

MEASUREMENT OF LAMB WAVE PHASE VELOCITY USING LOW-COST EQUIPMENT

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Abstract: Lamb waves are a family of guided ultrasonic waves that propagate in plate structures. The phase velocity is an important characteristic for material characterisation and locating defects in non-destructive testing applications. The phase velocity may be measured by exciting the Lamb wave at one location and then measuring the response at a set of equally spaced points extending radially from the source. These measurements are often performed using a fixed piezoelectric excitation transducer and a non-contact laser vibrometer to measure the response at several points. This research aims to use low-cost equipment to perform these measurements by replacing the laser vibrometer with a moving piezoelectric transducer or electromagnetic acoustic transducer (EMAT). It was previously found that the piezoelectric transducer had limited repeatability, and this is investigated further. An EMAT was developed and compared to the piezoelectric transducer. The EMAT has poor signal to noise ratio and a high number of averages was required. Measurements at a single location showed repeatability similar to the piezoelectric transducer. When the EMAT was moved to a series of measurement positions the performance was not better than that of the piezoelectric transducer and development of a more accurate positioning technique is required.

Keywords: guided wave ultrasound, low-cost measurement system

1. Introduction

Guided ultrasonic waves can propagate in structures where the boundaries of the structure constrain the propagation of the elastic waves [1]. Lamb waves, propagating in plate structures, are guided waves of great importance in non-destructive testing and monitoring applications because of the potential to inspect a large area from a few transducer locations [2]. The use of guided waves is complicated by the existence of numerous modes of propagation and dispersion, which causes distortion of the wave packet with propagation [1]. Research in this area generally requires both simulation and experimental measurement. While expensive measurement equipment is available in some laboratories, the development and use of low-cost equipment, costing less than USD 1000, would make this field of research accessible to more researchers. Measurements of the phase velocity of the A_0 Lamb wave mode in plates was performed using two custom made piezoelectric transducers and low-cost instrumentation and these were compared to measurements using a state-of-the-art laser vibrometer based system [3]. One piezoelectric transducer was permanently glued to the plate and was used to transmit the waves. The transducer used to measure the response must be positioned at a series of measurement points and therefore was not bonded. It was observed that measurements were not completely repeatable, and it was speculated that the coupling of the piezoelectric transducer to the plate using ultrasonic coupling gel was less consistent than required. In this paper an alternative sensor, an electromagnetic acoustic transducer (EMAT) is developed and compared to the piezoelectric sensor. The EMAT consists of a copper wire coil and permanent magnets and has the potential to be a very low-cost sensor. The sensors do not require mechanical coupling to the structure and can operate as noncontact sensors. The signal to noise ratio (SNR) of EMATs is known to be significantly lower than that of piezoelectric sensors. However, the relative repeatability of the EMAT measurements was not known and this is investigated.

2. Measurement Techniques and Equipment

The phase velocity in plates is often measured to verify theoretical predictions for composite structures or anisotropic materials. When there are multiple modes of propagation, measurements are performed at a series of equally spaced measurement points arranged in the direction of wave propagation. The two-dimensional Fourier transform was used to estimate the dispersion curves from these measurements in [4] and this was extended by adding the matrix pencil method in [5] where 488 equally spaced points were measured using a laser vibrometer. When only a single mode of propagation is present it is possible to estimate the phase velocity from measurements at two points and this is illustrated in Figure 1. Figure 1a shows two response signals measured at two positions, which were 5 mm apart. The first wave packet is the excitation signal electrically coupled in the oscilloscope and this is independent of the receive transducer position. The wave packet arriving at 10 ms is the arrival of the A_0 mode (fundamental flexural/bending mode of propagation), which is of interest and the slight delay between the two signals is visible. The wave packet at the end of the time trace is a wave reflected from a boundary of the plate. The phase delay between the two signals is estimated by firstly time gating the signals to retain only the parts of the signals containing the arrival of the A_0 Lamb wave mode as shown in the figure. The fast Fourier transform (FFT) of the time gated signals is then computed and one frequency domain signal is divided by the other to yield a ratio. The phase angle of this ratio is then computed, and this is plotted in Figure 1b. At the frequency of 101169 Hz the phase difference between the two signals is 1.72236 rad. The wavelength may be calculated using the distance between the two measurement points of 5 mm as 18.24 mm. The phase velocity is then calculated by multiplying the wavelength by the frequency (1845 m/s). Note that the spacing between the two measurement points was less than one wavelength and this is required.

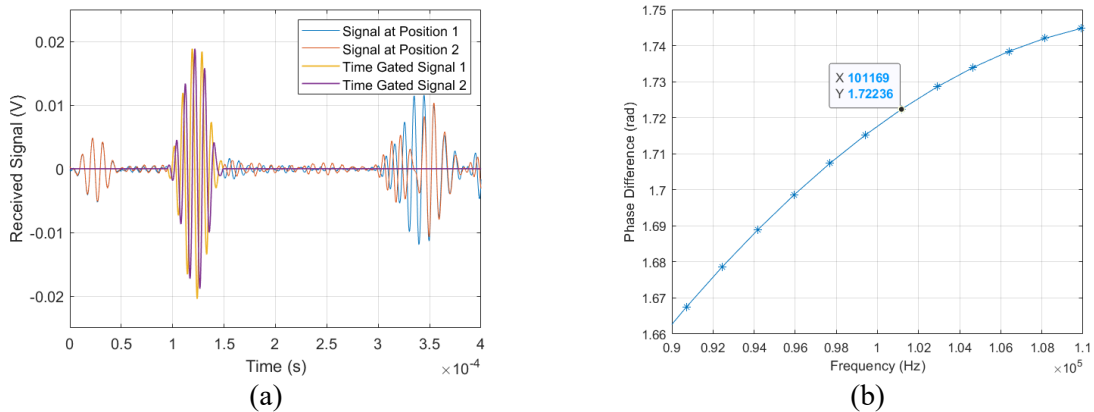


Figure 1. (a) Measured signals at two positions 5 mm apart and (b) estimation of the phase difference.

While it is possible to obtain an estimate of the phase velocity from only two measurement points it is expected that a better estimate will be obtained by using a larger number of points spanning a greater length on the plate. In our previous work [3], 100 measurement points were used in the laser vibrometer measurements, while 21 measurements were performed when manually scanning the piezoelectric receive transducer.

The equipment used in the low-cost measurement setup used in this paper is listed in Table 1 along with price estimates. The cost of the equipment is less than the target of USD 1000, believed to be acceptable for most researchers. The focus of this paper is not on further cost reduction but rather on investigating whether the EMAT transducer can provide better performance than the piezoelectric transducer as a replacement for the laser vibrometer.

Table 1: Low-cost measurement equipment.

Equipment	Make and Model	Cost Estimate Piezo System (USD)	Cost Estimate EMAT System (USD)
USB Oscilloscope	Digilent Analogue Discovery 2 Pro Bundle	430	430
Power Amplifier	Juntek DPA-2698	70	70
Power Transformer	EPCOS N87 RM14 ferrite core	-	20
Piezoelectric Transducers	Custom made - estimate for material purchases of USD 50 per transducer	100	50
EMAT Transducer	N42 permanent magnets	-	20
Pre-amplifier	Custom made – estimate for electronic components.	-	30
Total Cost		600	620

A piezoelectric transducer was glued to the plate using a gel superglue and this transducer was used to excite the plate. The transducer was a custom-made sandwich transducer with stainless steel front and back sections and a single piezoelectric ceramic ring (Ferroperm Pz29 material). A second identical piezoelectric transducer and a custom made EMAT were used to measure the response of the plate. The changes in position of the receive transducers were measured using a vernier calliper attached to the plate. The transducers are shown in Figure 2.

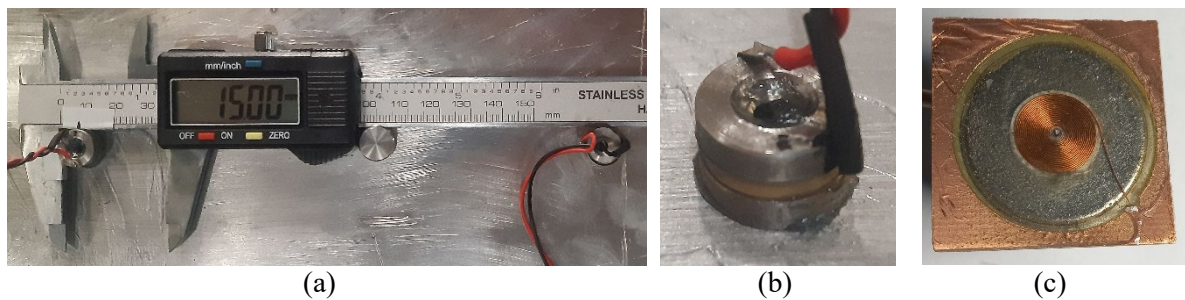


Figure 2. Transducers and positioning (a) piezoelectric transducer on the right glued to plate, (b) moveable piezoelectric transducer, (c) EMAT showing coil which would be facing the plate.

The transmit transducer was driven with a peak-to-peak amplitude of 53 Vpp by using a Juntek DPA-2698 amplifier and a transformer. The signal supplied to the amplifier was a 10 cycle Hanning windowed tone burst generated by a Digilent Analog Discovery 2 USB oscilloscope. The USB oscilloscope was used to measure the response from the transducers. When the piezoelectric transducer was used for measuring the response, the transducer was connected directly to the USB oscilloscope. The EMAT produced a very small current and a custom-made preamplifier was used to amplify the signal. This preamplifier used a transimpedance amplifier as the first stage to convert the current to a voltage and then two subsequent gain stages to increase the amplitude of the voltage signal. Averaging and filtering were performed by the USB oscilloscope and the data was saved in files for later processing.

3. Electromagnetic Transducer Development

EMATs may be used when waves in conductive materials are to be excited or sensed. The EMAT comprises a magnet (usually a permanent magnet) and a coil. The transduction mechanisms can include Lorentz force, magnetisation force, and magnetostriction in magnetic metals. When the structure is aluminium the only mechanism of transduction is the Lorentz force. The Lorentz force arises when current flows within a magnetic field and the force generated is directed perpendicularly to the current

and magnetic field. It should be noted that in an EMAT a conductor is positioned near the structure and induces a current in the skin of the conductive structure, therefore the Lorentz force acts near the surface of the structure. This means that EMATs can operate without physical contact with the plate. The same mechanism may be used for sensing the velocity of the metallic surface. In this case the velocity of the surface normal to the magnetic flux gives rise to a current flowing in the surface of the structure and this current induces a current in the nearby conductor, which can be measured. A quantitative analysis of the excitation and reception of Lamb waves in plates was provided by Thompson [6].

The wavelength of the A_0 mode in the plate at 100 kHz is approximately 20 mm and the active area of the transducer should be no more than half of the wavelength. Ideally the receive transducer should be omnidirectional, i.e., have the same sensitivity for waves approaching from any direction so that the angular orientation of the sensor is not critical. It was decided to use a spiral coil and axisymmetric magnets in the EMAT design. When a cylinder is positioned vertically above a horizontal plate the magnetic flux density is perpendicular to the plate along the axis of the cylinder. At points on the plate away from the axis of symmetry there will be a component of the magnetic flux density in the radial direction and this component is largest near the outer radius of the cylinder. The two components of magnetic flux density will cause radial shear stresses and normal stresses and can excite and sense radially polarized shear waves and longitudinal waves in a dual-mode EMAT [7]. In this paper the radial component of the magnetic flux is used with the spiral coil to detect the motion of the surface in the direction normal to the surface. Instead of using a small cylindrical magnet it was thought that it would be possible to use a larger ring magnet and use the radial component of the magnetic flux density near the inner radius of the magnet. The magnetic flux densities in the plate were investigated using finite element modelling.

The software FEMM 4.2 was used to analyse the magnetic field produced in the surface of an aluminium plate by a permanent magnet positioned above the plate. As the magnet geometries are cylinders and rings it was possible to use axisymmetric models. The FEMM software was driven from Matlab 2020b using the OctaveFEMM interface. This meant that parametric studies could be rapidly conducted. Only results for two available magnet sizes are presented in this paper although other sizes were considered. The dimensions of the cylinder magnet were 3 mm diameter and 4 mm length, while the ring had 25 mm outside diameter, 7 mm inside diameter and 5 mm thickness. The material of the neodymium magnets was N42. Four models were prepared: a cylindrical magnet above an aluminium plate, a ring magnet above the plate, a combination of the concentric cylinder and ring magnets above the plate and a combination of the concentric cylinder and ring magnets above the plate but with the polarisation of the cylinder magnet reversed. The plate was aluminium and had a thickness of 5 mm. The gap between the magnets and the plate was 0.5 mm in all models. Figure 3 shows the model of the cylinder and ring magnets and the computed magnetic flux density distribution for this model. The magnetic flux density a small distance inside the surface of the plate was extracted from the models. The component of the magnetic flux density tangent to the plate (radial component) for the different configurations is plotted in Figure 3c as a function of the radial position. These results show that for the cylinder alone the maximum of the tangential magnetic flux density occurs near the outer radius of the cylinder (1.5 mm) and for the ring alone there is a maximum near the inner radius (3.5 mm) and a minimum near the outer radius (12.5 mm). The combination of the cylinder and the ring produced greater magnetic flux densities close to centre of the model as expected. When the cylinder was inverted (polarisation direction reversed) the magnetic flux density was initially negative peaking near the outer radius of the cylinder and then becoming positive and peaking near the inner radius of the ring. This configuration would be expected to be significantly less sensitive than the original cylinder – ring configuration, which is predicted to be the most sensitive configuration. Due to the wavelength of the Lamb wave to be measured the diameter of the coil was limited to 10 mm, therefore we are interested in the magnetic flux density from the axis of symmetry to a radius of 5 mm. The flux density was numerically integrated from a radius of 0 mm to 5 mm to provide a single measure of sensitivity for each configuration, which could be compared to the measured sensitivity of each configuration.

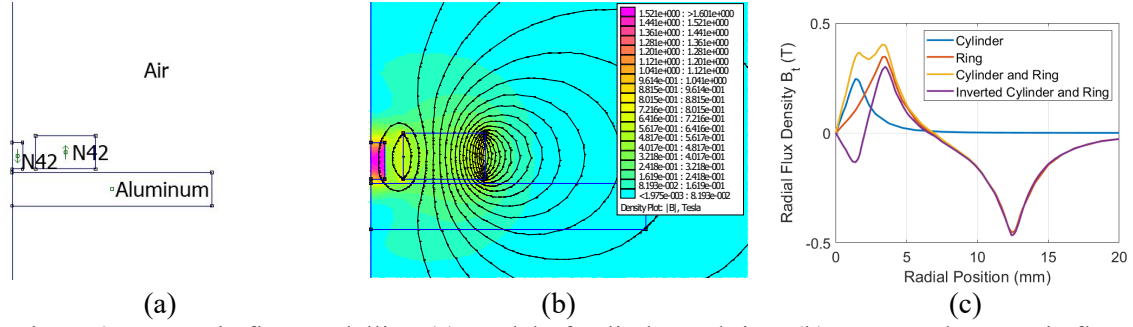


Figure 3. Magnetic flux modelling (a) model of cylinder and ring, (b) computed magnetic flux density, (c) radial component of magnetic flux density in plate surface for the four models.

A spiral coil of approximately 10 mm diameter was wound by hand using 0.18 mm enamel coated copper wire. Different magnet configurations were placed on top of the coil to determine the sensitivity of each configuration.

The measurement setup described in section 2 was used and the response at approximately 260 mm from the excitation was measured for each magnet configuration for the first arrival of the ultrasonic waves. The results of these measurements are listed in Table 2 where they are compared to the integrals of the magnetic flux densities from the numerical modelling. The measured and computed values were normalised by dividing by the value for the cylinder-ring configuration. The normalized results show very good correlation between the measured and predicted sensitivities for the three less sensitive configurations. It is believed that the numerical model could be used to optimise the dimensions of the magnets if non-standard sizes are to be considered in future.

Table 2: Measured sensitivities compared to predicted magnetic flux densities.

	Measured (Vpp)	FEM Integral (T.mm)	Measured Normalised	FEM Integral Normalised
Cylinder	0.55	3.21	0.32	0.37
Ring	1.15	5.57	0.66	0.64
Cylinder & Ring	1.73	8.72	1	1
Inverted Cylinder & Ring	0.48	2.41	0.28	0.28

The cylinder-ring configuration was selected for further development and testing. The cylinder magnet was glued inside the ring magnet and the coil was glued to the magnets. An epoxy layer was applied to the coil side of the EMAT. To allow for accurate orientation of the EMAT a rectangular piece of printed circuit board with a hole in the middle was glued to the EMAT, as shown in Figure 2c.

4. Measurement Results

When performing the phase velocity measurement there are various sources of error. Noise in the signals, changes in the contact conditions between the receive transducer and plate and inaccuracies in the measurement of the position of the transducer will cause errors. Changes in the transducer (either transmitting transducer or receiving transducer) and changes in the phase velocity in the plate (possibly due to temperature changes) will appear as phase velocity errors. Measurements were performed without moving the transducers to determine how noise in the signals contributes to phase errors. Measurements were then performed with removal of the transducer and replacement in the same position (against a mechanical guide) between measurements to determine if this had an influence on the measured phase of the signals. Finally, measurements were performed with the receive transducers positioned at a series of measurement points for estimating the phase velocity.

A series of measurements was performed with the EMAT and a piezoelectric receive transducers to compare the performance of the two transducers without repositioning. The random noise in the signals may be reduced by averaging and the noise decreases in proportion to the square root of the number of averages. One hundred measurements were performed with 1, 10, 100 and 1000 averages each. The decrease in noise that can be obtained by averaging when using the EMAT is shown in Figure 4 where each plot contains 100 measurements performed with different numbers of averages. The measurements performed with the piezoelectric receive transducer do not show such a large improvement with averaging because the SNR is already good without averaging.

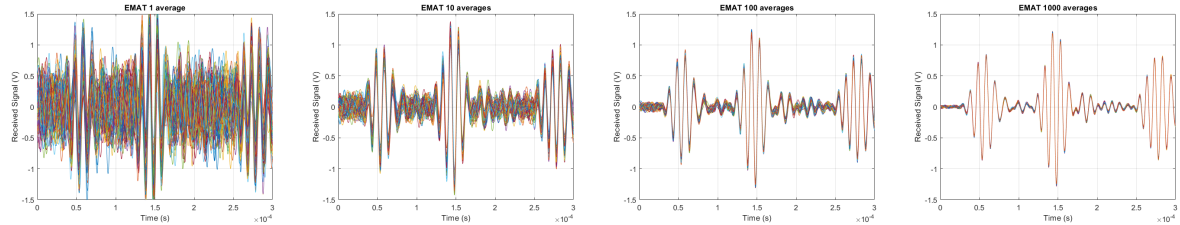


Figure 4. Decrease in EMAT measurement noise by increasing number of averages (1, 10, 100, 1000).

Each of the 100 signals captured for each of the four numbers of averages was processed to extract the phase of the signal at 100 kHz and this is plotted in Figure 5 for the two different receive transducers. The average phase and the standard deviation of the 100 measurements is listed in Table 3. It is evident that the variation in the phase measurements performed with the EMAT decreases with the number of averages. The standard deviation improved slightly for the piezoelectric receiver measurements with 10 or 100 averages but was worse for the 1000 average measurements. The 1000 average measurements took approximately 90 minutes and there appears to be some gradual change in the average phase during this time, which could be due to temperature changes. From these results it was decided that 1000 averages should be used when measuring with the EMAT while 10 or 100 averages is adequate when measuring with the piezoelectric receive transducer.

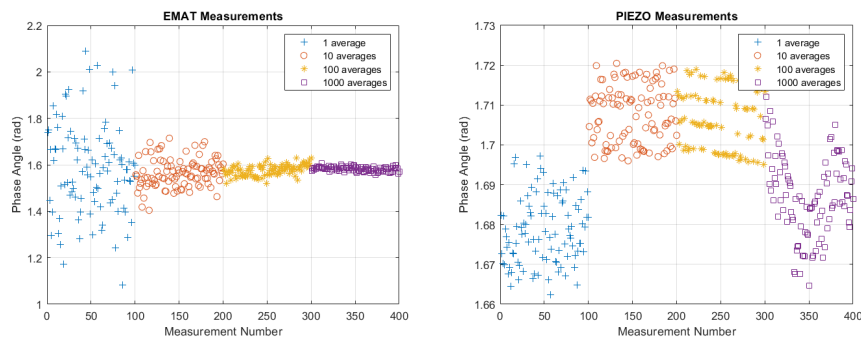


Figure 5. Variations in phase measurement for different numbers of averages.

Table 3: Influence of averaging on the repeatability of phase measurements.

No. of Averages	EMAT average phase (rad)	EMAT standard deviation (rad)	Piezo average phase (rad)	Piezo standard deviation (rad)
1	1.5854	0.1982	1.6788	0.0086
10	1.5653	0.0615	1.7079	0.0072
100	1.5763	0.0237	1.7071	0.0074
1000	1.5821	0.0099	1.6871	0.0101

Next the effect of removing the transducers and replacing them between measurements was considered. A position guide was glued to the plate and used to ensure repeatable repositioning of the transducers between measurements.

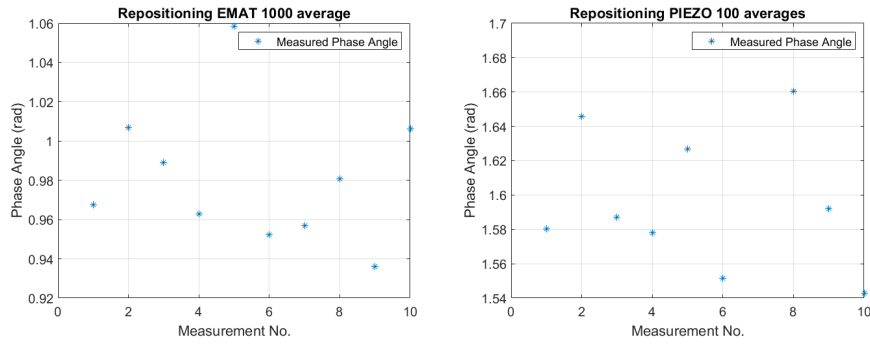


Figure 6. Phase measurements with repositioning of the transducers between measurements.

When the piezoelectric receive transducer was removed the ultrasonic coupling gel was wiped off the transducer and the plate and new gel was applied before the transducer was repositioned. The phase measurement results are shown in Figure 6. The standard deviation of the EMAT phase measurements was 0.0354 rad while that of the piezoelectric transducer measurements was 0.0481 rad. These values are similar but larger than those recorded without repositioning in Table 3, especially for the piezoelectric transducer. The repositioning of the transducers has therefore caused a decrease in the consistency of the phase measurements.

Finally, the measurements were performed along a line from the transmit transducer at 21 positions with 5 mm steps between measurement locations. The phase was estimated at each of the locations and is plotted in Figure 7a for the EMAT measurements and Figure 7b for the piezoelectric receiver measurements. A linear curve fit was performed. The slope of this line can be used to calculate the phase velocity. It is noticeable that the measured points lie closer to the line for the piezoelectric transducer measurements than for the EMAT measurements. The distances between the measurement points and the lines (the residuals) are plotted in Figures 7c and 7d.

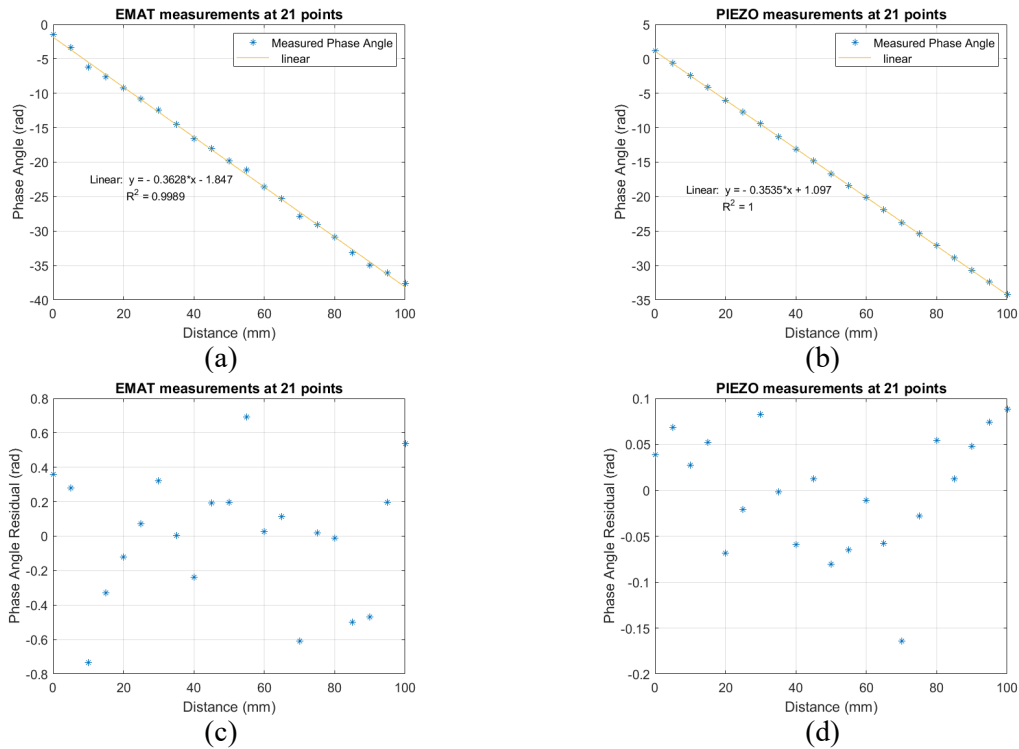


Figure 7. Phase measurements performed with (a) EMAT and (b) piezoelectric sensor, phase angle residuals from linear regression of (c) EMAT measurement and (d) piezoelectric sensor measurement.

The standard deviation of the residuals was 0.3716 rad and 0.0654 rad for the EMAT and piezoelectric transducer measurements respectively. The standard deviation of the piezoelectric transducer measurements was only slightly worse than that of the measurements performed with repositioning of the transducer, while for the EMAT the standard deviation was significantly worse. During the measurements it was difficult to position the EMAT and obtain signals with consistent amplitude and it is suspected that the positioning jig was lifting the EMAT at times. Further work is required to improve the positioning of the EMAT without disturbing the orientation and distance from the plate surface.

5. Conclusions and Recommendations

The EMAT developed for this research produced high levels of noise and averaging of 1000 repeated measurements was required to reduce the influence of the noise. Improving the SNR could be investigated in future by trying better electrical shielding of the EMAT and higher drive levels on the piezoelectric transmit transducer. Removing and replacing the transducers in nominally the same position caused increased variations in the phase of the received signals, especially when the piezoelectric receive transducer was used. A more repeatable coupling method could be explored for this transducer. When the EMAT transducer was positioned at different locations there appeared to be positioning errors and the method of positioning should be improved. If this can be achieved it is expected that the EMAT could produce phase velocity measurements with similar accuracy as those achieved with the piezoelectric receive sensor. Significant further improvements would be required to achieve the performance of the laser vibrometer system.

Acknowledgements

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