Towards traceable calibration of acoustic emission measurement systems: development of a reference source at the UK's National Physical Laboratory

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Abstract

Acoustic emission (AE) has been in use for many years without the use of internationally agreed measurement standards and has not been the subject of traceable measurement requirements. This has limited the applicability of AE measurements on safety critical structures. The accepted method of characterising the measurement system, often termed system calibration, is the Hsu-Neilsen pencil lead break. The UK's National Physical Laboratory (NPL) is undertaking work to develop a reference source that will provide a traceable alternative to the pencil lead break and add an element of traceability to this system calibration. This will contribute to greater acceptance of AE techniques in general, by meeting quality system and other traceability requirements.

In this paper the key issues surrounding the characterisation of such a traceable reference source are reviewed, including the establishment of a calibration method for the source transducer using a laser interferometer and a suitable test block. The use of an optically transparent glass block and displacement interferometer provide the ability to calibrate the transfer source for contact displacement at a given voltage drive level. This method provides traceability to the wavelength of light.

Keywords
Reference source, acoustic emission, conical transducer

1 INTRODUCTION

For many years the internationally accepted method of characterising an AE measurement system has been the Hsu-Neilsen pencil lead break [1]. Its use was initially proposed to provide a step-force point source function and gained popularity due to the ease of its use in practice. Although this method is still very useful for characterising an AE measurement system to a step-force function input, it does not offer traceability to fundamental standards and therefore cannot meet all the demands of modern AE applications which require traceability.

The UK's National Physical Laboratory (NPL) is undertaking work to develop a measurement facility and methodology for the characterisation of a point contact transducer such that it could be used as a traceable reference source on AE measurement systems. Ultimately, such a reference source would be used on systems with calibrated sensors traceable to national or international standards to provide traceable linkages at each stage of the measurement chain.

Previous work [2][3] has been undertaken on the use of a conical transducer as an energy source for system calibration which adopted a different method to that described in this paper for the calibration of the transducer. This paper presents a measurement method which relies on an optically transparent propagation medium (glass) and a displacement interferometer to measure the contact displacement at the transducer.

2 REFERENCE SOURCE DESIGN

The transducer characterised in this paper is the conical piezoelectric transducer, which was originally proposed by NIST [4][5][6] as a broadband point contact reference sensor. The actual transducer used for this work was a modified design manufactured by Imperial College, UK, employing a 3 mm thick conical piezoelectric element with a top diameter of 10 mm and contact diameter of 1 mm [7][8]. The piezoelectric element was mass loaded with a 14 mm layer of tungsten-loaded epoxy and a 14 mm layer of pure epoxy backing layer with a 20 mm diameter as shown in Figure 1.

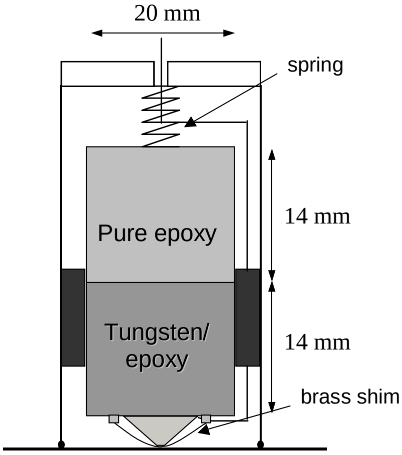

Figure 1. Construction of tungsten loaded epoxy backed conical transducer.

The transducer was designed to contact the surface via a 50 µm brass shim which provides both the electrical earth and a protective wear layer for the piezoelectric element. The transducer design also incorporated a spring to maintain the contact force of the active element when the transducer case is secured to the surface.

The small contact area of such a transducer design reduces aperture effects and coupling variability [7], and although a conical element has more mechanical resonances than a disc-shaped element, these resonances are less dominant, giving such transducers an improved broadband frequency response. The tungsten loaded epoxy and pure epoxy backing also serve to dampen the response of the conical piezoelectric element by reducing internal reflections.

3 MEASUREMENT SETUP

Although it might seem preferable to employ metals as test block materials for acoustic emission reference facilities as these are frequently the materials used in practice, it was decided that glass would be used as the test block material. The reasons for this choice were:

1. It is easy to polish and coat glass materials to provide a suitable surface for the optimum reflection of the laser signal.
2. It is difficult to produce large samples of metals, and of aluminium in particular, which have homogeneous acoustic properties.
3. An optically transparent material allows the laser interferometer beam to be directed through the block to the contact surface of the transducer.

4. The sound speed of longitudinal and the shear waves in glass are comparable to those of aluminium.

A block of Schott NBK7 standard optical quality borosilicate glass of approximate dimensions 240 mm by 250 mm by 160 mm was therefore used with a ~100 nm chromium coating on one of the large faces.

The conical transducer was coupled to the centre of the chromium coated face of the glass block and a displacement interferometer was positioned on the opposite side of the glass block such that the optical beam reflected from the chromium coating at the contact point of the transducer after passing through the glass block. This arrangement is depicted in Figure 2.

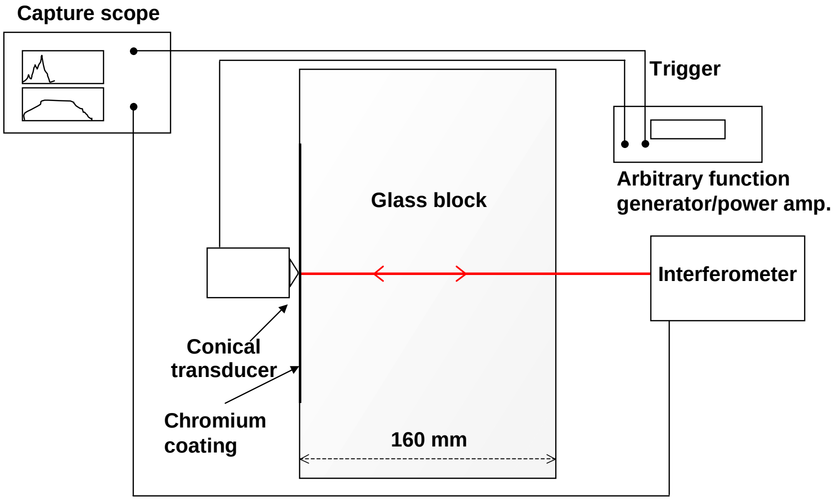

Figure 2. Measurement setup.

The time of flight for a compressional wave through the 160 mm thick glass block is approximately 27 µs. In this case, where the source transducer and the laser measurement spot are located in the same position, the first arrival at this point will be the direct echo from the opposite face which will arrive approximately 54 µs after the initial excitation.

The interferometer used for the measurements was a standard Michelson homodyne design for measurement of normal surface displacement and was developed by Photometric Consultants Limited (PCL). The device has a measurement frequency bandwidth from 20 kHz to 3 MHz, with an RMS noise equivalent displacement of around 5 pm in this bandwidth. The interferometer is shown in Figure 3 with the conical transducer coupled to the glass block. This setup allows the interferometer to measurement the surface displacement directly at the contact point of the conical transducer.

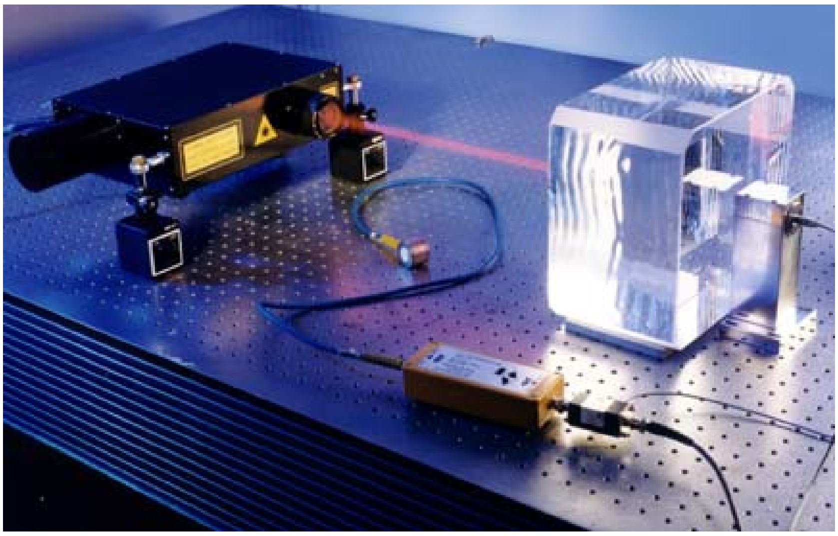

Figure 3. Measurement setup.

4 RESULTS AND DISCUSSION

A series of measurements were performed to investigate the method of displacement measurement through the glass block using the interferometer and to further characterise the transducer. For these measurements, the conical transducer shown in Figure 1 was used as a transmitter and was coupled to the centre of the Chromium coated surface with a thin layer of water based coupling gel and held in place with a rigid mount. The transducer was excited with a steady-state tone-burst, a short pulse and a white-noise source to fully characterise its response to the way in which it might be used in practice.

4.1 Steady-state excitation

The transducer was excited with a 100 µs tone-burst using an AG33220A function generator coupled to an ENI 240L 50 dB linear power amplifier to provide a drive level of around 50 $V_{p\text{-}p}$. This was performed at a number of frequencies between 50 kHz and 3 MHz at steps of 50 kHz up to 1.2 MHz, at steps of 100 kHz from 1.2 MHz to 2 MHz and then 200 kHz steps up to 3 MHz. The contact displacement for each tone-burst was measured using the PCL self-calibrating interferometer as shown in Figure 2 and captured using a Tekronix TDS 5054 oscilloscope at a sample rate of 125 MHz with 30 time averages. An FFT was then performed on the steady-state part of the time domain waveform. To remove the end effects from the FFT data, the steady-state section of the waveform was windowed prior to FFT analysis using a Tukey window with a 0.1 taper ratio [9]. The unwindowed time domain signal from the interferometer and the windowed FFT signal are shown in Figures 4a and 4b respectively. The displacement was obtained from the FFT signal to obtain the displacement at the drive frequency component only. This was repeated for each frequency. The results from this analysis are shown in Figure 5. Given that the drive level remained the same throughout the measurements, it can be assumed to represent the steady-state transmit response of the transducer on the glass block. Although the actual drive levels were known, the results were not plotted as a sensitivity curve for units of displacement per unit voltage applied because a complete electrical impedance analysis of the transducer had not been completed at this stage.

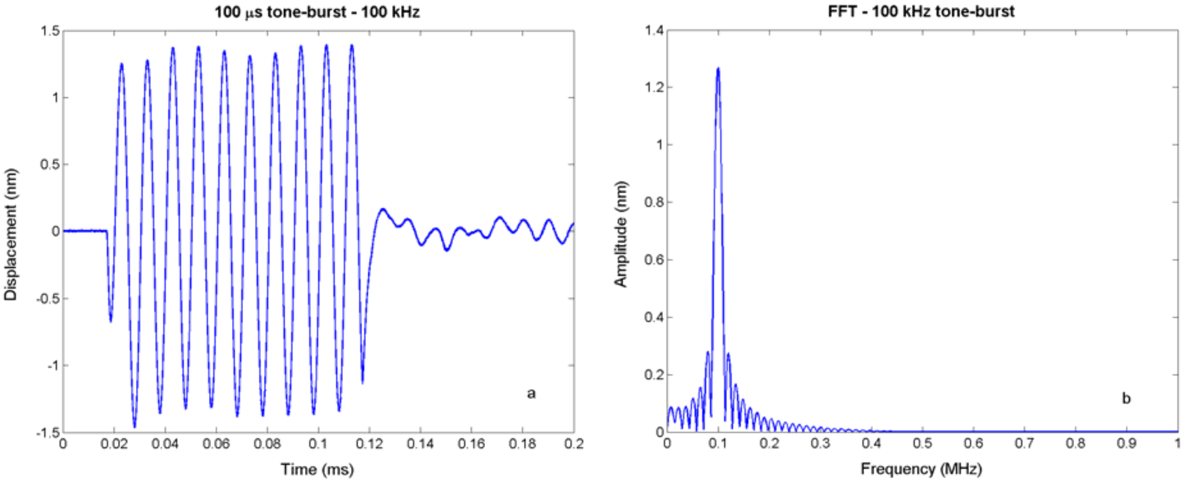

Figure 4. Tone-burst excitation of conical transducer.

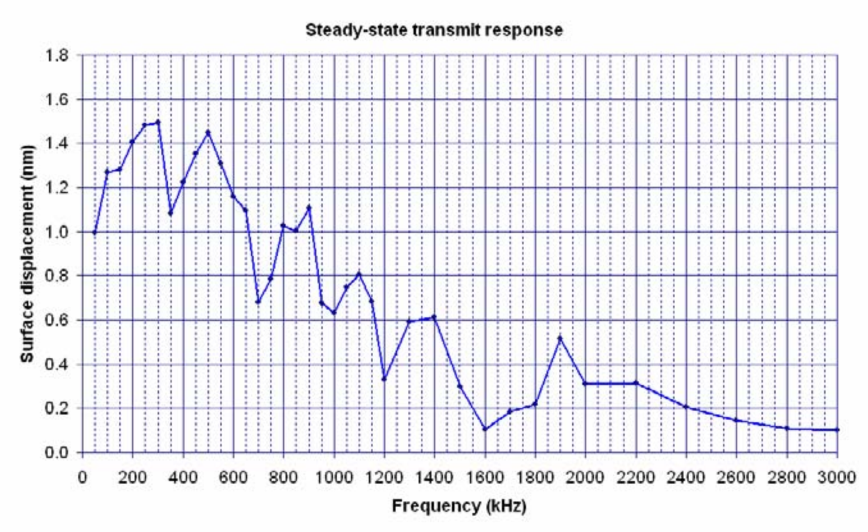

Figure 5. Steady-state transmit response of conical transducer.

The steady-state response shown in Figure 5 shows that the transducer does have a number of resonant points although as suggested in section 2, these are not dominant. It was expected that the transducer would have a dominant response below 1 MHz due to the radial modes at the top of the cone around 200 kHz, also with a radial mode at the 1 mm contact tip around 1.8 MHz. One would also expect a thickness mode to dominate for the 1 mm diameter flat contact area at around 500-600 kHz. Other resonances would be introduced throughout the frequency range due to the conical shape, particularly if there were any ridges present due to the machining of the conical element.

4.2 Pulse excitation

A 250 ns pulse with a 5 ns rise-time and a potential difference of around 120 V across the transducer terminals was generated using the AG33220A function generator and the 50 dB ENI 240L power amplifier. The displacement at the centre of the transducer contact point was again measured using the PCL interferometer and captured using the TDS 5054 oscilloscope using a sample rate of 500 MHz with 100 time averages. The spike produced at the transducer contact point is shown in Figure 6a, along with the windowed FFT signal in Figure 6b. The rise-time of the negative spike generated by the transducer was measured to be around 0.35 μs which corresponds to a response bandwidth of around 2.8 MHz. Figure 6b also indicates that there is still significant energy up to around 2.5 MHz. It should be noted that the reduced output of the transducer at higher frequencies is partly due to the roll-off of the input level at higher frequencies for the 250 ns pulse. Dividing the output signal by the input signal shown in Figure 6b would provide the response relative to the input and show a better response at higher frequencies. This was not plotted however as the input FFT was taken before power amplification and so the actual shape of the waveform at the transducer terminals could vary from that shown in Figure 6b. It should also be noted that the –3 dB point for the interferometer band-stop frequency is 3 MHz.

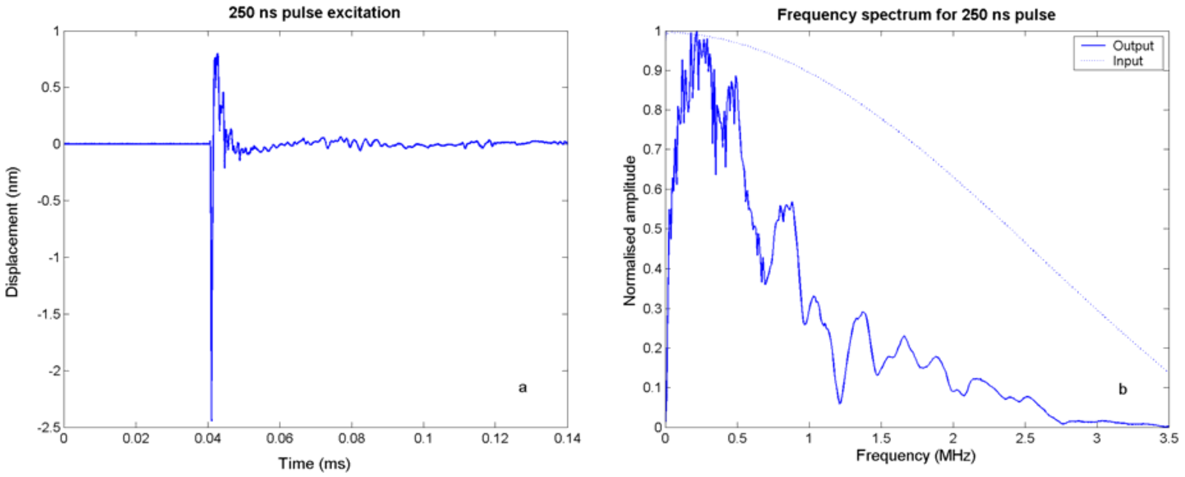

Figure 6. 250 ns pulse excitation of conical transducer.

The pulsed response of the transducer agrees fairly closely with the steady-state response showing resonances around 200 kHz, 500 kHz, 800 kHz and around 1.4 MHz but does show the transducer to be relatively flat over a 1 MHz bandwidth.

4.3 Noise excitation

The transducer was also driven using a broadband 10 Vp-p white-noise source using the AG33220A function generator. The same measurement procedure was used to measure the contact displacement, although no averaging was used in this case and the sample rate was limited to 50 MHz to maximise the measurement period. The noise spectrum obtained from the 1 ms time domain signal following the windowed FFT analysis is shown in Figure 7.

The noise spectrum shows the broadband response excellent up to around 1.2 MHz with significant output above this up to around 2.5 MHz and that the response agrees closely with the steady-state response.

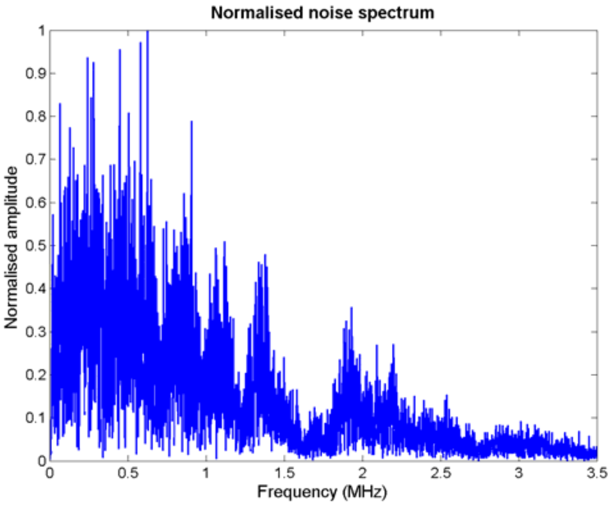

Figure 7. Measured frequency spectrum for white noise excitation of conical transducer.

4.4 Discussion

The steady-state, impulse and white-noise characterisation of the conical transducer when being used as a transmitter show that the transducer behaves as a broadband, low-Q device with a very good rise-time response of better than 350 ns. Some initial impedance analysis has also indicated that the Q of the conical transducer is very low, below 2. The performance of the transducer as a low-Q broadband device coupled with its point contact design make it particularly suited as a transmitter for testing AE measurement systems. In addition to this, the facility developed at NPL for measuring the displacement at the contact point when coupled to a glass block offer the potential to calibrate the transducer for its surface displacement output per unit charge/voltage across the transducer terminals. Although this would require some correction for surface loading conditions, it would allow the transducer to be used as a reference source to provide a traceable link to SI units when calibrating an AE measurement system.

Work beyond the scope of this paper aims to optimise the design of the transducer as a low-Q reference source using finite element modelling and to redesign the transducer to provide the robustness necessary to be used in practical applications.

5 CONCLUSIONS

A facility and method has been demonstrated for measuring the displacement at the contact point of a transmitting conical transducer using a displacement interferometer and an optically transparent glass block. This method has then been used to characterise a conical design of piezoelectric transducer for tone-burst, impulse and noise excitation which showed the transducer to be relatively flat across a 1 MHz bandwidth with energy present up to around 2.5 MHz. The point contact design of the transducer and its low-Q, broadband performance make it good candidate as a transmitter for testing AE measurement systems. The calibration of the transducer using the optical methods described in this paper could be developed further to allow the transducer to be used as a reference source to provide a traceable alternative to a pencil lead break for AE measurement system characterisation.

ACKNOWLEDGEMENTS

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