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**Feasibility study for in-plane
displacement calibration of
acoustic emission sensors**

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FEASIBILITY STUDY FOR IN-PLANE DISPLACEMENT CALIBRATION OF ACOUSTIC EMISSION SENSORS

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ABSTRACT

The calibration of acoustic emission sensors is vital for industrial users to maintain a calibrated measurement system and to demonstrate measurement traceability. Currently, no independent calibration service for acoustic emission sensors is available within Europe. The National Physical Laboratory is undertaking work to develop a measurement facility which will enable traceable calibration of acoustic emission (AE) sensors in terms of their response to out-of-plane and in-plane displacements.

This report documents the results of a feasibility study into possible methods for the calibration of an AE sensor for its response to an in-plane surface displacement. The study has demonstrated the feasibility of the method by successfully measuring the transverse acoustical particle displacement of a propagating shear wave and also analyses the future requirement to implement such a method as a calibration method.

This report is a result of work undertaken as part of Milestone 2.4.01.7 of the National Measurement System NMS 2001-2004 Acoustical Metrology Programme entitled 'Feasibility study of in-plane displacement calibration of acoustic'.

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1 INTRODUCTION

1.1 Acoustic emission background

Acoustic Emission (AE) can be defined as a phenomena where transient elastic waves are generated by the rapid release of energy from localised sources within a material. This phenomena can be used to detect dynamic processes associated with the degradation of structures, such as crack growth or plastic deformation. The advantages of AE monitoring are that it is completely passive in nature and allows real-time monitoring of large, complex structures. The technique makes use of the fact that localised discontinuities will appear long before a structure fails allowing structural integrity weaknesses to be rectified without unnecessary and expensive early decommissioning of the structure, as well as providing the means to minimize expensive, and often dangerous, failures. Past examples where AE has been successfully used range from monitoring of large pressure vessels, storage tanks, and large structures such as bridges and aircraft structures, to studying tool wear and compositions of liquids.

1.2 Project details

This milestone aims to investigate the feasibility of developing a method for the in-plane displacement calibration of an acoustic emission sensor. The milestone entitled 'Feasibility study of in-plane displacement calibration of acoustic emission sensors' is milestone 2.4.01.7 of the National Measurement System (NMS) 2001-2004 Acoustical Metrology Programme of the UK Department of Trade and Industry.

1.3 Sensor calibration background

Transducers used for acoustic emission measurement almost exclusively employ piezoelectric elements which provide a charge output for a given strain across its dimensions. These sensors are generally sensitive to surface motion both normal and non-normal to the surface to which they are coupled. The sensors are designed to offer the maximum sensitivity possible over a given frequency range for the detection of discrete events which result in surface displacements in the sub-picometre range, with an acceptable signal-to-noise ratio. AE sensors are therefore typically resonant, high-Q devices with selected resonances between around 50 kHz and 800 kHz, with this being the most commonly used frequency range used in AE measurement. It should also be noted that AE sensors are electrically coupled with matching band-pass filter/preamplifier units, generally with bandwidths of around one-octave. Although it is common for these units to be external, or part of the measurement system, there are commercial sensors available with integral filter/pre-amplifier units meaning that the sensor and filter/preamplifier units should be treated as a single entity for calibration purposes. For the purpose of this report, the transducer, filter and preamplifier combination will be referred to as the sensor unless otherwise stated.

AE sensor calibration has traditionally been performed to enable prediction of the displacement or velocity of the measurement surface given the voltage signal generated at the sensor output. A method for the primary calibration of AE sensors was outlined in an ASTM guide in 1986 [1]. This method was adopted by NIST as a calibration service which used a measurement facility consisting of a high quality steel test block, a reference capacitance transducer and a mechanical capillary fracture source. The capillary fracture acts as a step-

force release at the surface [2]. By placing this mechanical source epicentrally between the reference transducer and an AE sensor under test, an impulse calibration of the AE sensor for a surface wave can be provided for both magnitude and phase [3]. This approach has also been used in the past by other equipment manufacturers [4]. There are two disadvantages to this approach. Firstly, the surface area of the sensor under test will lead to a phase cancellation [5,6], which will contribute to calibration uncertainties and the transferability of the calibration. Secondly, the sensor under test will respond to both the out-of-plane and in-plane displacement components of the surface wave, where the capacitance transducer will respond only to the out-of-plane displacement component, leading to an erroneous calibration. Furthermore, the equivalent calibration for a compression wave uses a theoretical prediction of the surface deflection at the opposite surface of the test block as ‘the reference’ due to the fact that the actual reference transducer and sensor under test cannot both occupy the central position. This is one of the main disadvantages of using a mechanical, non-repeating source.

Reciprocity calibration techniques have also been applied to acoustic emission sensors and essentially employ the same methodology as that of the NIST comparison method - calibrating the sensor for its impulse magnitude and phase response to a surface wave when coupled to a large steel block [7, 8, 9, 10, 11, [12]. The advantage of reciprocity calibration is that it is entirely electrically based, and is not reliant on a mechanical source (which has inherent poor reproducibility), nor on the use of a reference transducer. Reciprocity does however depend on the assumption that the sensors are completely reciprocal in nature [13] and relies on propagation theory for a given material to calculate the reciprocity parameters. Although reciprocity overcomes the error associated with the reference transducer and the sensor under test responding to different planes of surface motion, the derived sensitivity is still subject to phase cancellation errors when the surface wave is used.

1.4 Rationale for in-plane sensor calibration

NPL’s approach to sensor calibration is two fold. Rather than state the sensitivity to a particular wave mode, the NPL approach is to calibrate the response of the sensor for two, one-dimensional planes of displacement, such that the sensitivity is provided for a uniform out-of-plane displacement and an in-plane displacement (see Figure 1). The main reasons for this approach are that:

- the output from the sensor is a scalar quantity, so this provides a more metrologically sound calibration;
- deconvolving a vector displacement component is not possible from a scalar voltage output;
- it allows a true like-for-like comparison against a reference sensor which responds to a single plane of displacement;
- it allows more information about how a sensor will perform for different propagation modes.

A method for stating the vector response of an AE sensor has been considered previously in the literature [14], although this only considered the relative response of the sensor and did not describe a method which could be used for the traceable calibration of the sensor. For calibration purposes, it is more metrologically sound to describe the sensitivity of the sensor as its response to a single plane of displacement rather than an unknown combination of in-plane and out-of-plane displacements, given that the output voltage is a scalar quantity. As

the piezoelectric elements used in AE sensors are generally disc shaped, it is probable that a sensor will have both radial and thickness resonances, which will be excited predominantly by in-plane and out-of-plane displacement components respectively. Understanding how a particular sensor will respond to different wave modes, or waves arriving from different angles of incidence therefore requires an understanding of how the sensor will respond to both in-plane and out-of-plane displacement components.

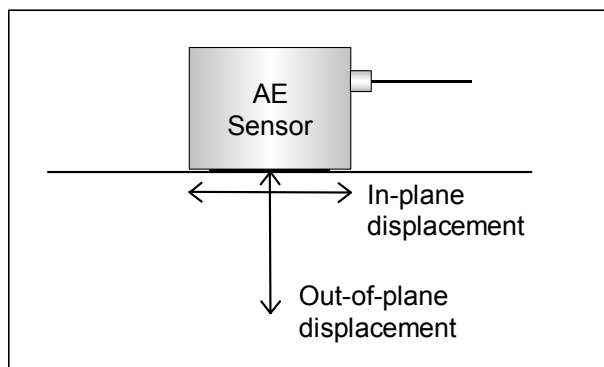


Figure 1. Planes of displacement to which the sensor should be calibrated.

As part of a previous project in the 1997-2001 NMS Acoustical Metrology Programme, NPL has already proposed a possible methodology for the out-of-plane displacement calibration of an AE sensor [15]. The measurement facility used a repeating source transducer, a glass propagation block and a displacement interferometer capable of measuring in the picometer range. The plane compression wave generated by the source transducer was windowed on its arrival such that the out-of-plane surface displacement history was measured by the interferometer. The process was then repeated with the sensor coupled to the surface at the location where the displacement history had been established. The out-of-plane calibration method is depicted in Figure 2. The presence of only an out-of-plane displacement component at the surface allowed direct comparison of the interferometer output and the sensor output to provide a calibration of the sensor for its out-of-plane displacement sensitivity.

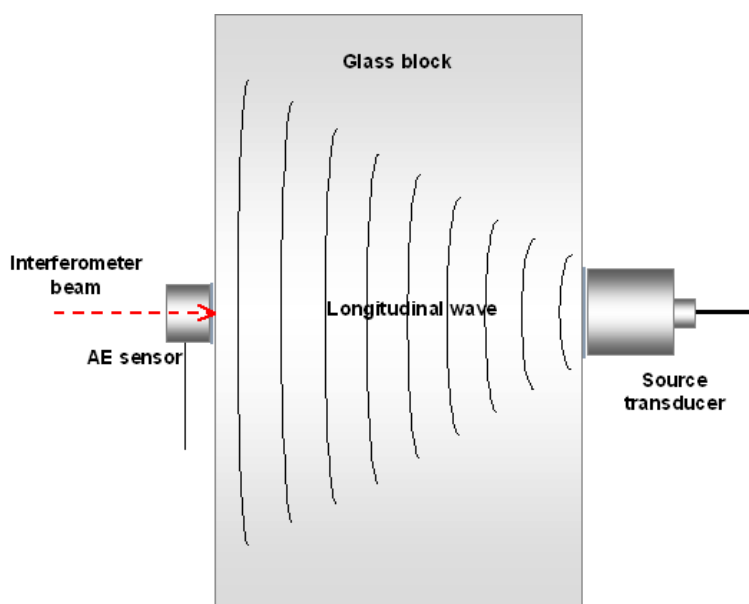


Figure 2. Measurement arrangement for the out-of-plane displacement sensor calibration.

Unfortunately, a similar strategy for an in-plane displacement sensor calibration is not so easily realised. This is due to the difficulty in producing a displacement with an in-plane component at the surface of a test block and the difficulty in measuring such a small in-plane displacement using a laser interferometer. This report suggests a number of possible methods and assesses the feasibility of each as a potential in-plane displacement sensor calibration technique.

2 INVESTIGATION OF POSSIBLE METHODS FOR IN-PLANE DISPLACEMENT CALIBRATION OF AE SENSORS

A number of methods are proposed in this section, of which only methods one and two are considered feasible for in-plane displacement calibration of AE sensors. Methods three, four and five were initially considered but, due to reasons described in more detail in this section, were rejected and therefore were not investigated thoroughly.

As suggested in Section 1, the favoured method of calibration is to isolate a wave mode such that it provides a single plane of displacement and to measure that component of the displacement using an optical method. Using this single displacement plane approach, one ensures that the reference optical interferometer and the sensor under test respond to the same excitation.

2.1 Method one

This first and most favoured method uses a glass block design which is bisected with an acoustically transparent but optically reflective boundary. Glass was chosen because of its optical transparency and its similar acoustic wave speeds to commonly used metals [15]. The aim of this method is to propagate an acoustic shear wave along the optical boundary so that it arrives at the opposite surface with only an in-plane displacement component which can be measured using an interferometer normal to the optical boundary as shown in Figure 3. The method relies on the ability to window the shear wave arrival using its much slower wave speed than the longitudinal wave and also on the ability to propagate a shear wave directly along the optical boundary such that its particle displacement is perfectly normal to the plane of the optical boundary. It is also important that the optical boundary is acoustically transparent.

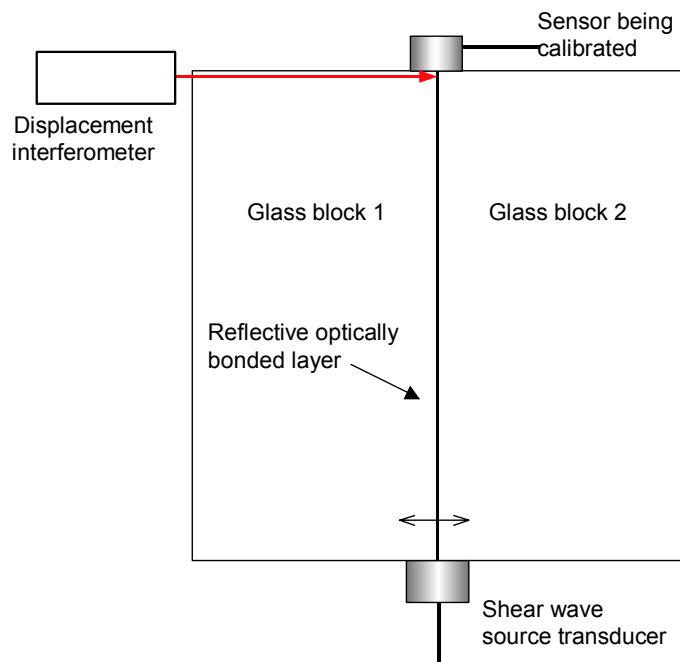


Figure 3. Arrangement for method one for in-plane sensor calibration.

To test the feasibility of this method, a small test sample was constructed with cubic dimensions of 60 mm. The sample was constructed using two blocks of BK7 glass, each

measuring 60 mm x 60 mm x 30 mm. One of the blocks was coated with a ~200 nm aluminium coating on the 60 mm x 60 mm surface and then both blocks were bonded together using a UV cured urethane methacrylate based adhesive such that the aluminium coated surface formed the required optically boundary as shown in Figure 4. The adhesive layer was estimated to be around 15 μm thick from total block thickness measurement with and without the adhesive.

2.1.1 Testing the optical boundary

Ideally, the optical boundary should be completely transparent. To test this, a series of pulse-echo measurements were performed on the glass block using a pulse-echo unit and three different transducers with centre frequencies of 1 MHz, 5 MHz and 10 MHz. Each transducer was coupled in turn to the surface of the glass block parallel to the optical boundary as shown in Figure 4.

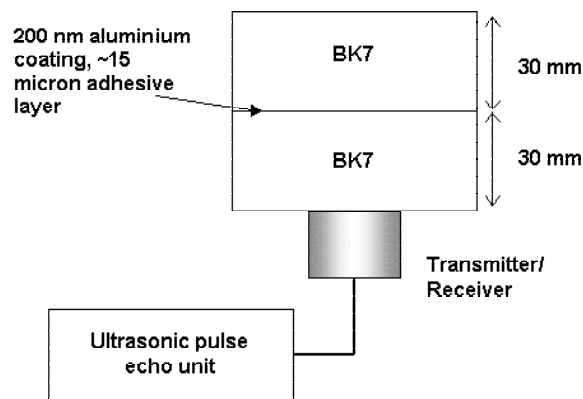


Figure 4. Pulse-echo test setup.

For an acoustically transparent boundary, one would not expect an echo until 20 μs after the initial pulse, corresponding to a longitudinal wave propagation distance of 120 mm, to the back of the 60 mm block and back. As can be seen from Figure 5, the first echo occurs only 10 μs after the initial pulse which itself begins at 10 μs on the plot. This corresponds to a total longitudinal wave propagation distance of 60 mm which is consistent with an echo from the optical boundary.

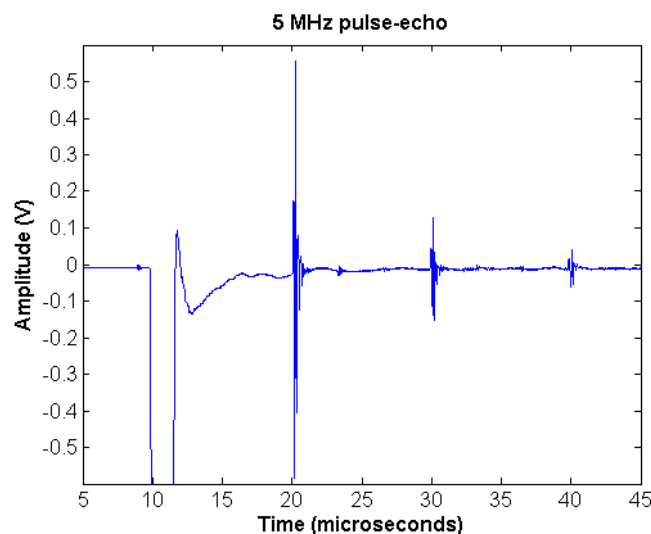


Figure 5. 5 MHz pulse-echo test result.

Due to the relative nature of the pulse-echo test, it is not possible to quantify the extent of the reflection but it does indicate that the optical boundary is not completely acoustically transparent. To help quantify the acoustical reflection and transmission coefficients, a simple three-boundary transmission model was produced for the block shown in Figure 4. The layers used for the model are shown in Figure 6, where a 200 nm aluminium and a 15 μm optical cement layer were sandwiched between two infinite layers of BK7 glass. The material properties for the optical cement were estimated from polymer material properties [16].

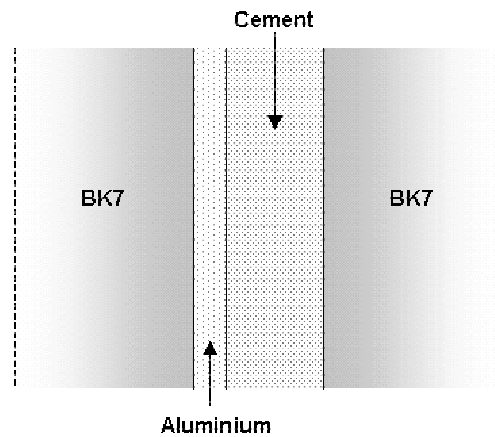


Figure 6. Arrangement for three-boundary transmission model.

The three-boundary transmission model predicted a reflection coefficient of 0.13 at 1 MHz and 0.54 at 5 MHz as shown in Figure 7. It should be remembered that the highest frequency component of interest for an acoustic emission application is usually no more than 1 MHz, although even at this frequency, the loss of transmission would be very high given that the shear wave has to travel along the boundary. More importantly, the obvious acoustic impedance mismatch of the boundary would also mean that the boundary would not accurately follow the acoustic particle displacement.

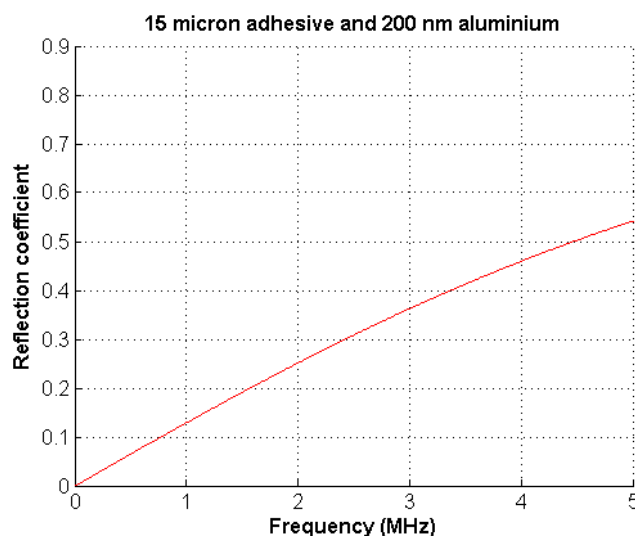


Figure 7. Reflection coefficient for the model shown in Figure 6.

To further investigate the source of the impedance mismatch, the model was reconstructed as a two-boundary configuration with only a 200 nm aluminium layer, thus removing the thicker

adhesive layer. It was thought that the adhesive layer was the reason for the large reflection coefficient given its thickness and its large impedance mismatch with the surrounding glass blocks. The two-boundary model clearly shows that the aluminium has a negligible influence on the transmission across the boundary, with a reflection coefficient of around 0.0001 at 5 MHz.

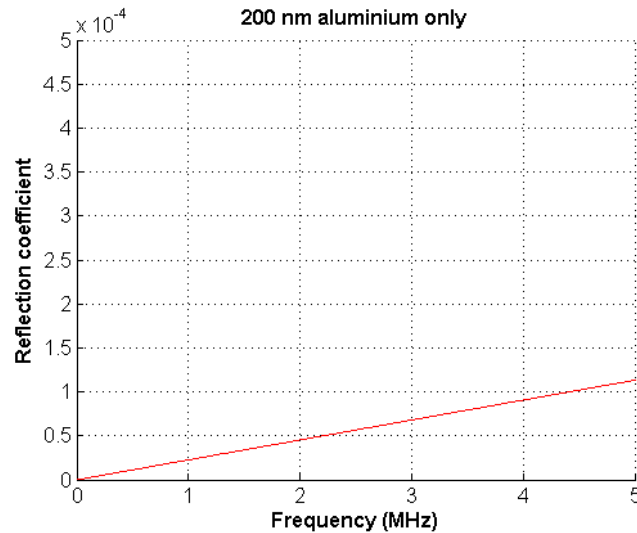


Figure 8. Reflection coefficient for two-boundary transmission model with only an aluminium layer.

The implications of this are that the optical cement used for bonding the two glass blocks together needs to have an acoustic impedance closer to the glass, or needs to be of negligible thickness. As a result, a number of two-piece sample blocks were fabricated using silver-loaded and aluminium-loaded adhesives. The loaded adhesives provided a much closer impedance match to that of the glass but still resulted in significant acoustic reflection, comparable with that shown in Figure 5. The reason for this was that the greater viscosity of the adhesive made it much more difficult to produce a thin bond, resulting in an adhesive layer significantly greater than 15 μm . Other bonding methods were also investigated, including clamping the two polished surfaces of the blocks together with and without an ultrasonic coupling gel layer. Both of the methods resulted in a significant reflected component during pulse-echo testing. Unfortunately, it was not possible to test thinner bonding layers, although it was thought that under the right bonding conditions, a sub-micron layer adhesive might be possible. This is something that should be tested in future work.

2.1.2 Measurement of transverse acoustic particle displacement

To test the feasibility of using such an optical boundary to measure the transverse acoustic particle velocity of a propagating shear wave, a series of measurements were performed using the NPL AE interferometer [15] along the length of the boundary. The shear wave was produced using a Panametrics 0.5 MHz normal incident shear wave transducer coupled using highly viscous honey to the surface of the glass block such that the plane of the optical boundary passed through the acoustic centre of the transducer as shown in Figure 3. An interferometer measurement performed ~ 9 mm along the optical boundary from the source shear wave transducer is shown in Figure 9. The arrival time of the first arrival observed in Figure 9 is consistent with the shear wave velocity of around 3200 m/s. As expected, the longitudinal wave, which would pass this point around 1.5 μs after the trigger, is not observed

as this would have no transverse component. It should be noted that only the first positive and negative spike are associated with the shear wave in Figure 9. After 5 μs , one would expect longitudinal reflections from the side of the block which would arrive at an angle of incidence such that the acoustic particle velocity would be normal to the plane of the optical boundary and therefore be detected by the interferometer.

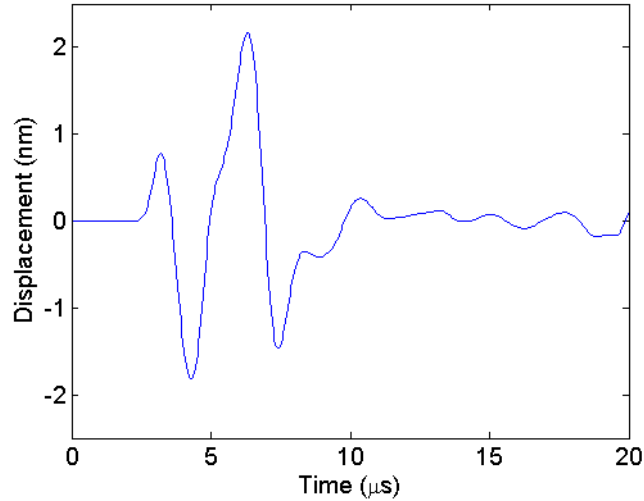


Figure 9. In-plane displacement measurement at optical boundary.

Successful measurement of the transverse acoustic particle displacement of a propagating shear wave using a laser interferometer shows that such a method could be used for the calibration of an acoustic emission sensor for its in-plane displacement sensitivity.

The feasibility of using a glass test block with an optical boundary has been demonstrated although the boundary has been shown that the boundary is not truly acoustically transparent and therefore does not accurately follow the acoustic particle velocity. This would be a disadvantage of this method if the acoustic impedance of the boundary cannot be better matched to the surrounding glass. However, providing the shear wave travels perfectly parallel with the boundary and therefore no mode conversion takes place, the loss associated with the impedance mismatch could be predicted.

2.2 Method two

The second favoured method considers measuring the vector surface displacement to determine both the in-plane and out-of-plane displacement components, see Figure 10.

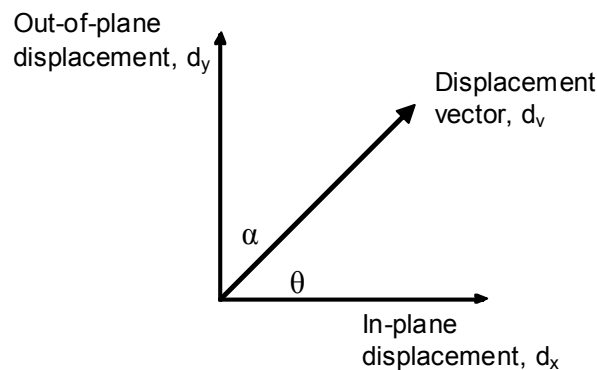


Figure 10. In-plane and out-of-plane displacement components

Using a diffuse surface, the in-plane and out-of-plane components can be found from the vector displacement using equations (1) and (2),

$$d_x = d_v \cos \theta \quad (1)$$

$$d_y = d_v \cos \alpha \quad (2)$$

where d_x and d_y are the in-plane and out-of-plane displacement components respectively and d_v is the measurement displacement vector.

The use of a suitable interferometer positioned such that the laser beam is incident on the measurement surface at an α from the normal, the in-plane displacement component can be found from the vector displacement measurement using equation (1). Although the use of an interferometer at both $\alpha = 0$ and $\alpha = \alpha$ could resolve both components of displacement, for the purpose of calibration the in-plane and out-of-plane components should be isolated as the AE sensor will respond to both and it would not be possible to deconvolve the sensor output. For this reason, the method shown in Figure 11 shows the use of a shear wave propagating normal to the measurement surface. The use of a normal incident wave shear transducer or a shear wave wedge could be used for this if a sufficiently large block was used to window the shear wave arrival in the absence of the longitudinal wave.

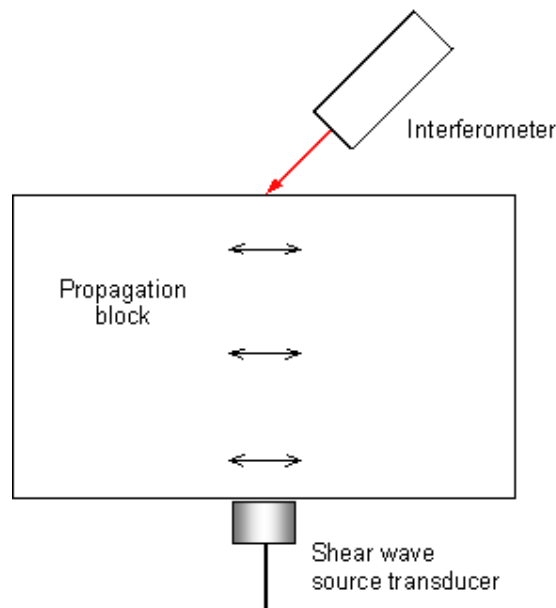


Figure 11. Vector surface displacement method.

Scattered light from a diffuse surface can be described using Lambert's cosine law of diffusion [17]. For this type of scattering surface the light is very low and is completely depolarised. The NPL AE interferometer cannot operate under such low conditions due to limited laser power (5 mW) and the requirement for phase locking of the interference fringe. Although a more powerful laser interferometer could provide more light, the noise floor performance would always be limited for such application. Vibrometers, which employ a heterodyne interferometer configuration for velocity measurement are often much more versatile for low light applications and are often used off Lambertian type surfaces.

For this reason, the use of a Polytec PSV300 vibrometer with a 1.5 MHz measurement bandwidth was investigated using an aluminium test block and a normal incident shear wave transducer. The test block measured 279 mm in length with a diameter 254 mm and the surface was prepared to have a diffuse surface, roughened in only one direction. The vibrometer was aligned at an angle α to scatter off the opposite flat surface to which the shear wave transducer was coupled as shown in Figure 11. Measurements were attempted at a number of angles, α but the noise floor of the vibrometer was too small to detect the direct shear wave arrival, even with averaging. Due to the dynamic and frequency range decoders fitted to the vibrometer, the sensitivity on the full 1.5 MHz bandwidth was limited. However, other decoder units might be available in future which provide a better sensitivity, or smaller dynamic range setting with the required frequency range.

Other options similar to this method could use a one piece block to measure the in-plane displacement at the surface under which the sensor would be calibrated by reflecting the laser from a micro-notch or a similar surface step.

2.3 Alternate methods

Using the vibrometer and aluminium test block described in Section 2.2 a series of measurements were made of a surface wave generated by a conical source transducer as shown in Figure 12. The angle of incidence of the vibrometer was varied to establish if the in-plane component of the surface wave could be detected. However, increasing the angle from the normal, resulted in a decrease in amplitude consistent with equation (2) indicating that only an out-of-plane component was being detected. The likely reason for this was that the in-plane component of the surface wave was very small compared with the out-of-plane component. This type of method would not be favourable for an in-plane sensor calibration and is not ideal as an out-of-plane sensor calibration due to the phase cancellation across the sensor face and the presence of both displacement components. However, surface wave calibration is probably the most widely used type of AE sensor calibration. These measurements show that the error associated with the in-plane component, which the reference sensor does not respond to in these calibrations is probably quite small.

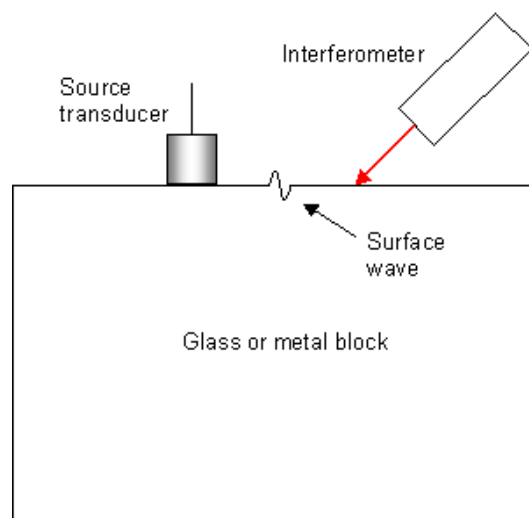


Figure 12. Vector surface displacement measurement of surface wave.

To generate larger in-plane displacement components a piston transducer was used as shown in Figures 13 and 16. Although neither of these methods are suitable for sensor calibration due to the presence of both in-plane and out-of-plane displacement components, mode conversion at the surface and phase cancellation across the face of the sensor, they have been included in this feasibility study as possible back up options.

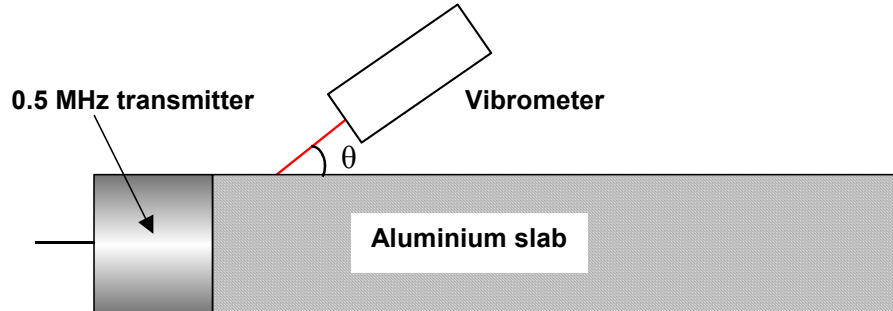


Figure 13. In-plane displacement generated using a piston transducer.

The setup shown in Figure 13 was used to generate large in-plane displacements where the vibrometer was incident only 20 mm from the end of the 1.5 inch aluminium slab to which the Panametrics 0.5 MHz piston transducer was coupled. Figure 14 and 15 show the measured vector displacement measured using the PSV300 vibrometer at two angles of θ . The measurements show a trend for the measured displacement to decrease with increasing angle θ , showing the presence of a relatively large in-plane displacement component.

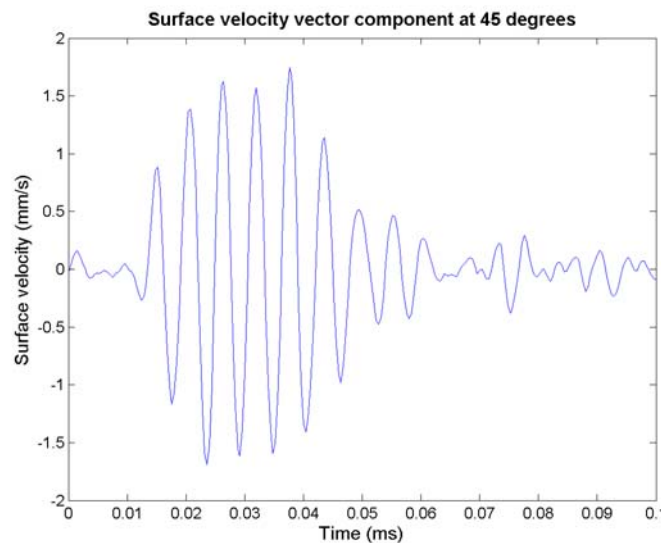


Figure 14. Vector displacement measured using laser vibrometer at $\theta = 45^\circ$.

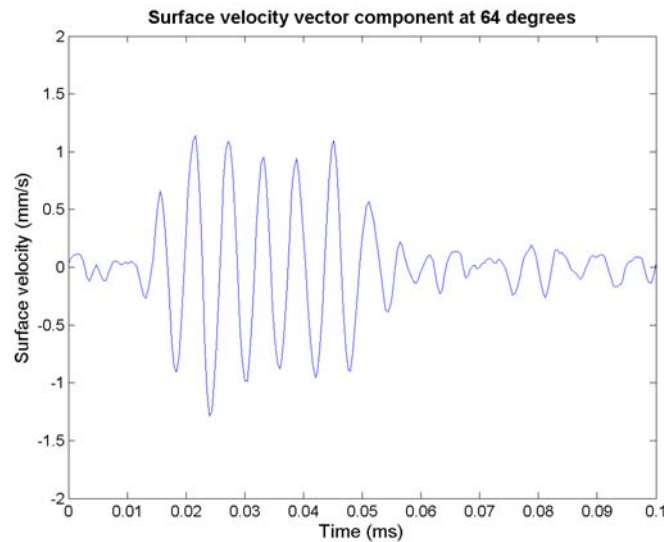


Figure 15. Vector displacement measured using laser vibrometer at $\theta = 64^\circ$.

A similar measurement methodology was used for the arrangement shown in Figure 16, which employed a large wedged block and Panametrics 0.5 MHz piston transducer to generate both in-plane and out-of-plane displacement components at the surface. Whilst this method also showed that it was possible to generate measurable in-plane displacement components, the generated surface waves on the measurement surface make it difficult to isolate the direct arrival. This method also suffers from the same disadvantages as the method shown in Figure 13 and is therefore not suitable for sensor calibration for in-plane displacement sensitivity.

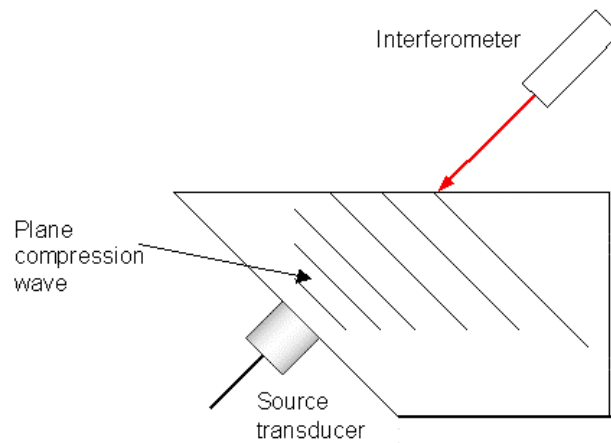


Figure 16. In-plane displacement generated using a piston transducer and wedge shaped block.

3 DISCUSSION

3.1 *Feasibility of in-plane sensor calibration*

The requirements for an accurate calibration of the response of an AE sensor to in-plane displacement are that the AE sensor should be excited with only an in-plane displacement component and that the reference sensor should measure the in-plane displacement for the same excitation. It has been shown that an in-plane only displacement can be generated using a shear wave transducer which propagates a shear wave in a direction normal to the measurement. To calibrate a sensor using this technique, the shear wave should be windowed on arrival from the longitudinal mode by using a large enough block to separate the wave modes using their wave speed.

Two methods suitable for AE sensor calibration have been considered in this report, the first using the standard NPL AE interferometer, the second requiring an interferometer capable of measuring from a Lambertian surfaces. Both methods rely on the same principle for generating the in-plane displacement and differ only in the way they measure the in-plane displacement component for calibration. The first method is the most favoured as it offers the potential for measurement of in-plane displacement component in the picometer range by measuring the transverse particle displacement component of a shear wave propagating along an optically reflective but acoustically transparent boundary. This approach has been tested and the transverse acoustic particle displacement of a propagating shear wave has been successfully measured using the NPL AE interferometer, although testing has shown that the optical boundary is not completely acoustically transparent. The acoustic impedance mismatch of the adhesive used to bond the two sub-blocks which make up the glass test block means that the optically reflecting boundary is not accurately following the particle displacement of the propagating shear wave, making the displacement measurement erroneous. However, it is possible that this could be rectified in future with the use of sub-micron adhesive layers or by a theoretical correction.

The second method, which is possibly the easiest to realise has the disadvantage that the displacement measurements possible are severally limited by the performance of the interferometer used. The displacement equivalent noise floor of an interferometer is inherently related to the light level returned from the target. This second method relies on a vector displacement measurement obtained by bringing the laser interferometer beam on to a diffuse scattering surface at an angle. In this case the light level returned to the interferometer is much lower than that for a mirrored surface, thus the displacement equivalent noise floor of the interferometer is much higher. As part of this feasibility study, the noise floor obtained from a scattering surface proved too high to detect the in-plane displacement generated by the shear wave at the surface of the test block.

3.2 *Future work*

Future work should consider developing a calibration methodology based on method one described in this report. A shear wave transducer can clearly be used to produce an in-plane displacement but the optical boundary used in this feasibility study proved to introduce an acoustic impedance mismatch which for the thickness of the adhesive layer was too great. Methods for producing a similar block should be investigated which employs sub-micron adhesive layer, thus allow the optical boundary to follow the acoustic particle velocity more faithfully. An aluminium block with a sub-millimetre step at the surface should also be considered which would allow in-plane displacement measurement by reflecting the

interferometer laser beam from the vertical stepped surface. The sensor under test could then be coupled to the surface with the edge of the sensor element aligned with the step from which the in-plane displacement component was measured.

Which ever block type is used, a suitable test block size needs to be established for the calibration such that the shear wave can be isolated from other wave modes and reflections at the lowest frequency required.

4 CONCLUSIONS

The feasibility of in-plane displacement sensor calibration has been demonstrated using a displacement laser interferometer to measure the transverse acoustic particle velocity of a propagating shear wave. This was achieved using two BK7 glass blocks, bonded together to form a single block with an optically reflective, acoustically transparent boundary. The use of a normal incident shear wave transducer allowed the propagation of a shear wave along this optical boundary. The use of this method to accurately measure the shear wave acoustic particle displacement would allow an AE sensor to be calibrated for its sensitivity to in-plane displacement. Initial investigations showed that the thickness of the adhesive and its acoustic properties used to bond the two glass blocks compromised the acoustic transparency of the optical boundary. This means that the optically reflecting boundary does not accurately follow the particle displacement of the propagating shear wave, making the displacement measurement erroneous. However, it is possible that this could be rectified in future with the use of sub-micron adhesive layers or by a theoretical correction.

5 ACKNOWLEDGEMENTS

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