Guided ultrasonic wave measurement in plates using low-cost equipment

P. Fromme[a], P.W. Loveday[b]
[a] Department of Mechanical Engineering, University College London, UK
[b] University of the Witwatersrand, Johannesburg, South Africa

ABSTRACT

Guided waves can propagate along thin-walled structures, such as pipes and plates, with limited energy loss, thus enabling the efficient inspection and monitoring of large structures from a limited number of sensor locations. This allows Structural Health Monitoring (SHM) using permanently installed monitoring systems with limited access and sensor requirements. However, guided wave propagation is complicated due to multiple propagating wave modes and dispersion, potentially causing the signals to become distorted. Both analytical and numerical analysis and experimental measurements are essential for guided wave research. Specialized laboratory equipment such as non-contact laser vibrometers can be expensive and unaffordable. This contribution presents a preliminary investigation on what can be achieved experimentally using low-cost sensors, suitable for research and teaching in circumstances with limited budgets. For low frequency guided wave propagation in an isotropic plate (A_0 Lamb wave mode), the influence of different measurement configurations on the accuracy of group velocity quantification was investigated. Results from experimental setups employing different receive transducers were evaluated and quantified. Accuracy of sensor placement and coupling as well as measurement repeatability and signal-to-noise ratio (SNR) were investigated. Accurate experimental quantification of the group velocity, using the different movable sensors, was demonstrated by comparison to theoretical predictions based on the nominal aluminum material properties.

Keywords: Lamb waves, ultrasonic guided waves, group velocity, EMAT.

1. INTRODUCTION

Guided ultrasonic waves (GUW) can be employed for the nondestructive evaluation (NDE) and structural health monitoring (SHM) of large, thin structures [1], e.g., pipelines or plates. The propagation characteristics in isotropic plates, where multiple dispersive wave modes can propagate (Fig. 1), were originally predicted by Lamb [2]. Experimental verification of guided wave propagation and sensitivity for defects thus typically requires the use of excitation signals, equipment, and transducers that are designed to selectively excite a particular guided wave mode within a selected frequency bandwidth [3, 4]. This specialized equipment typically comes at quite a high cost, limiting the accessibility to such measurements for research, training, and industrial applications [5]. The main objective of the research reported here was to compare the sensitivity of high and low-cost guided wave measurement equipment and gain an understanding where expensive equipment is advantageous or required and when similar or acceptable performance may be obtained with more affordable instrumentation for the measurement of guided waves in plates at low frequencies.

As the propagation of GUW modes is dispersive, measurements are often performed to characterize the dispersion relations, e.g., the influence of anisotropy on guided wave propagation in composite specimens [6]. Signal processing of measurements at equally spaced locations using a two-dimensional Fourier transform allows the quantification of dispersion characteristics of guided wave modes [7]. Dispersion curves can also be extracted using the matrix pencil method [8], e.g., from laser vibrometer measurements on an aluminum plate. Below the cut-off frequencies of the higher Lamb wave modes, only the fundamental A_0 and S_0 modes (Fig. 1) can propagate in a plate and can be excited selectively [3]. This allows for simpler methodologies to evaluate the experimental measurements of a single guided wave mode propagating. Fourier transform can be used to calculate the phase spectra and thus difference between measurement signals at different locations, allowing the calculation of the phase velocity [9], e.g., in plates using pure mode excitation by air-coupled transducers [10].

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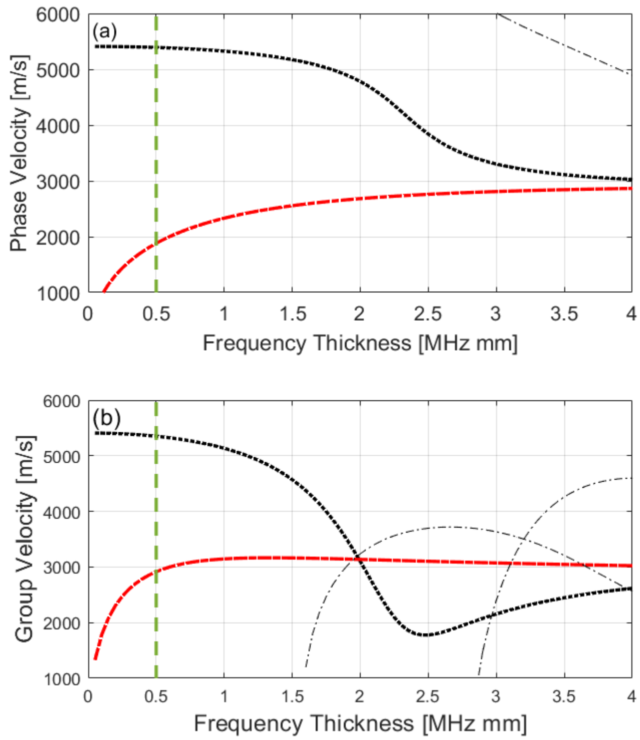

Figure 1. Dispersion diagram for aluminum plate, nominal properties of AW-6082 T6. A_0 mode: red, dash-dots; S_0 mode: black, dots; operating point at 0.5 MHz-mm (100 kHz, 5 mm thickness): green, dashed.

The group velocity of the fundamental A_0 Lamb wave mode at 100 kHz in a 5 mm thick aluminum plate (frequency-thickness region around 0.5 MHz-mm) was measured using different experimental configurations and transducers, e.g., from laser vibrometer measurements and using custom-made piezoelectric transducers [11], as well as employing Electro Magnetic Acoustic Transducers (EMATs) [12]. Results obtained from different measurement setups for the guided wave signal acquisition are compared.

2. MEASUREMENTS

Measurements were performed and compared on an AW-6082 T6 aluminum plate (1 m x 1 m x 5 mm) with nominal material properties of 2700 kg/m^3 density, 70 GPa Young's modulus, and 0.33 Poisson's ratio. The Disperse software [13] was used to calculate the phase and group velocity dispersion curves (Fig. 1). Based on previous experience [14], a center excitation frequency of 100 kHz of the A_0 Lamb wave mode was selected, giving a 0.5 MHz-mm frequency thickness product (Fig. 1) with nominal values of 1878 m/s (phase velocity) and 2908 m/s (group velocity) at 100 kHz. Excitation of the A_0 Lamb wave mode was achieved using a PZT transducer (PIC 255 disc, polarized through thickness: 5 mm diameter, 2 mm thickness; brass backing mass: 5 mm diameter, 6 mm thickness). This had previously been found to provide a low-cost, selective point source excitation of the A_0 mode in the frequency range below 200 kHz. The excitation transducer was permanently bonded (Loctite 2-part epoxy glue) to the center of the aluminum plate (Fig. 2). Measurements were conducted using either a laser vibrometer or custom-built PZT and EMAT transducers. The laser vibrometer was mounted on a scanning rig and could be moved with good accuracy parallel to the plate [5, 11]. Measurements to calculate the group velocity were conducted along a radial line from the excitation transducer, recording the time signals at 100 points with a step size of 1 mm and starting 100 mm from the excitation transducer to avoid near-field effects. Three custom-made sandwich type PZT transducers [5] were employed as moveable transducers that included a single piezoelectric ring (Ferroperm Pz29) and stainless-steel front and back masses. Two of the transducers (PZT#2, PZT#3) were of identical design (12 mm diameter contact area), while the third PZT transducer (PZT#1) had a casing and a smaller contact area of 7 mm diameter (Fig. 2). Additionally, a custom made EMAT (circular, radially polarized ring magnet: 18 mm outer diameter, concentric coils) optimized for out-of-plane motion measurement of the A_0 Lamb wave mode at low frequencies was employed.

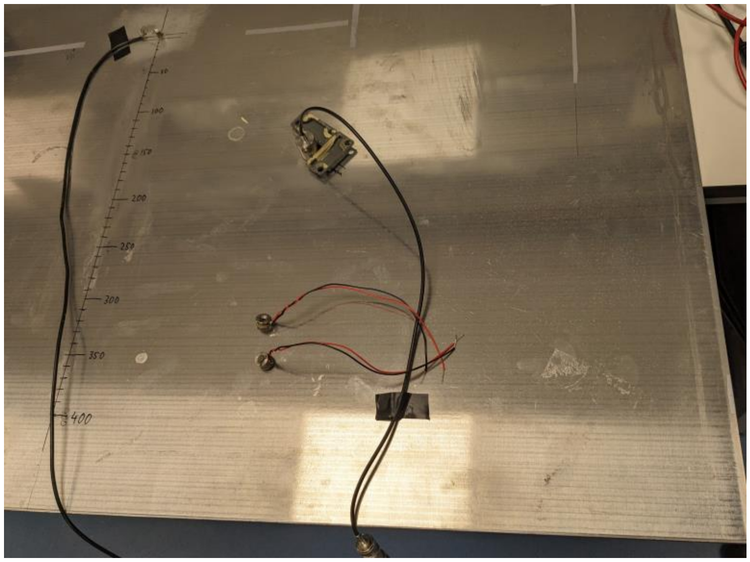

Figure 2. Photograph of aluminum plate (1 m x 1 m x 5 mm) for experiments, showing fixed excitation PZT at plate center and three employed moveable PZT transducer for repeatability and velocity measurements.

Measurements were conducted at one location 250 mm away from the excitation transducer to quantify the repeatability of the hand-held contact PZT transducer measurements. The PZT transducers were coupled with a liquid ultrasonic couplant and pushed with a finger against the plate and two plastic restraints to achieve good localization accuracy (Fig. 2). Measurements for the guided wave velocity were conducted along a radial line from the excitation transducer, moving the PZT transducer (PZT#1) with a step size of 10 mm from 100 mm to 400 mm away from the excitation location. For the EMAT measurements a step size of 10 mm and distance of 200 mm were selected. The excitation signal was chosen as a narrowband 5-cycle sine wave pulse with 100 kHz center frequency, modulated by a Hanning window. The signal was defined in Labview, generated using a programmable function generator, and amplified to 400 V_{pp} with a wideband amplifier. A bandpass filter with cut-off frequencies of 75 and 125 kHz was employed to reduce the noise in the signals received from either laser vibrometer or movable transducers. Using a digital storage oscilloscope, the full time-trace signals were averaged (20 averages) and recorded for analysis using MATLAB. Due to the low signal amplitude of the EMAT measurements, 100 averages and 40 dB amplification in the bandpass filter were employed.

3. REPEATIBILITY OF MEASUREMENTS

The measurements using the laser vibrometer had good positioning accuracy and repeatability, and almost no variability of signal amplitude and phase was visible for repositioning of the laser beam repeatedly at the same measurement location. However, as the moveable PZT transducers are manually positioned and in contact with the plate, both the ultrasonic couplant and exact placement (uneven pressure, localization, …) can have an influence on the recorded signal. The three contact PZT transducers were each positioned manually 10 times against plastic constraints fixed to the plate with double-sided tape and the repeatability of the received signal investigated. Figure 3(a) shows the received time traces using PZT#1 with overall good amplitude, repeatability, and signal-to-noise (SNR) ratio for 10 repetitions. Figure 3(b) shows a zoom on the direct incident 5-cycle wave pulse at 0.1 ms. Amplitude variation by about 15% can be observed, likely due to slight variations in the manual pressure and amount of couplant. Only small variations in the arrival time and thus phase of the received signal are visible. These were quantified from the zero crossing at the pulse center adjacent to the largest peak. For the 10 signals recorded using PZT#1 the maximum difference was about 0.2 μs or 2% of the time period at 100 kHz, which is likely acceptable for velocity measurements. Figure 3(c, d) shows the 10 repeated time traces recorded with the identical PZT transducers (PZT#2 and PZT#3) with a larger contact area than PZT#1. Higher variability of the recorded amplitude (40%, 25%) and zero crossing time (1.5 μs, 0.7 μs) was recorded and is clearly visible. The cause of this will require further investigation but could be related to the geometry of the transducers with difficulties achieving a uniform contact pressure. For velocity measurements the amplitude variability would likely not cause problems, but significant variations in the recorded arrival time and phase potentially have a negative influence on the accuracy of the group velocity evaluation.

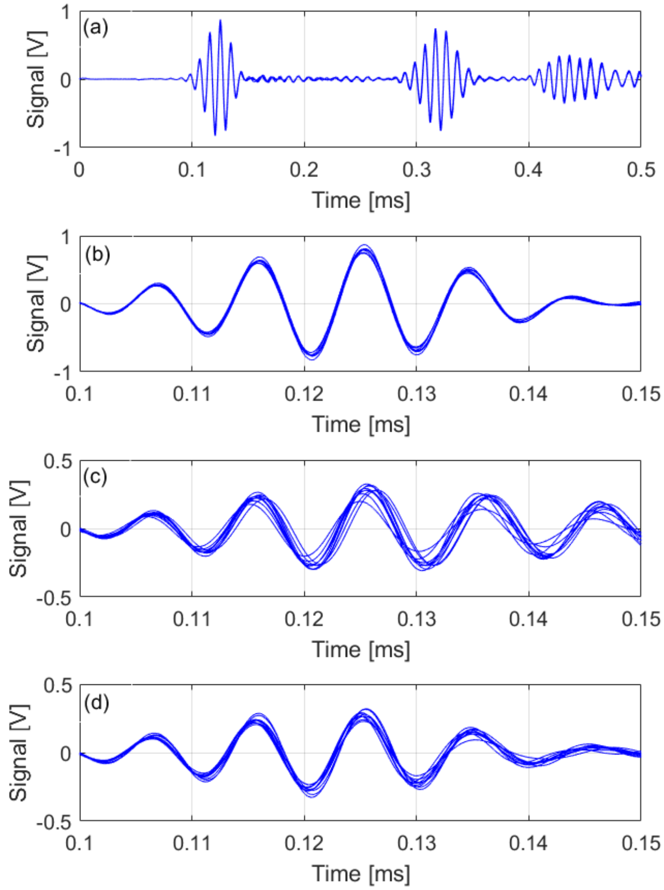

Figure 3. Measurement of repeatability of moveable PZT transducers, received at 250 mm from excitation transducer. (a) overlay of 10 time traces (PZT#1); (b) zoom on incident wave pulse, overlay of 10 time traces (PZT#1); (c) zoom on incident wave pulse, overlay of 10 time traces (PZT#2); (d) zoom on incident wave pulse, overlay of 10 time traces (PZT#3).

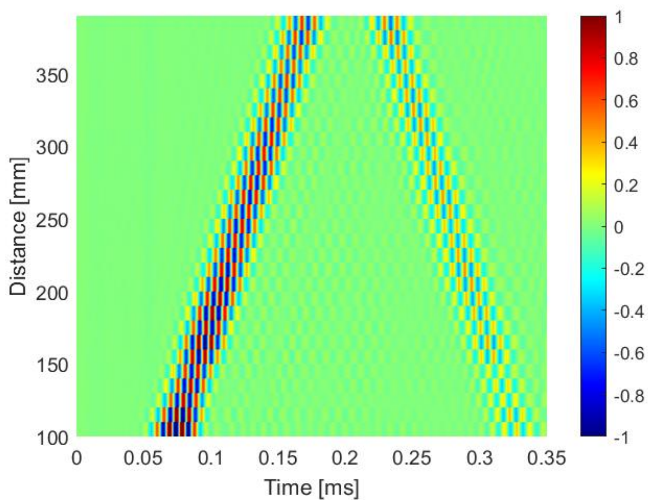

Figure 4. B-scan plot of recorded guided ultrasonic wave time signals against distance using moveable PZT#1 transducer, amplitude color-coded (units [V]), 300 mm scan distance, 10 mm step size.

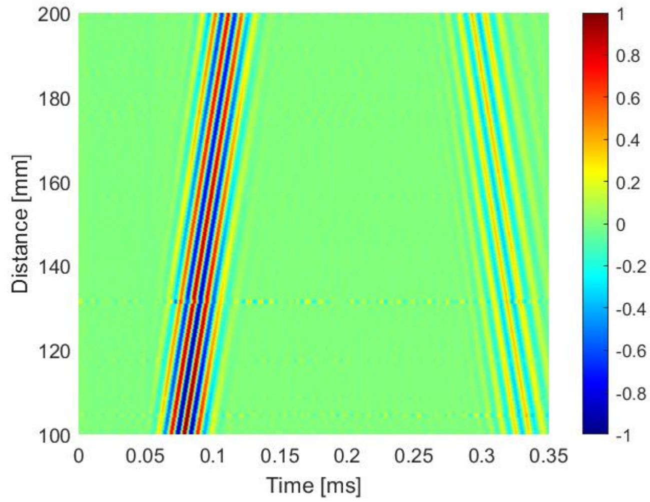

Figure 5. B-scan plot of recorded guided ultrasonic wave time signals against distance using laser vibrometer, amplitude color-coded (units [V]), 100 mm scan distance, 1 mm step size.

4. GROUP VELOCITY MEASUREMENT AND EVALUATION

Measurements were conducted to evaluate the group velocity for comparison against the theoretically predicted value, using both the laser vibrometer [5] and the moveable EMAT and PZT#1 transducer. Figure 4 shows a waterfall plot of the signals recorded using PZT#1 along 300 mm propagation distance with a step size of 10 mm. Both the incident A_0 Lamb mode wave pulse and the reflection at the plate edge can be clearly observed with good SNR. Figure 5 shows the equivalent data measured using the laser vibrometer over a shorter propagation distance of 100 mm with 1 mm step size [5]. The smaller step size enables tracing of individual peaks in the wave packet along the propagation distance and illustrates the dispersive nature of the A_0 Lamb wave mode propagation (at 0.5 MHz-mm frequency thickness product) as the individual peaks clearly propagate at a different phase velocity compared to the overall wave pulse (group velocity). Signals recorded using the EMAT are shown in Fig. 6, with a propagation distance of 200 mm and 10 mm step size. Even with amplification of the received signal, the signal amplitude is much lower than for the PZT and laser measurements. While the SNR is acceptable, small offsets of the recorded signal in the order of up to 2 mV can be observed, which were corrected for in the guided wave velocity evaluation. At 0.02 ms, large crosstalk from the excitation signal is clearly visible, but for the chosen measurement locations this did not overlap in time with the guided wave pulse and could be easily removed.

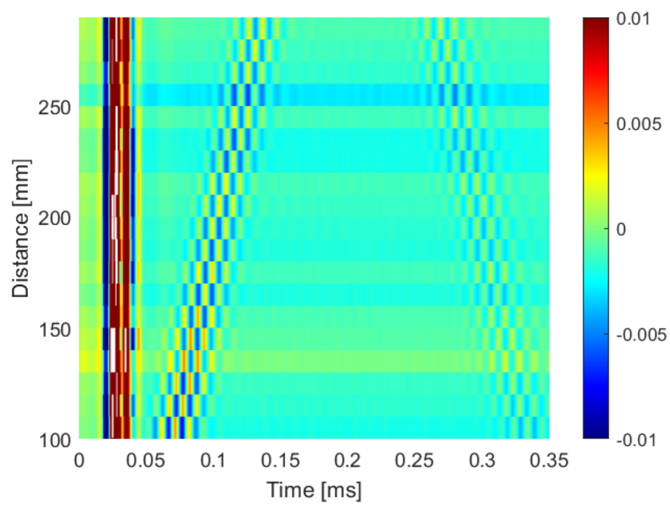

Figure 6. B-scan plot of recorded guided ultrasonic wave time signals against distance using EMAT, amplitude color-coded (units [V]), 200 mm scan distance, 10 mm step size.

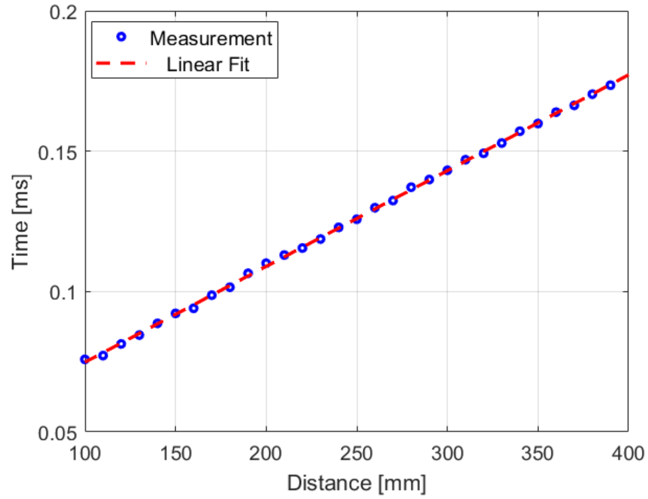

Figure 7. Plot of recorded guided ultrasonic wave arrival time against distance using movable PZT#1 transducer, 300 mm propagation distance, 10 mm step size; blue dots: measurements, red dashed line: linear fit for group velocity evaluation from MATLAB fitting tool.

For all measurements, the incident wave pulse was isolated using time gating and the maximum of the guided wave pulse identified using Hilbert transform in MATLAB. A straight line was fitted to the arrival times of the maxima plotted against propagation distance (shown in Fig. 7 for the PZT#1 measurement) and the group velocity was calculated from its gradient. Results showed good agreement with the theoretically predicted group velocity of 2908 m/s based on the nominal material properties of the aluminum plate. The evaluation of the laser vibrometer measurement gave the smallest difference of 0.3% with a group velocity value of 2900 m/s, followed by the PZT measurement (2931 m/s, 0.8% difference) and the EMAT (2972 m/s, 2.2% difference). The R^2 value for the linear fit to the experimental arrival time data (Fig. 7) was above 0.99 for all three measurements. Some slight variability of the measured arrival time at different locations was observed for the PZT and EMAT measurements, likely due to inaccurate positioning of the handheld transducers or changes in the contact conditions for the PZT transducer. Overall, good characterization of the guided wave propagation could be achieved for the low-cost, handheld receive transducers. Combining the inexpensive, movable transducers with low-cost equipment for the generation and recording of the guided wave pulses [5] allows for the cost-efficient characterization of material properties in large structures.

5. CONCLUSIONS

Different measurement setups and receive transducers were used to measure the group velocity of the fundamental A_0 Lamb wave mode in an aluminum plate. For the handheld, contact PZT transducers quite significant amplitude and phase variability, likely due to the contact conditions, was observed and further measures should be investigated to control and minimize these. The EMAT signals were of low amplitude, as expected, and required additional amplification and averaging to achieve acceptable SNR. The non-contact laser vibrometer measurements had the advantage of small laser beam spot size and excellent positioning accuracy due to the positioning using a scanning rig. From the evaluation of all experiments with the different receive transducers, good accuracy of the group velocity measurement within 3% of the nominal value was achieved, allowing adequate characterization of the guided wave propagation. The inexpensive PZT and EMAT sensors could be employed together with low-cost equipment for the excitation and measurement of guided waves, either for the characterization of guided ultrasonic wave propagation characteristics or permanently deployed in a Structural Health Monitoring approach for the long-term monitoring of developing defects and degradation in large, thin-walled structures.

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