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PZT SENSORS BENCHMARKING AND A WAVELET TRANSFORM APPROACH FOR ACOUSTIC EMISSION SOURCE LOCATION

Ian Martinez
Dynamics Research Group, Department of Mechanical Engineering, The University of Sheffield, Mappin Street S1 3JD, United Kingdom
email: iemartinezefremov1@sheffield.ac.uk

Matthew Marshall
Leonardo Centre for Tribology, Department of Mechanical Engineering, The University of Sheffield, Mappin Street S1 3JD, United Kingdom
email: m.b.marshall@sheffield.ac.uk

Ifigeneia Antoniadou
Dynamics Research Group, Department of Mechanical Engineering, The University of Sheffield, Mappin Street S1 3JD, United Kingdom
email: i.antoniadou@sheffield.ac.uk

Recent developments in non-destructive testing have been reliant upon Acoustic Emission (AE) measurements to identify damage and localise defects in mechanical and other similar components. Presently, in the research area of AE testing, there is a growing interest in the development of sensor systems that are more economically viable than the current commercial ones. This latter point is addressed in this paper, where one of the main objectives is to investigate the performance of bare PZT elements for localisation problems in AE testing compared to commercial AE sensors. Performance constraints of the PZT sensors are explored in the context of a proposed localisation approach, taking into account measurement uncertainties, as part of this benchmarking activity. This is experimentally examined by performing lead break tests on the surface of a thin aluminium plate. The waves generated in finite-bounded media like plates, are in most cases Rayleigh-Lamb waves, and this imposes certain challenges regarding the accuracy of such localisation measurements. Rayleigh-Lamb waves have infinite propagation modes that travel at different frequencies and different velocities. This means that standard triangulation methods, commonly used for arrival time estimation of AE waves, have limitations as they assume a single wave propagation speed. Similarly, determining the onset of wave arrival is a challenging task for time-domain based algorithms, as the problem in such a case does not only involve the determination of the time of arrival of an AE burst but also its corresponding frequency. In order to address these issues a localisation approach based on a time-scale analysis of the AE signals captured is proposed. Specifically, the Continuous Wavelet Transform (CWT) is used, with the aim to demonstrate a cost-effective solution for AE sensor systems, and to improve the accuracy of AE source location estimates by acquiring a more informative representation of the frequency range of the AE signals.

Keywords: acoustic emission, PZT, benchmarking, localisation, uncertainty

1. Introduction

The release of sudden elastic waves due to the generation of defects such as dislocations in materials can be captured using AE sensors which are based on piezoelectric materials. These sensors generate a voltage output when they are excited by a displacement input. Due to the increasing interest in this field a few commercial options for AE signal measurement were made available with a broad range of specifications (diameter size, bandwidth, configurations, etc).

AE sensors are basically built using a piezo electric material, and a backing plate that damps the oscillations, sometimes a pre amplifier will be included, this features will enhance the captured signal but will represent an additional cost. In the other hand bare PZT elements provide a more affordable solution. Even though both options work with the same principle a benchmarking test should be done in order to understand their capabilities in an AE localization scenario.

2. Wave propagation in plates

AE localization in plates represents a challenge due to the propagation of multiple dispersives modes. This mainly imposes a few problems as the whole AE signal does not travel at a unique velocity, in fact dispersive modes will travel at different velocities according to their frequency values, therefore affecting any localization algorithm which assumes a constant propagation speed.

2.1 Lamb's equation

From the problem formulated in the previous section, the equation that describes the phenomenon of the Rayleigh-Lamb's waves is defined as [1]:

$$\frac{\tan(qh)}{\tan(ph)} = -\left(\frac{4k^2pq}{(q^2+k^2)^2}\right)^{\pm 1} \tag{1}$$

Where the exponent ± 1 will be +1 for a symmetric mode and -1 for an anti-symmetric mode respectively. The terms k, p and q where also in terms of the angular frequency ω are defined as:

$$k = \frac{\omega}{C_p(\omega)} \tag{2}$$

$$p = \sqrt{\left(\frac{\omega}{C_L}\right)^2 - k^2} \tag{3}$$

$$q = \sqrt{\left(\frac{\omega}{C_T}\right)^2 - k^2} \tag{4}$$

The term $C_p(\omega)$, C_L and C_T represent the phase, longitudinal and shear velocity. In order to solve this equation a numerical approach was used assuming wave propagation in lossless media, therefore neglecting the imaginary part of the Lamb's equation solution. The resulting phase and group velocities for the zero order symmetric S_0 and anti-symmetric mode A_0 for an aluminium plate with a 5.5 mm thickness, longitudinal and shear wave speed propagation of 6300 m/s and 3130 m/s [2] respectively are shown in the Fig. 1.

2.2 The Continuous Wavelet Transform

The transient response of an acoustic emission burst imposes difficulties using conventional tools such as Fast Fourier Transform algorithms (FFT) for spectral analysis. The Continuous Wavelet

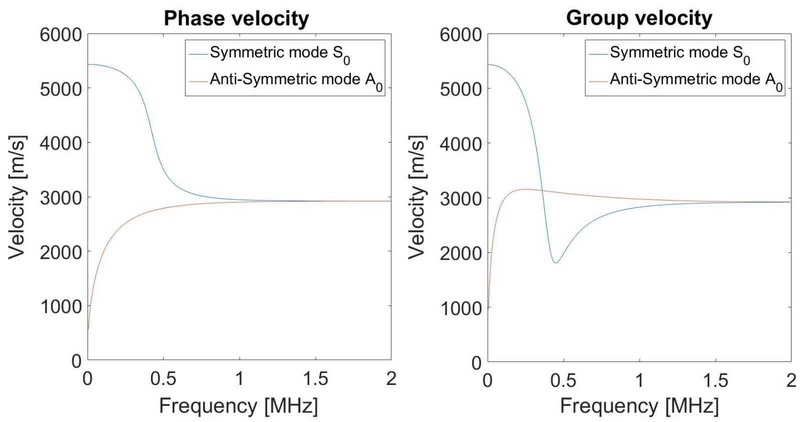

Figure 1: Dispersion curves for a 5.5mm Aluminium plate: Phase Velocity (left), Group Velocity (right)

Transform (CWT) provides useful information about the frequency content along time of a transient signal such as the case for an AE burst. Applying the CWT to a function defined with two harmonic waves using the Gabor wavelet ψ_g with central frequency ω_0 gives the following expression[3, 4]:

$$\mid \psi(x,a,b) \mid = \sqrt{2a} \mid \psi_g(a\omega) \mid (1+\cos 2(\Delta k x + \Delta\omega b))^{0.5} \tag{5}$$

Where the maximum values should occur at these points on the plane a-b:

$$a = \frac{\omega_0}{\omega} \tag{6}$$

$$b = \frac{\Delta k}{\Delta\omega} x = \frac{x}{C_g(\omega)} \tag{7}$$

These two terms mean that if the peaks of the coefficients obtained from the CWT of the AE signal are localized then it is possible to determine the mode arrival.

2.3 AE Triangulation

Localization problems for AE signals usually involve the usage of three or more sensors. Stated that the initial time t_0 when the AE was generated is not known beforehand, most of the triangulation methods exploit the fact that the position can be resolved based on the time difference between a pair of sensors and geometrical relationships, a well detailed method is described by Tobias where three sensors where used to determine the AE location[5].

Where C is the constant wave propagation speed and Δt is the time difference between two points. A simple triangulation method using only three sensors can be stated as follows using the polar coordinates:

$$R = \frac{x_1^2 + x_2^2 - \delta_1}{2\sqrt{x_1 \cos\theta + y_1 \sin\theta + \delta_1}} \tag{8}$$

Where R is the radius, x_i and y_i represents the sensors positions and δ_1 is the distance calculated using the time difference between sensors B and C Δt_{bc}. The angle θ is defined as:

$$\theta = \phi(\Delta t_{ba}, \Delta t_{bc}) + \cos^{-1}(K(\Delta t_{ba}, \Delta t_{bc})) \tag{9}$$

Where K and ϕ are in terms of the time of flight between sensors. The inverse cosine of K will give two different solutions, the right value for θ will be the one that yields a positive value of R.

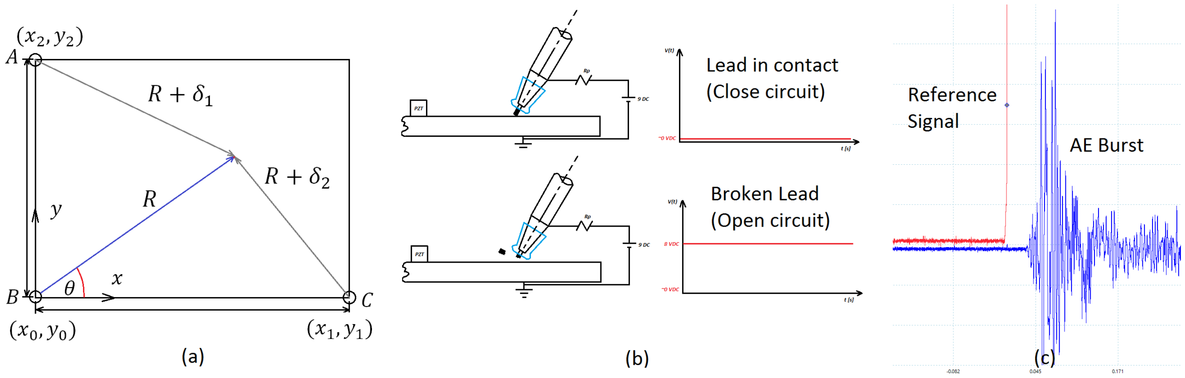

Figure 2: (a) Triangulation method, (b) Triggering Signal and (c) Reference signal and AE burst

3. Methodology

The proposed method for position benchmarking will be validated with a triangulation method using an analytical velocity from the dispersions curves, an AE burst will be generated using a Hsu-Nielsen source mechanism [6], an initial estimate of the wave onset will be calculated using the Akaike Information Criterion (AIC) and then corrected within a certain frequency tolerance. The sensors comparison will be performed using a triggering mechanism where allows to estimate a distance using one sensor, once again within a specific frequency tolerance.

3.0.1 Triggering Mechanism

Based on the original Hsu-Nielsen source mechanism, and by the fact that pencil leads are made of electrical conductive materials, a step function of the voltage can be expected just in the right moment when the cross-sectional area completely fractures and stops making contact with the plate as shown in Figs. 2(b),2(c). The initial time will be estimated based on a threshold level above the signal's noise level.

3.0.2 Wave onset estimation

The wave onset estimation will be based on the Akaike Information Criteria (AIC), the AIC function is defined as [7]:

$$AIC(i) = i \log(var(y(1:i))) + (N - i - 1) \log(var(y(i+1:N))) \tag{10}$$

Where y represents the signal defined for $i = 1, 2, ..., N$. The onset of arrival of the AE signal will be determined by a global minima, in order to get this value a time window should contain the onset, and also have the appropriate window length as this method can give multiple local minima.

3.0.3 Time of Arrival Correction

The AIC method provides a good estimation of the time of arrival (TOA) of an AE burst but it does not discriminate between the captured frequencies, as in the case of AE events generated in plates, multiple frequencies can be captured, this implies that the propagation speed cannot be longer considered constant. According to the sensor's bandwidth defined between 150kHz–400kHz, it is possible to capture velocities within a range of 5250.5–2259.7 m/s in an 5.5 mm aluminium plate. This problem can be targeted by selecting a particular frequency or at least narrow the frequency range. This method is described in Fig. 3a and ensures that the frequency range captured is narrowed by finding the local maxima at the CWT coefficients until certain tolerance is reached. Figure 3b

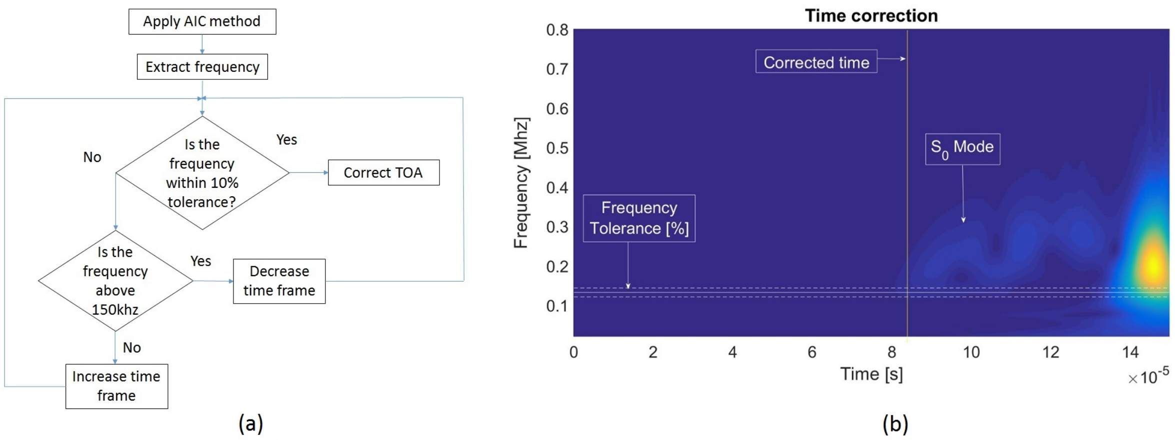

Figure 3: (a) Time of Arrival correction method, (b) Time of Arrival from CWT

shows the scalogram of an AE burst generated at 450 mm from the sensor and its time correction. The yellow line represents the corrected time within a specified frequency bandwidth tolerance at 150kHz for the S_0 mode, where its analytical velocity value is 5250.5 m/s.

4. Experimental set-up

Based on the methodology described in the previous sections, two different experiments where set up, the first one was designed to validate the localization benchmarking technique and the second one as a benchmark between a commercial sensor and a bare PZT element.

4.0.1 Equipment

The sensors used in this experiment were the NANO30 FO82 and the MICRO-30D these sensors differ between their configuration, as they are single and differential sensors respectively. The single

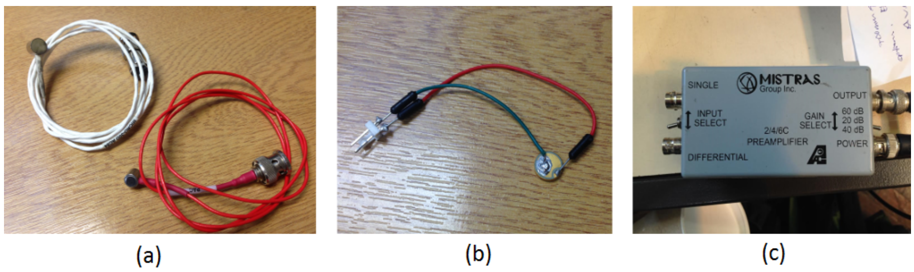

Figure 4: (a) NANO-30D (white) and NANO30 FO82 (red), (b) bare 10x1 mm PZT element, (c) Amplifier

sensor was amplified using 20dB and the differential used 40dB. The amplification was set according the sensor configuration.

4.0.2 Benchmarking test

The objective of this test was to understand and quantify the error obtained during localization using a standard method and the proposed benchmarking technique. The test was performed using 9 points grid. Each point of the grid were equally separated at 12mm, the sensors were placed equidis-

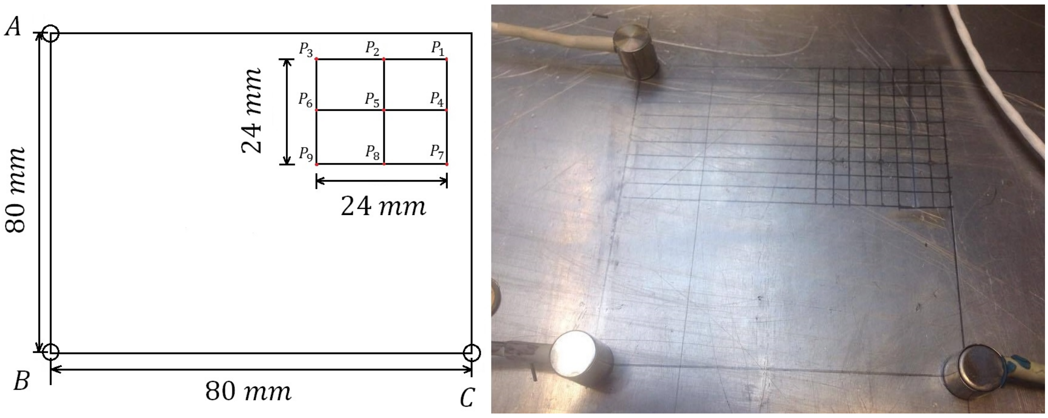

Figure 5: Sensor arrangement and grid dimensions

tant from each other at 80 mm, this was performed in order to make the experiment congruent. The signal was amplified at 40dB (Differential amplification), the sensors where adhered with a thin layer of Cyanoacrylate, and the signal was recorded using a sampling rate of 20 MHz. In total, 100 measurements were taken for each point on the grid, this allowed to understand the error distribution on each measurement and make the results statistically significant. The Hsu-Nielsen technique was used to excite the AE signal at each point, the pencil lead was kept at a fixed length of 3.5mm.

4.0.3 Sensors Benchmarking experiment

The sensor benchmarking experiment was perform in order to understand the localization error obtained using different sensors, in this case a comparison between the bare PZT element and a single configuration AE sensor was done. The AE burst were generated in a 4 mm grid on a 160 x 80 mm rectangle, a total of 5 measurements were performed at each node.

5. Results

The error calculated at distances closer to the sensors tends to increase as shown on Table. 1 and 2, this is due to a difficulty in distinguishing between modes arrival. A maximum errors of 15.41% and 14.32% were obtained for the triangulation technique and the triggering signal respectively, both maximum error values occurred at the same position of the grid.

Error values at 10% tolerance						
	Radial Distance			Angle		
	C3	C2	C1	C3	C2	C1
R1	12.52	0.04	0.79	6.88	9.04	6.17
R2	7.63	17.49	5.73	8.12	0.33	3.44
R3	15.41	8.38	8.77	1.14	13.37	1.35

Table 1: Error values obtained from triangulation test.

Calculated values at 10% tolerance						
	Radial Distance [mm]			Abs. Error [%]		
	C3	C2	C1	C3	C2	C1
R1	85.52	94.22	102.53	7.13	5.17	4.61
R2	78.50	82.75	92.72	4.80	8.57	6.68
R3	63.01	77.32	85.06	14.32	6.24	7.63

Table 2: Radial distance and error using a triggering signal.

The benchmarking test results on Table. 3 and 4 shown that a better localisation accuracy was achieved by the bare PZT elements. The maximum errors obtained were 13.92% and 6.55% for the commercial and bare PZT element respectively.

Error [%] commercial sensor							
	C7	C6	C5	C4	C3	C2	C1
P1	7.58	5.16	0.92	1.81	1.32	4.93	1.33
P2	7.95	3.23	2.25	4.54	13.92	3.54	1.12
P3	7.57	5.04	3.21	3.26	4.22	5.03	0.27
P4	4.47	3.06	5.69	2.74	6.42	3.70	2.10
P5	4.40	4.03	2.86	6.63	4.10	3.93	2.03
P6	6.15	6.54	2.12	3.79	5.93	6.33	5.39
P7	7.80	4.91	1.63	5.38	4.04	4.89	9.45

Table 3: Error percentage commercial AE sensors

Error [%] bare PZT element							
	C7	C6	C5	C4	C3	C2	C1
P1	0.14	0.73	0.89	0.75	1.21	3.78	1.69
P2	0.55	1.23	1.21	0.69	1.86	0.75	3.14
P3	0.56	2.73	2.84	0.89	4.22	0.52	0.64
P4	2.61	2.38	0.67	0.96	0.88	2.42	0.20
P5	0.16	0.89	0.14	1.99	1.29	1.26	1.36
P6	2.67	1.79	2.01	2.01	2.35	0.13	0.28
P7	0.67	2.53	2.79	6.55	4.21	1.10	0.22

Table 4: Error percentage using a PZT element

6. Discussions

Using a time-frequency approach will lead to a more detailed signal analysis and representation, resulting in an improved understanding of which modes propagate in plates. In order to make the experiments consistent a common frequency band was chosen. An additional problem encountered in the primary experiment for the PZT sensors benchmarking was that a few AE burst specifically close to the sensors (less than 160 mm) had rather weak features that cannot be used to distinguish different modes of arrival of the AE bursts. Increasing the distance where the AE emission was generated potentially allows enough time for the modes to separate from each other due to their different relative velocities. Figure 3a and 3b show the mode separation at different distances, the resulting scalogram on Fig. 3c and 3d shows the effect of the distance and its relative separation.

7. Conclusions

Using a CWT approach could potentially address some of the above issues: it might allow for the possibility to distinguish all the modes arriving at each sensor, therefore a better estimation of the time of arrival at a particular mode can be performed, and any localisation approach can be focused to specific frequencies and modes of the AE signals. This methodology shown that bare PZT elements can be targeted for localisation tasks, achieving a better location accuracy.

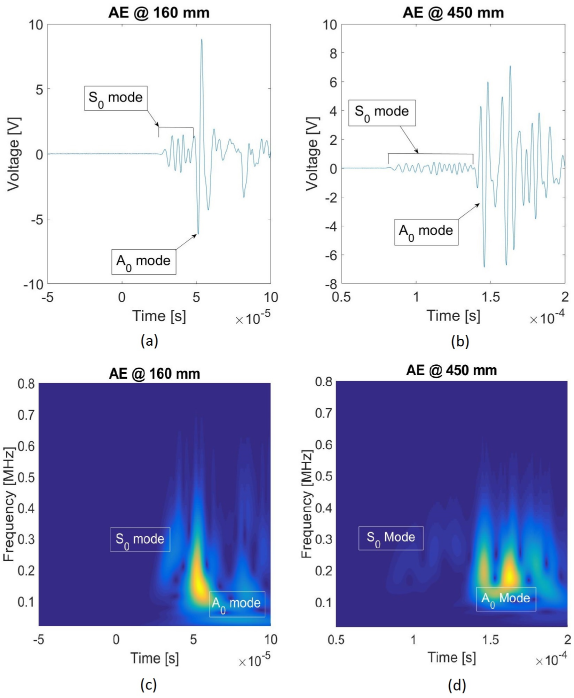

Figure 6: AE bursts at different distances.

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