Velocity sensitivity calibration of AE sensors using the through wave method and laser interferometry

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Keywords: AE sensor, calibration, sensitivity, ISO 12713, ASTM E 1106

Abstract

Acoustic emission sensors are generally designed to respond to motion normal to the surface and are predominantly manufactured as resonant devices to increase sensitivity around a frequency range of particular interest. The resonant design is usually assumed to provide a resistance controlled velocity response, particularly around resonance. This simple approximation is usually fairly accurate and is adopted when stating sensitivities, with resonant sensors having their sensitivity stated in terms of voltage output per unit velocity, whilst broadband, mass controlled (damped) sensors are usually stated in terms of voltage output per unit displacement. Although it is possible to calibrate a sensor for its displacement sensitivity, given the popularity of resonant type sensors this paper considers a method for the calibration of AE sensors for their velocity response, using a through-calibration (or P-wave) method. In the method, a broadband transducer is coupled to a large test block, and used to excite a plane wave pulse on the opposite face of the block, which is then directly referenced to velocity using a heterodyne laser interferometer. This paper demonstrates the through-calibration method, and shows velocity sensitivity calibration results on an AE sensor between 100 and 1.4 MHz, along with discussion about the sources of uncertainty. The method discussed will form the standard method adopted by the UK’s National Physical Laboratory.

Introduction

Acoustic emission (AE) sensors are generally piezoelectric devices designed to provide a voltage output when exposed to an ultrasonic motion at the surface to which they are coupled, usually generated from an elastic stress wave resulting from a defect or unwanted mechanism within the structure [1]. The design of an AE sensor allows it to respond most prominently to motion generated normal to the surface where the amplitude or other parameters can relate to the severity of the defect. Calibration of the sensor provides the sensitivity of the sensor to a surface motion in terms of the voltage produced at the sensor output for a given physical input at the sensor face.

There are two main principles which can be used for the calibration of AE sensors. The first is reciprocity, which has been used extensively in other acoustic fields for the calibration of microphones in airborne acoustics and hydrophones in underwater acoustics [2, 3]. The principle of reciprocity [4,5] allows the calibration of a device using a reciprocity parameter [4] and a number of devices, one of which is reciprocal, to obtain the sensitivity of a device through the measurement of only the driving current and the open circuit receive voltage. The main advantage of this method is that no reference device is required. Reciprocity has been applied to the calibration of AE sensors successfully for their response to both surface waves and longitudinal waves [6-9] and it forms the standard method for calibration through the Japanese Society for Non-destructive Inspection [10]. The second principle which can be used for the calibration of AE sensors is the direct comparison of the AE sensor response with that of a reference sensor, which provides an absolute measure of the surface motion. This has been employed using a well characterised step-force excitation measured using an absolute capacitance.
reference transducer by Breckenridge and Greenspan [11] and others [12]. This method formed the primary standard for sensor calibration at NIST until 2003 and is the method stated in the ASTM and ISO standards [13, 14]. The main advantage of this method is that it is more direct and provides a direct realisation of the surface motion, making it better suited as a primary standard. A comparison of the different methods has been undertaken by Keprt and Benes [15], which does show some differences between the calibrated sensitivities. Although a capacitance type transducer has traditionally been used as the reference sensor, a laser interferometer can provide an absolute measure of surface displacement or velocity with traceability to the wavelength of light. The advantage of the interferometer is that it is a point sensor and is not subject to phase averaging across its aperture at the frequencies used for AE sensor calibration. Laser interferometric methods have been used for steady-state AE sensor calibration [16] and for sensitivity calibration of AE sensor to both out-of-plane and in-plane displacements [17-20].

To maximise the probability of detection, an AE sensor will often be a resonant design, tuned to have maximum sensitivity over the frequency range of interest. The resonant design is usually assumed to provide a resistance controlled velocity response, particularly around resonance. Resonant AE sensors have therefore historically had their sensitivity stated in terms of voltage output per unit velocity, whilst broadband, mass controlled (damped) sensors have usually been stated in terms of voltage output per unit displacement. Although it is possible to calibrate a sensor for its displacement sensitivity, given the popularity of resonant type sensors this paper considers a method for the calibration of AE sensors for their out-of-plane velocity response, using a through-calibration (or P-wave) method.

**Broadband source 'through' calibration method**

The method described here uses a large test block with a broadband source transducer used to excite a plane wave pulse on the opposite face of the block, which is then directly referenced to velocity using a heterodyne laser Doppler interferometer. This method falls within the general requirements of the ASTM/ISO standards [13, 14], although it differs from the example procedure described in the ASTM/ISO standards in that it does not use a mechanical step-force type source. The use of a repeating source transducer allows for time averaging, significantly improving the signal-to-noise ratio at the reference sensor. It also removes the requirement that the sensor under test and the reference sensor are measured simultaneously, making through calibration easier to perform. The ASTM and ISO standards consider a surface wave calibration by reference measurement, but in the example method described for the P-wave or longitudinal wave, a predictive through calibration method using the Green's function is employed. One reason for this is the difficulty of performing the sensor under test measurement and reference measurement simultaneously at the same position in space. The method described in this paper considers the longitudinal wave calibration only. There are two main advantages to this ‘through’ method of calibration when compared to a surface wave calibration: i) The aperture effect, of both the sensor being calibrated and the reference sensor, is avoided. The measurement is performed such that plane wave front at the measurement location can be approximated to avoid other phase cancellation errors. ii) The use of a longitudinal wave arriving normal to the measurement surface ensures that the sensor and reference sensor (interferometer) respond only to this ‘out-of-plane’ component. Surface wave methods can have an associated error in that the reference sensor responds only to the normal component of displacement or velocity whilst the sensor being calibrated can in some cases, due to Poisson coupling, respond to the ‘in-plane’ displacement or velocity component of the propagating surface wave. Although surface waves are an important wave mode of propagation in acoustic emission measurement, for traceability purposes it is important to expose the sensor being calibrated to the same surface motion which the reference sensor (interferometer in this case) measures; this allows the true response of the sensor to out-of-plane motion to be measured.
It should be noted that this calibration provides the free-surface sensitivity of the sensor under test to a longitudinal wave which is normally incidence on the surface, generating only out-of-plane surface motion. The free-surface sensitivity is obtained as a result of performing the reference (interferometer) measurement in the absence of the sensor. The implication of this is that any surface motion measured using the sensor in units of velocity will be the surface velocity which would exist if the sensor were not in place.

**Sensor calibration procedure**

In the calibration method, the surface motion was generated by a source transducer (Panametrics UT V101 for low frequency range and Panametrics UTV103 for high frequency range) which was coupled to the opposite side of the block to the sensor under test, as shown in Fig. 1, and was exited by a pulse with a temporal width of 1 µs for the low frequency range and 0.5 µs for the high frequency range. An Agilent 33220A function generator and AG Series T&C Power Conversions Inc. power amplifier was used to drive the source transducer. The pulse generated was repeated at 200 ms intervals to enable time averaging for improved signal-to-noise ratio, and utilised the shortest edge-time available on the 33220A in order to approximate a square wave pulse.

The test block used is a hemispherical aluminium test block as shown in Fig. 1, with a diameter of 420 mm. The hemispherical design removes the first longitudinal side reflections and reduces the overall mass of block required to obtain the same isolation from side reflections. The block provides an approximate total measurement window before the arrival of the longitudinal wave echo of around 96 µs. In the case described here, this is reduced to around 66 µs due to the arrival of a shear wave generated at the edge of the source transducer.

For the reference measurement, the velocity of the test surface was measured directly using a Polytec PSV400 vibrometer, capable of measuring surface velocity DC to 1.5 MHz, and captured using a Tektronix TDS 5054 digital storage scope sampling at a rate of at least 25 MS/s with at least 1000 time averages performed. The sensor under test was then coupled to the test surface using Castrol Spheerol EPL2 such that its geometric centre was aligned with the laser axis of the interferometer. This couplant was used as it provides the best compromise in terms of stability during the calibration and ultrasonic transmission properties. The output transient voltage signal from the sensor under test was also captured using Tektronix TDS 5054 digital storage scope at a sample rate of at least 25 MS/s with at least 500 time averages performed. The sensor was re-coupled and measured a total of 6 times, with any re-couplings which resulted in a peak amplitude that was below a pre-determined percentage of the maximum achieved being rejected. The output of the sensor under test was electrically coupled through an external PAC Model 2/4/6 pre-amplifier with a gain of 20 dB and a 20 kHz high-pass filter. It is important to note that the applied gain of the external pre-amplifier was removed from the calculated sensor sensitivity data. Following the sensor measurements, the reference velocity measurements were repeated with the interferometer. This provided a check that the calibration system had not changed during the sensor measurements.
Analysis of sensor sensitivity

The sensitivity of the sensor under test was calculated from the quotient of the spectra of the sensor output voltage and the interferometer velocity output. The spectra were obtained for the longitudinal first arrival by performing an FFT on the windowed data, which was zero padded. The window used was a tukey window with a taper ratio of 0.1 and a length of 66 µs (see Fig. 2). A 66 µs window was used so that the shear wave arrival (or any other reflections present) were not included in the sensitivity calculation - this is indicated in Fig. 3. The sensor under test can potentially detect in-plane surface motions caused by other wave arrivals, but the normally incident laser interferometer is only able to respond to out-of-plane motion. The shear wave identified in Fig. 3 is generated at the edge of the source transducer and does not necessarily arrive at the measurement surface at normal incidence, thus generating a response at the interferometer. Although the amplitude of the shear arrival appears low, an AE sensor will generally show a much larger response to this arrival than observed on the interferometer output (because of great in-plane sensitivity) which would lead to an error in the calibration.

The calibration provides the free-surface sensitivity of the sensor when coupled to an aluminium half-space using Castrol Spheerol EPL2. Other test materials and couplants will result in a different sensitivity [21].
The sensitivity is provided in units of volts per unit velocity as a function of frequency at around 3 kHz intervals with zero padding off the FFT's, with the actual frequency resolution resulting from the 66 µs being around 15 kHz. The dimensions of the block only allow accurate sensitivity information above around 100 kHz, below which the accuracy of the sensitivity data would be compromised and not fall within the uncertainties specified in the ASTM/ISO standard [13, 14]. For these measurements, the use of the V103 source transducer also limited the upper frequency range to around 1400 kHz. To achieve the complete frequency range from 100 kHz to 1.4 MHz, two calibrations were performed for the sensor under test for two different frequency ranges. The V101 (500 kHz nominal centre frequency) source transducer was used to perform the calibration between 100 kHz and 500 kHz and the V103 (1 MHz nominal centre frequency) was used between 500 kHz and 1.4 MHz.

Fig. 4 and 5 show the free-surface normal velocity sensitivity to a longitudinal wave for a pinducer AE sensor between 100 kHz to 500 kHz and 500 kHz and 1.4 MHz respectively, obtained from the average of 6 measurements in each case.

Fig. 3. Time waveforms showing the different wave arrivals and the time gate position

The sensitivity calibration showing Fig. 4 and 5 is for a relatively broadband pinducer AE sensor manufactured by Ergotech which operates up to over 1 MHz. Although this is a lower sensitivity sensor, it has been selected here to demonstrate the calibration frequency range possible with the method presented in this paper.

At this stage, a fully validated uncertainty budget has not been completed for the calibration method and so error bars or uncertainties are not included. However, the random uncertainty from re-coupling of the sensor is the largest single contributor to the overall uncertainty budget. This depends on the design of the sensor and on the couplant used. However, the uncertainty due to the re-coupling can be improved by the use of a polished measurement surface, controlled force mounting mechanism and by choice of a low viscosity couplant. The grease type couplant used in this paper is a compromise between ultrasonic transmission, short-term temporal stability and repeatability. As the measurement time is very short for each repeat, the short-term temporal stability is less important when compared to other factors and so a different reference couplant might be used in future calibrations.
Ideally, the couplant used for the calibration should provide the maximum sensitivity possible with the sensor, although it might be considered more useful to the end user if the couplant replicates the performance of a typical, practical couplant. Most importantly, the reference couplant used during the calibration should have known, traceable properties and its performance should not change with time else the ability to compare historic calibration data for a given device would be compromised.

Fig. 4. Out-of-plane free surface longitudinal velocity sensitivity of a pinducer AE sensor using V101 source transducers

Fig. 5. Out-of-plane free surface longitudinal velocity sensitivity of a pinducer AE sensor using V103 source transducers
Conclusions

A method has been described for the free-surface out-of-plane velocity sensitivity for AE sensors based on a broadband source approach which is designed to fall within the requirements of ASTM E1106 and ISO 12713. The method allows the sensitivity calibration to be performed between 100 kHz and 1400 kHz, with potential to improve this both below the lower limit or above the upper limit. The use of a broadband repeating source allows time averaging to be used to improve the signal-to-noise ratio and also removes the necessity to perform the sensor under test measurement and the reference measurement simultaneously. This makes it easier to perform a through calibration, allowing the sensor under test and the reference sensor to measure the same point in space. The use of a laser interferometer as the reference sensor for broadband calibration provides traceability to the wavelength of light, providing a more direct calibration than for reciprocity.

References