buffer pins is eliminated because the delays of acoustic signals in the transmitter and receiver buffer pins are identical.

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.

PIPE WALL THICKNESS MEASUREMENT

Since the time of flight data includes the electronic time delays introduced by the amplifiers and filters, a proper calibration on a sample of the same material 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 fitting parameters corresponding to the electronic delay are obtained. With the same fitting parameters, the TOF data of other regions are converted to plate thickness accordingly. Fig. 4 shows the measurement of regions with different thickness vs. the measurement done with a micrometer. Note that the fit of the data is to better than 1%.

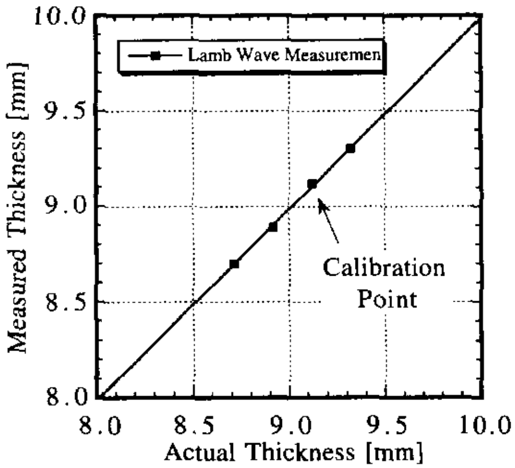

Figure 4. Calibration measurement is performed on a steel step wedge plate with thickness measured using a micrometer. With known distance between the transmitter and receiver pin tips, one point of the time of flight data is corrected for the electronic delay and fitted to the theoretical dispersion curve. Other thickness points fit the calculated curve within 1% error.

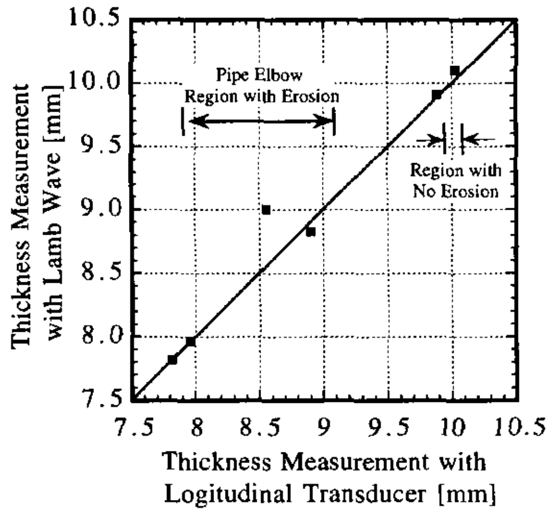

Figure 5. Thickness measurement performed on a section of steel pipe. Thickness variation measured with Lamb wave technique is plotted against the data obtained from a 10MHz longitudinal transducer.

The system was used to measure erosion/corrosion in a steel pipe elbow that was removed from service. As shown in Fig. 2, the diameter of the pipe is 35 cm, and the wall thickness is of the order of 1 cm. A similar calibration run was made 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. 5 shows a comparison of the pipe thickness as measured with both methods. Overall, there is excellent agreement between the two measurements.

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. 6 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 200kHz. 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 3.2mm and a height of 5mm to obtain the 200kHz 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.

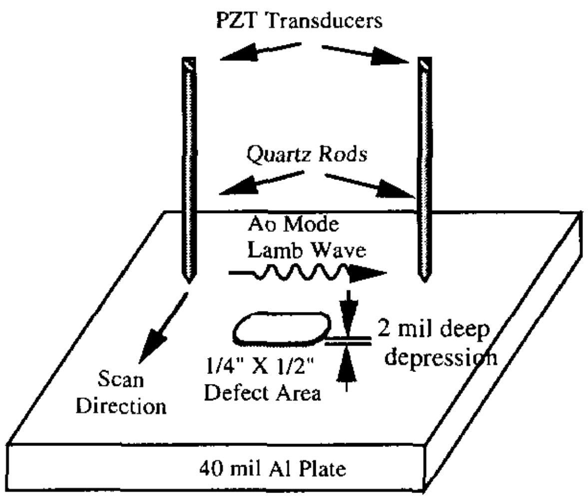

Figure 6. Imaging system for aircraft skin. A 2 mil (0.05mm) depression is milled into the aluminum plate to simulate a defect. 64 time of flight data point is take along each scan path. A total of 60 scans are taken at an interval of every 3°.

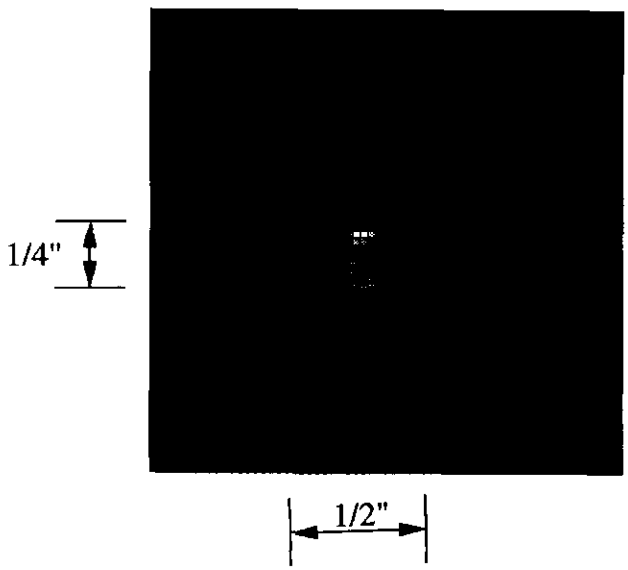

Figure 7. Reconstructed time of flight image of the depression shown in Fig. 6 using the back-projection algorithm. The field of view is 3.2 inches x 3.2 inches (8.1cmx8.1cm) with 64x64 pixels of resolution.

A 0.05mm deep 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[7] 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 with a resolution of 64×64 pixels. The depression region is clearly shown in the image.

CONCLUSION

We presented a novel technique 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 plates for characterizing homogeneous and composite materials. Real time imaging system can be realized with Lamb wave pin transducer arrays.

ACKNOWLEDGMENTS

This work was supported by EPRI under contract #W03148-13.

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