

Article

A0 Lamb Mode Tracking to Monitor Crack Evolution in Thin Aluminum Plates Using Acoustic Emission Sensors

El yamine Dris ^{1,2} , Mourad Bentahar ^{3,*} , Redouane Draï ¹ and Abderrahim El Mahi ³ 

¹ Research Center in Industrial Technologies (CRTI), Cheraga, P.O. Box 64, Algiers 16014, Algeria

² Ecole Nationale Polytechnique, 10 Avenue Hassen Badi, El Harrach, P.O. Box 182, Algiers 16200, Algeria

³ Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR CNRS 6613,

Institut d'Acoustique—Graduate School (IA—GS), CNRS, Le Mans Université, 72085 Le Mans, France

* Correspondence: mourad.bentahar@univ-lemans.fr

Abstract: This paper presents a real time monitoring methodology to identify the location of acoustic emission (AE) sources generated by microcracks created within an aluminum plate when submitted to a tensile load. The real time detection of the AE hits was performed by means of a network of piezoelectric sensors distributed on the surface of the plate. The proposed localization approach is based on the combination of the time-frequency analysis of the detected AE hits with an extended Kalman filter (EKF). The spatial coordinates of the AE sources were determined by solving a set of nonlinear equations, where the extended Kalman filter is based on an iterative calculation. By considering the statistics related to the estimation of the coordinates' errors, results show that the proposed method is in agreement with the experimental observations related to the propagation of the crack when the aluminum plate is under load.

Keywords: acoustic emission (AE); tensile test; AE events localization; lamb waves; continuous wavelet transform (CWT); extended Kalman filter (EKF); crack propagation



Citation: Dris, E.y.; Bentahar, M.; Draï, R.; El Mahi, A. A0 Lamb Mode Tracking to Monitor Crack Evolution in Thin Aluminum Plates Using Acoustic Emission Sensors. *Appl. Sci.* **2022**, *12*, 12112. <https://doi.org/10.3390/app122312112>

Academic Editor: Hwa Kian Chai

Received: 12 October 2022

Accepted: 21 November 2022

Published: 26 November 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Plate-like structures are omnipresent in different fields such as civil engineering and aerospace with different applications including bridge girders, aircraft wings, fuselages, etc. [1,2]. Depending on the involved materials, damage can be of different kinds. Corrosion, fatigue cracking, and impacts are among the most significant threats that are encountered most frequently [3]. Among the metallic structures, those made of aluminum, including aluminum alloys, are very attractive thanks to their mechanical high strength and physical corrosion resistance properties [4,5]. At the time where the most common defects (i.e., cracks) created within aluminum structures and components can be detected reliably using different non-destructive techniques (ultrasound, radiography, etc.), those created during their manufacturing process (non-metallic inclusions, small pores, etc.) are not easily detected on time and can thus be at the origin of severe crack creation [6,7]. In order to account for the deterioration of the various structures, different structural health monitoring (SHM) techniques were developed. SHM is motivated by the need to perform permanent monitoring to diagnose the state of structures especially when the application of classical testing methods is difficult or impossible [8,9]. Among SHM techniques, those based on the use of piezoelectric sensors in a passive mode have undergone significant development. Indeed, the deployment of a network of sensors allows to receive acoustic emission (AE) hits (i.e., elastic waves) emitted during the creation and propagation of damage (i.e., cracks) in order to localize AE sources in plate-like structures [10–21]. Depending on the required level of analysis, AE based SHM can be used to detect defects, and/or localize their position and orientation, and/or assess their size. In time, these three levels can be used to estimate the remaining lifetime of the monitored structures in real time [8]. Time and/or frequency

domain methods have already been used to analyze AE hits in order to define reliable parameters during the monitoring of structures [22,23].

Model-based approaches have also been proposed for damage/impact location and identification in different structures [24]. In the latter, the location and type of impact are iteratively changed until convergence is reached between the experimental results and those predicted by the proposed model. Ciampa and Meo [25] used Newton's iterative method to calculate the coordinates of the impact location and the wave velocity. Other contributions used the nonlinear least square optimization technique, based on the Gauss–Newton method, to determine the location, time lag, and velocity of AE signals as performed in refs [26,27]. In order to minimize errors related to wave velocity, Dong et al. proposed an iterative solution, which does not depend on the P-wave velocity [28]. In the latter, the location accuracy has been improved by taking advantage of the multiple sensors. More recently, Zhou et al. proposed an algebraic solution for AE source localization without premeasuring wave velocity. This is performed by minimizing the sum of squared residuals of the linear time difference of arrival (TDOA) equations [29]. On the other hand, Liu et al. used multiple iterations to optimize the clustering in the development of the Generalized Regression Neural Network Based on Time Difference Mapping [30]. Iterative solvers have also been used and compared with direct solvers to perform an automatic three-dimensional source localization of acoustic emission sources within large concrete structures [31]. Das et al. proposed a nonlinear method to locate acoustic emission sources, in which the sensors with high residuals are first quarantined. Then, the spacial location and event time are iteratively optimized along with the updating of velocity with the help of a feedback loop [32]. Reliability in AE source localization can be enhanced by combining iterative and closed-form methods i.e., of non-iterative nature. In order to avoid local convergence and improve the level of noise tolerance, the latter method can be used to estimate the initial value of the iterative calculations [33]. In addition to time domain methods based on the use of the least-square technique [34,35], those based on Bayesian filters revealed to be an efficient alternative thanks to the simplicity of their implementation [36].

The aim of this paper is to present results related to the use of the extended Kalman filter (EKF) technique applied on AE signals in order to monitor the creation and propagation of a crack propagating in thin aluminum plates (as shown in Figure 1). Conventionally, AE based SHM techniques use the first arrival time of AE signals detected at multiple receiving points to locate the damage. This approach works relatively well for simple metallic structures, when the group velocity (V_g) of the involved guided wave(s) and the arrival time (t_i) at sensors' locations are known. In general, the arrival time of the detected elastic waves and their related velocities are two uncertain parameters, where uncertainties can be caused by random and systematic errors [13,37–42]. These uncertainties can reduce the reliability of source localization approaches in particular in the case of an automatic damage detection. To overcome the limitations related to the abovementioned uncertainties, several methods have been proposed for damage or impact location [13,37,43–48]. EKF was used in passive sensing in order to estimate AE source location in guided wave conditions, where the AE coordinates and guided waves velocity were treated as unknown gaussian variables [13]. On the other hand, the Kalman filter was also used with the triangulation method to track multiple AE sources created successively. Despite the good accuracy of this method (i.e., in the case where AE sources occur in a straight line), results become less accurate as soon as the AE events move away from the straight line [49]. This paper presents the application of EKF in the case of AE sensors to locate impacts created using the pencil lead breaks procedure. After this calibration procedure, EKF is applied in situ when samples are submitted to a mechanical tensile test. Initial values were taken as uniformly distributed random variables. Analyses are performed on the basis of the generated Lamb waves during the creation and propagation of the cracks, which do not evolve as a straight line. In such a case, results show that by taking into account uncertainties, the localized AE sources are in accordance with the experimental results.

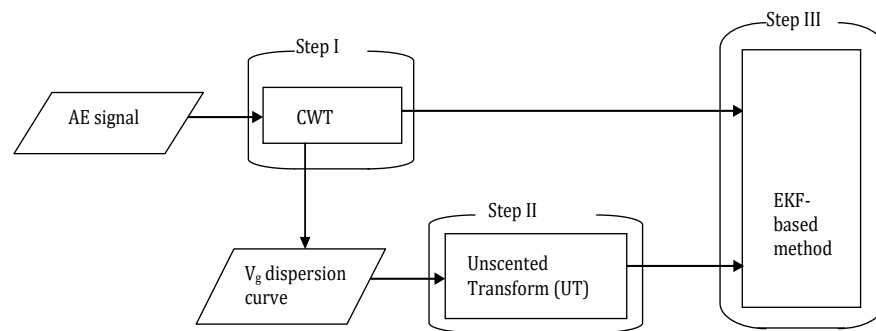


Figure 1. Flowchart of the proposed approach.

2. Wave Propagation in a Plate

The propagation of elastic waves in a plate is different from that of thick materials. The generated waves, called Lamb waves, have the particularity of setting the entire thickness of the plate in motion [50–53]. Two types of wave modes moving at different velocities can be identified, and the parent members of these two modes are called the S0 and A0 modes, respectively, where the S0 mode is the extensional mode and the A0 mode is the flexural mode.

The propagation of a Lamb wave along a thin plate of thickness ($e = 2h$) can be expressed with the help of the Rayleigh-Lamb equations [54]. The numerical resolution of the latter gives the dispersion curves corresponding to symmetric and antisymmetric Lamb modes. Figure 2 shows the dispersion curves corresponding to guided waves generated within an aluminum plate taken at the initial intact state. Depending on the involved frequency, the group velocity of the propagating guided modes can be taken from the abovementioned dispersion curves in order to locate the AE sources.

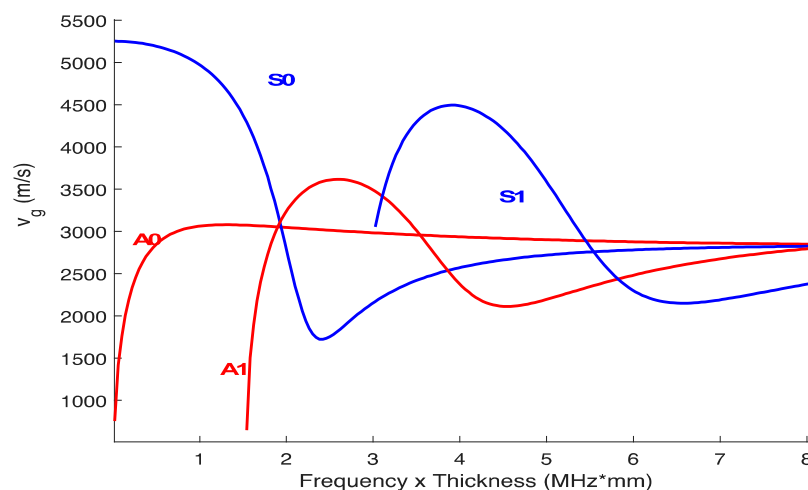


Figure 2. Group velocity dispersion curves for Lamb waves propagating in an aluminum plate. The characteristics of the plate are: Young modulus $E = 69$ GPa, Poisson ratio $\nu = 0.34$ and density $\rho = 2900$ kg/m³.

3. Source Localization by Means of Acoustic Emission

Acoustic emission is often used in real-time nondestructive testing applications to monitor structures. Collected data can also be used to locate events at the origin of the detected AE hits. To locate an AE source, the triangulation method is often applied to signals detected by the different sensors at multiple reception points. This method revealed to be efficient when the wave group velocity (V_g) and the arrival time (t_i) of the AE hits are known. However, one should keep in mind that errors and uncertainties are inevitable in the process of measuring and identifying the location of AE sources [12,26].

Figure 3 illustrates a simple model to locate AE sources. In order to minimize errors related to the localization of AE sources, two main steps are performed. First, the continuous wavelet transform (CWT) is applied to determine the TOA of the AE signals detected by each sensor. Then, the EKF is used in order to iteratively estimate the location of the AE source. Errors related to the localization of the AE sources will be presented and discussed in the paper.

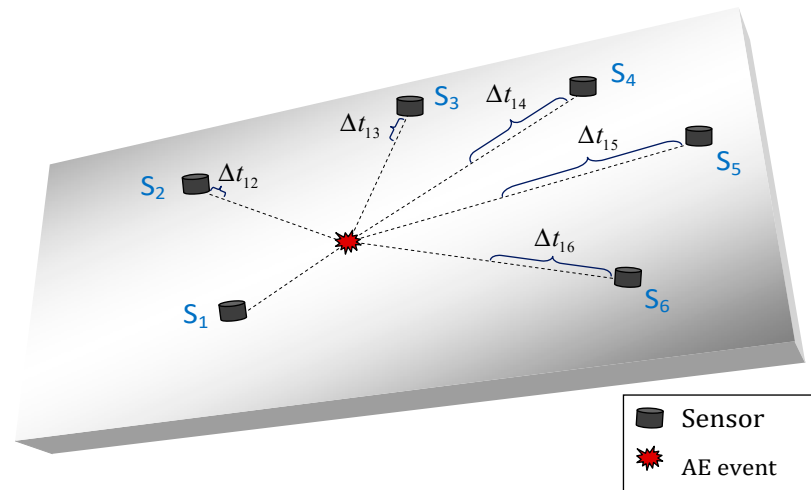


Figure 3. Two-dimensional localization principle of AE source.

Assuming a Cartesian coordinate system, where (x_s, y_s) are the unknown coordinates of the AE source, (x_i, y_i) are the known coordinates of the sensors and t_i is the arrival time of the elastic wave from the AE source to the i^{th} sensor, as shown in Figure 3. The distance (d_i) between the i^{th} sensor and the AE source can be calculated by multiplying the TOA and the propagation velocity of the involved elastic wave:

$$d_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2} = V_{g_i} \cdot t_i \quad (1)$$

AE source location is then performed by calculating the differences between the TOA detected by the different sensors:

$$(x_i - x_s)^2 + (y_i - y_s)^2 = (V_g \cdot t_i)^2 = [(t_m + \Delta t_{mi}) \cdot V_g]^2 \quad (2)$$

By combining Equations (1) and (2) we can determine Δt_{mi} , the time difference between the master sensor and the i^{th} sensor [13,37,55]:

$$\Delta t_{mi} = \frac{\sqrt{(x_i - x_s)^2 + (y_i - y_s)^2} - \sqrt{(x_m - x_s)^2 + (y_m - y_s)^2}}{V_g} \quad (3)$$

As stated above, the accuracy of the arrival times is essential to well localize the AE sources. An imprecise knowledge of the properties of the propagation medium will have an impact on the estimation of the wave propagation velocity (V_g). For that reason, V_g is defined as an unknown parameter to be identified in addition to the coordinates of the AE source (x_s, y_s) . It should also be noticed that, since the propagation of Lamb waves is dispersive, the time difference of arrival (TDOA) corresponding to AE events will consequently depend on the frequency. The single frequency component in the output signal can be extracted, for each sensor, on the basis of a time-frequency analysis with the help of a continuous wavelet transform (CWT), whose effectiveness for studying dispersive waves was evaluated in different contributions such as in reference [56]. In order to take into account the uncertainties, the unknowns (x_s, y_s, t_i, V_g) are therefore treated as mutually independent gaussian random variables when applying the probabilistic approach. Based

on this assumption, the probability density function of the time difference Δt_{mi} can also be defined as a gaussian random variable with mean and variance given as: [13,37]

$$\Delta t_{mi} = t_i - t_m, \sigma_{\Delta t_{mi}}^2 = \sigma_{t_i}^2 + \sigma_{t_m}^2 \quad (4)$$

3.1. Continuous Wavelet Transform (CWT)

The CWT of the time signal $x(t)$ is defined as [13,37]:

$$X(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt \quad (5)$$

where $\psi^*(t)$ denotes the complex conjugate of the mother wavelet $\psi(t)$. a is the dilation or scale parameter defining the support width of the wavelet and b is the translation parameter locating the wavelet in the time domain. The CWT is based upon a family of functions defined as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left(\frac{t-b}{a} \right) \quad (6)$$

The time and frequency resolution of the wavelet transform can be expressed as a function of the scale parameter a through the following equation [13,37]:

$$\sigma_t = a\sigma_{t_\psi}, \sigma_\omega = \frac{\sigma_{\omega_\psi}}{a} \quad (7)$$

where σ_{t_ψ} and σ_{ω_ψ} are the duration and bandwidth of the mother wavelet, respectively.

In literature, various studies based on the use of the wavelet transform have succeeded in locating AE sources in isotropic and anisotropic structures [13–15,21,39]. The present study relies on the use of a complex Morlet wavelet thanks to its ability to separate amplitude and phase information. The complex Morlet wavelet, which can also measure instantaneous frequencies and their time evolution, is defined by the following equation [13,37]:

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} e^{-\frac{t^2}{f_b}} [\cos(\omega_c t) + j \sin(\omega_c t)] \quad (8)$$

$f_c = \omega_c/2\pi$ is the central frequency. f_b represents the envelope factor and consequently controls the bandwidth of the wavelet spectrum. Values of f_c and f_b are fixed by considering the experimental conditions as it will be explained below [57].

When using Morlet as a mother wavelet, the function $\psi_{a,b}(t)$ presented above (see Equation (6)) is determined around $t = b$ and its Fourier transform is centred around $\omega = \omega_c/a$ [13,37].

The squared modulus of the CWT coefficients (scalogram) represents the energy density of a signal in the time–frequency domain. The maximum value of the coefficients of the scalogram is achieved at the dominant frequency. The arrival time of the wave packet is the time which corresponds to the peak magnitude in the time–frequency domain, reached at the dominant frequency [13,37]. The relationship between the scale parameter a and the frequency component f_i can be expressed as:

$$f_i = \frac{f_c}{a T_e} \quad (9)$$

where f_i is the frequency of interest, f_c is the center frequency of the wavelet and T_e is the sampling period. Since the dominant frequency can be different depending on the position of each sensor, an average frequency $\bar{f}$ is used to calculate the TOA:

$$\bar{f} = \frac{\sum_{i=1}^n f_i}{n} \quad (10)$$

Following these considerations, the time and frequency resolutions σ_t and σ_ω of the complex Morlet wavelet are given by the following equations [13]:

$$\sigma_t = \frac{f_c \sqrt{f_b}}{2\bar{f}} \quad (11)$$

$$\sigma_\omega = \frac{\bar{f}}{f_c \sqrt{f_b}} \quad (12)$$

Once the TOA is known, the time difference Δt_{mi} can be calculated using Equation (2). By substituting Equation (11) into Equation (3), the variance of the TDOA is given by the following equation [13]:

$$\sigma_{\Delta t_{mi}}^2 = 2 \left(\frac{f_c \sqrt{f_b}}{2\bar{f}} \right)^2 \quad (13)$$

This value is used to model the uncertainty of the measurement vector when applying the probabilistic approach. Hence, based on the algorithm discussed in the next section, the coordinates of the AE source as well as the wave group velocity can be identified.

3.2. Extended Kalman Filter (EKF)

In this work, an adapted EKF-based algorithm is used to locate AE source. The Extended Kalman Filter (EKF) is a recursive data processing algorithm that estimates the state of a noisy dynamic system. The EKF has been widely used in a lot of applications due to its simplicity, optimality, robustness, sensor fusion ability, and its capability of filtering out the uncertainties due to the mathematic model and measurements [31,58]. In general, the EKF is a two steps process: (1) state prediction according to a mathematical model; and (2) the correction of the state according to the measurements collected by sensors. For this reason, the EKF has been used to handle the set of nonlinear Equation (3). The state of the system consists of three parameters, the AE source location (x_k, y_k) and the wave velocity V_g of the involved elastic wave. The state of the system X_k is related to the measurement data vector through the nonlinear measurement function $Y_k = [(\Delta t_{mi})_k]_{(n-1)*1}$, $n \geq 3$ defined in Equation (3). If one assumes that the AE source location can be considered as an unmovable (static) or slowly fluctuating point, and the state has no superimposed noise [31], under this assumption the prediction stage can be neglected and the equations take the following forms:

$$\begin{cases} H_k = \nabla h_k(\hat{X}_{k-1}) \\ \hat{Y}_k = h(\hat{X}_{k-1}) \\ K_k = \hat{P}_{k-1} H_k^T (H_k \hat{P}_{k-1} H_k^T + R)^{-1} \\ \hat{X}_k = \hat{X}_{k-1} + K_k (Y - h(\hat{X}_{k-1})) \\ \hat{P}_k = (I - K_k H_k) \hat{P}_{k-1} \end{cases} \quad (14)$$

The uncertainty related to the measurement vector Y is modeled as a zero mean white Gaussian noise with covariance matrix R with diagonal terms defined in Equation (13):

$$R = \begin{bmatrix} \sigma_{\Delta t_{m1}} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{\Delta t_{m(n-1)}} \end{bmatrix} \quad (15)$$

The iteration starts with the initialization of the estimated state vector $\hat{X}_0$ and covariance matrix $\hat{P}_0$, which are defined below:

$$\hat{X}_0 = [\hat{x}_{s0} \quad \hat{y}_{s0} \quad \hat{V}_{s0}] ; \hat{P}_0 = \begin{bmatrix} \sigma_{x_{s0}}^2 & 0 & 0 \\ 0 & \sigma_{y_{s0}}^2 & 0 \\ 0 & 0 & \sigma_{V_{s0}}^2 \end{bmatrix} \quad (16)$$

In Appendix A.2 is presented the approach used to determine the AE initiation location and the starting group velocity.

Overall, and based on the abovementioned considerations, the proposed approach to simultaneously track and optimize the AE source location consists of two stages. The first stage provides information about TOA, frequency, and their uncertainties. The second stage iteratively estimates the state vector (AE source location and wave), according to the information obtained from the first stage.

4. EKF-Based Approach for AE Source Localization during Pencil Lead Breaks Tests

In order to validate the performance of the proposed EKF-based AE source localization algorithm, we consider an aluminum plate having the dimensions $(230 \times 250 \times 2) \text{ mm}^3$. The Young modulus, Poisson ratio and density of the aluminum plate are $= 69 \text{ GPa}$, $\nu = 0.34$, and $\rho = 2700 \text{ kg/m}^3$, respectively. To simulate broadband AE sources, Hsu–Nielsen pencil lead breaks (PLB) tests were performed on the specimen at 18 different positions [58]. A square mesh of 10 mm was made on the plate in order to ensure a good repeatability of the different PLB. Four identical broadband (0.1–1 MHz) PZT sensors (model PAC 15a) were used to detect the elastic waves propagating within the plate. Acoustic signals were 40 dB preamplified and then acquired using a data acquisition (DAQ) system (Mistras Micro Express) with 2 MHz sampling frequency.

The initial location was calculated based on Equations (A8) and (A9) defined in Appendix A.2. The use of the PLB method to generate elastic waves makes the amplitude of the extensional mode negligible compared to that of the flexural mode. Therefore, the flexural mode A0 was then easily distinguishable and was therefore used to locate the different AE sources. Acquired waveforms were processed following the EKF-based localization procedure as described in Section 3. With the help of the MatlabTM (version 2019b, MathWorks, Natick, MA, USA) code implemented by the authors, waveforms were analyzed based on the wavelet transform in order to find the arrival times and the dominant frequencies at the different sensors' positions. The number of iterations during the EKF stage was fixed at 5 and the complex Morlet parameters were taken as $f_c = 0.7 \text{ Hz}$ and $f_b = 1.2 \text{ s}^2$. f_b and f_c values take into account the broadband pulse excitation and the frequency bandwidth of the AE sensors which is from $\sim 100 \text{ kHz}$ to $\sim 1 \text{ MHz}$. Their values were fixed by performing several localization tests. On the basis of the time of arrival determined with the help of the CWT and the propagation distance, the calculated group velocities were found to be in agreement with the ones given by the dispersion curves. The EKF-based localization procedure is then applied to iteratively estimate the location of the acoustic sources. The peak of the squared modulus of the CWT corresponding to each AE signal was used to indicate the arrival time of the generated guided waves. Figure 4 shows the detected AE signals as well as their time–frequency characteristics when the artificial source position is at $PLB(15,30)$. For the latter position, for instance, the time-frequency analysis of the different AE signals showed that the frequency for which the energy is maximum is between 227.6 kHz and 298.3 kHz for all the sensors.

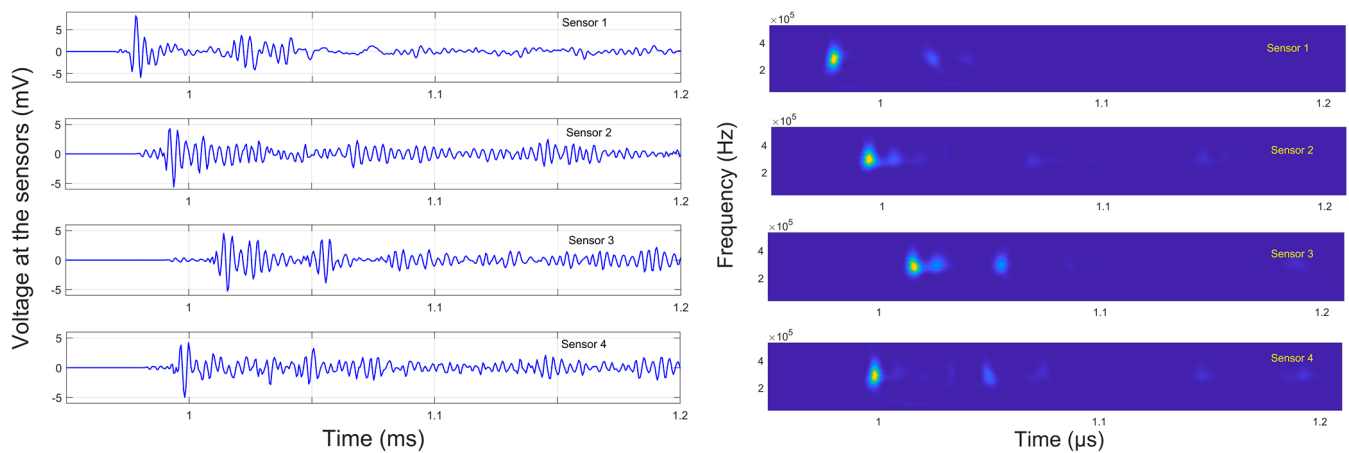


Figure 4. Time domain (left) and time–frequency domain (right) characteristics of the AE signals detected by sensors 1 to 4 when the source is located at PLB1(15, 30).

On the other hand, Figure 5 shows the line profile of the abovementioned signals at the average frequency $\bar{f} = 282.63$ kHz, where the time delay is taken at the maximum energy of each AE hit clearly appears. Besides, for each AE event, the group velocity was calculated with the help of the Monte Carlo simulation based on the randomly generated 150,000 samples of the variable $\bar{f}d$ as shown in Figure 6. Note that the starting values $\hat{V}_{g0}$ may not exactly coincide with the values that would be found in the dispersion curve of the group velocity. However, the algorithm based on EKF allows the convergence between the initial values $(\hat{x}_{s0}, \hat{y}_{s0})$ and $\hat{V}_{g0}$ as well as the differences in time of arrival of the AE signals detected by the different sensors. The injection of the variance is used to approach the true value. The interest of applying such an approach appears when the properties of the material are not known in a precise way or when the material is subjected to one or more constraints in which case the velocity of the propagating wave changes according to the state of stress.

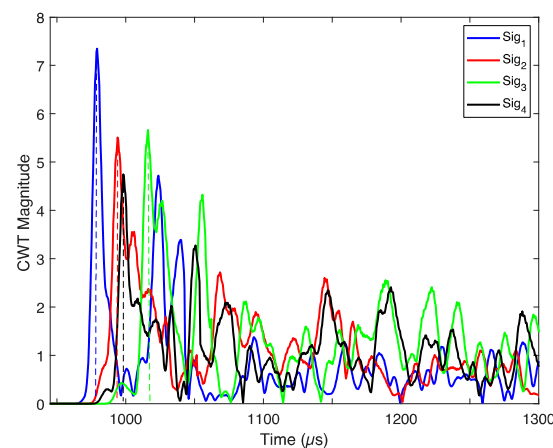


Figure 5. Line profile of the AE scalograms where the time of arrival is determined at the maximum magnitude of the wavelet transforms of the detected AE hits (i.e., PLB1) considered at the average frequency $\bar{f} = 282.63$ kHz.

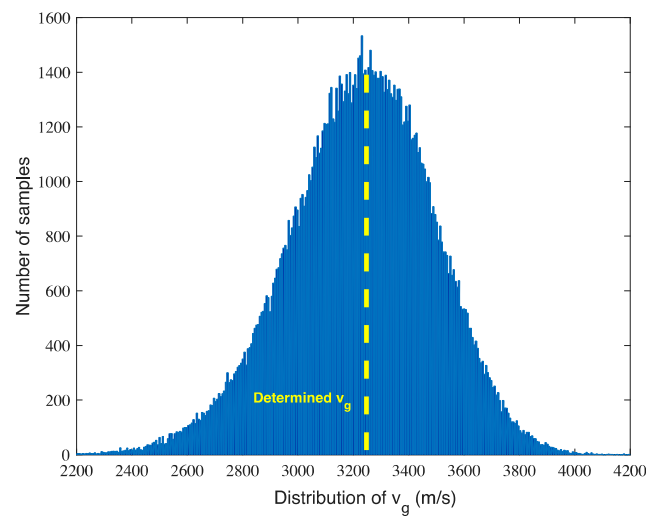


Figure 6. Group velocity determination based on the Monte Carlo simulation.

Table 1 gives the results related to the 18 Hsu–Nielsen excitation points. Errors corresponding to the different coordinates are expressed as:

$$\varepsilon_{x_s} = \frac{|x_s - \hat{x}_s|}{|x_s|}. \quad (17)$$

$$\varepsilon_{y_s} = \frac{|y_s - \hat{y}_s|}{|y_s|}. \quad (18)$$

where (x_s, y_s) are the coordinates of the real impact positions. $(\hat{x}_s, \hat{y}_s)$ are the coordinates of the PLB locations determined using the proposed algorithm. On the other hand, Figure 7 depicts actual and estimated source locations. As it can be seen from Table 1, this algorithm generates results with a good accuracy, where the maximum error to estimate the coordinates of impact locations did not exceed ~5 mm. This result shows the robustness and the effectiveness of the proposed approach. Note that errors can be attributed to the positions at which the PLB is performed as well as the sensors positions.

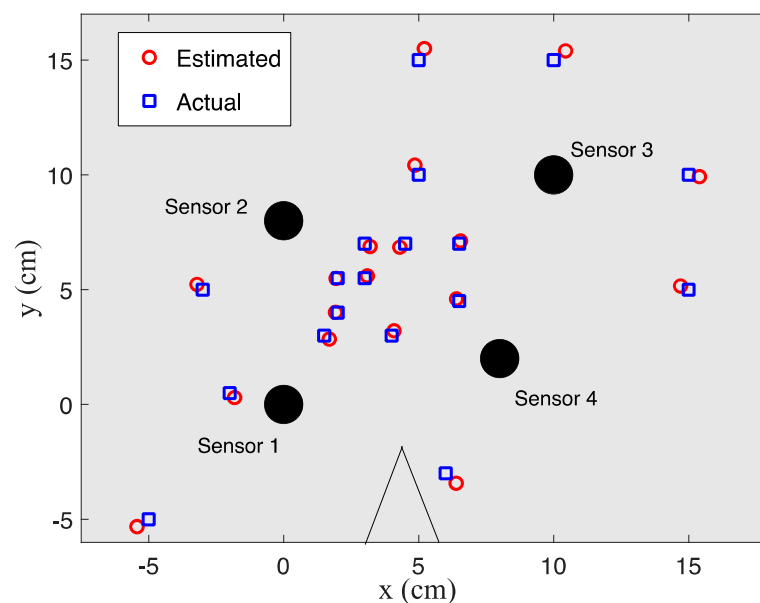


Figure 7. Location of the different AE hits emitted by the 18 pencil lead breaks performed on the aluminum surface on the basis of the abovementioned algorithm.

Table 1. Location data of the AE sources based on the EKF method and their corresponding group velocities.

AE Source Point	X Coordinate of Source (mm)	Estimated X Coordinate (mm)	Error in X (%)	Y Coordinate of Source (mm)	Estimated Y Coordinate (mm)	Error in Y (%)	Group Velocity (m/s)
PLB 1	15	17.2	14.67	30	28.12	6.26	3635
PLB 2	30	30.04	0.16	30	30.08	0.27	3264
PLB 3	20	18.95	5.25	40	41.82	4.56	3575
PLB 4	20	19.92	0.39	55	54.94	1.92	3470
PLB 5	30	30.90	3.01	55	56.04	1.92	3461
PLB 6	45	43.71	2.86	55	55.27	0.49	3526
PLB 7	55	53.89	2.00	55	57.59	4.71	3562
PLB 8	65	65.63	0.97	70	71.12	1.60	3.551
PLB 9	65	64.17	1.27	45	45.91	1.94	3417
PLB 10	30	31.63	5.44	40	42.54	6.17	3124
PLB 11	40	42.62	6.55	55	56.00	1.61	3547
PLB 12	50	52.70	5.41	55	56.90	5.13	3071
PLB 13	55	55.46	0.84	45	44.31	1.51	3506
PLB 14	50	52.73	5.47	70	68.01	2.64	3167
PLB 15	40	40.95	2.38	45	43.28	3.92	3631
PLB 16	30	31.89	6.31	70	68.73	1.73	3462
PLB 17	45	43.15	4.10	70	68.18	2.52	3501
PLB 18	40	40.21	0.53	30	32.66	8.56	3213

In the light of these preliminary results, it becomes possible for us to carry out measurements on real defects created during a mechanical tensile test performed on the same sample. The advantage of the proposed EKF-based algorithm is linked to its ability to take into account uncertainties related to time of arrival and group velocities in order to efficiently fusing multi-sensors data for an accurate AE source localization. The flexibility in adding or removing information within the matrix structure at the data processing step is very useful to characterize dispersive media where different propagating modes are involved. Finally, we note that the computational time on regular personal computer for each source location using the proposed algorithm took less than 0.06 s, which makes the proposed algorithm appropriate for real-time AE applications.

5. EKF-Based Approach for AE Source Localization during Quasi-Static Tensile Test

5.1. Mechanical Test and AE Monitoring

Tensile test experiments were performed on the above presented aluminum plate at the Acoustics Laboratory of Le Mans University. For these experiments, we used the same data acquisition system with the same settings and the same AE sensors as well. The latter were synchronized and triggered by one of them once the first detected signal exceeds the predefined threshold. A properly calibrated tensile test INSTRON hydraulic machine was used with a constant displacement rate. The load cell capacity of the test machine is 100 kN, where specimens were loaded at 1 mm/min. It is naturally expected that cracks will be generated from the notch and propagate through the specimen. The acoustic activity is simultaneously recorded with mechanical test data until the overall failure of the specimen. The acquired AE signals are processed following the EKF-based localization procedure described in Section 3. Figure 8a shows the aluminum plate mounted on the testing machine as well as the distribution of the AE sensors. Before the application of the tensile load, preliminary tests were performed in order to determine the AE acquisition threshold. Indeed, the latter was set at 45 dB in order to avoid the detection of signals emitted by the noisy environment. Once the quasi-static test is over, we obtain the results shown on Figure 8b. The latter shows that the cumulative AE events are in accordance with the different stages which characterize the evolution of the load as a function of time. We first note that in the elastic domain (1), where the load is between 0 kN and ~31 kN, the AE is almost absent and only few AE signals are detected. Damage is initiated beyond the yield point (2), where a sudden increase in the AE activity is observed. Within the uniform plastic strain domain which extends between the yield point and the ultimate strength ~34.5kN, strong AE peaks become visible. These relatively high energy signals are associated with the initiation and propagation of crack. The failure domain of the specimen begins as

soon as the stress begins to drop, until the final rupture. During this stage, the AE activity follows the evolution of the microstructural events until the complete fracture of the plate. In general, ductile fracture in metals is initiated by the nucleation of the existing micro-scale voids [59]. As the applied load increases, nucleated and pre-existing voids coalesce to form the crack by growing, changing shape, and getting closer to each other [59–62].

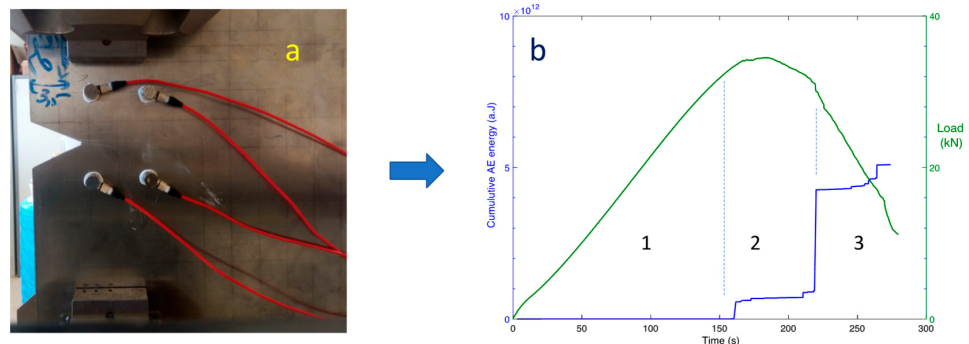


Figure 8. (a) Notched aluminum plate mounted on the testing machine; (b) evolution of the applied load as well the AE activity during the quasi-static tensile test, where AE is almost absent in (1), then a sudden and low increase in the AE activity is recorded in (2), and finally an important increase in the AE activity is recorded in (3).

Figure 9 shows the evolution of the created crack at the time when the AE increases suddenly, namely at $t \approx 160$ s, $t \approx 215$ s and $t \approx 270$ s, respectively. However, despite the sensitivity of AE to the microstructural evolution of the material, the link between the sudden increase of the AE activity and the crack propagation velocity is not straightforward.

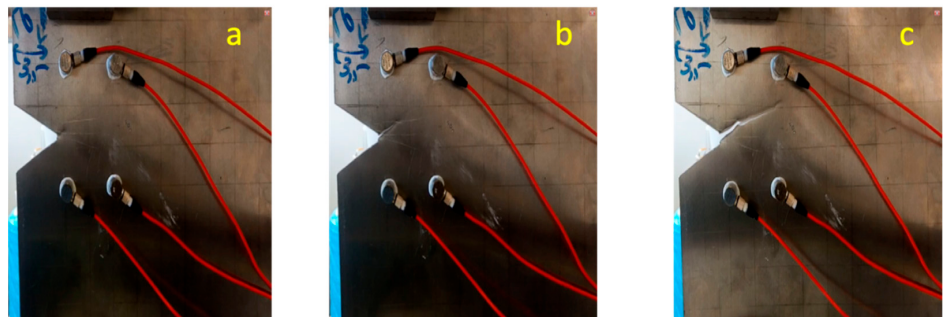


Figure 9. Evolution of the crack at the first (a) second (b) third (c) sudden increase of the AE signals which happen at $t \approx 160$ s, $t \approx 215$ s and $t \approx 270$ s, respectively.

Indeed, Figure 10 shows that the crack growth velocity remains constant (~ 0.3 mm/s) even after the sudden jump in the cumulated AE energy, which evolves by more than two orders of magnitude at $t \approx 160$ s. At the same time, the crack growth velocity becomes twice higher (0.68 mm/s) at the time when the cumulated AE energy evolves approximately one order of magnitude at $t \approx 215$ s. According to literature, the propagation of a ductile tearing crack can be influenced by the interplay between nucleation, growth, and coalescence of voids [59,63]. At this stage, our tests show that AE signals are sensitive to the creation and change of orientation of the created slanted crack. At the time when the underlying reasons for the initiation and propagation mechanisms of the crack are not yet fully understood [59,64], we will only focus in the present paper on the location of the different AE sources in order to locate the created cracks and monitor their propagation with the help of the continuous wavelet transform and the EKF method previously presented.

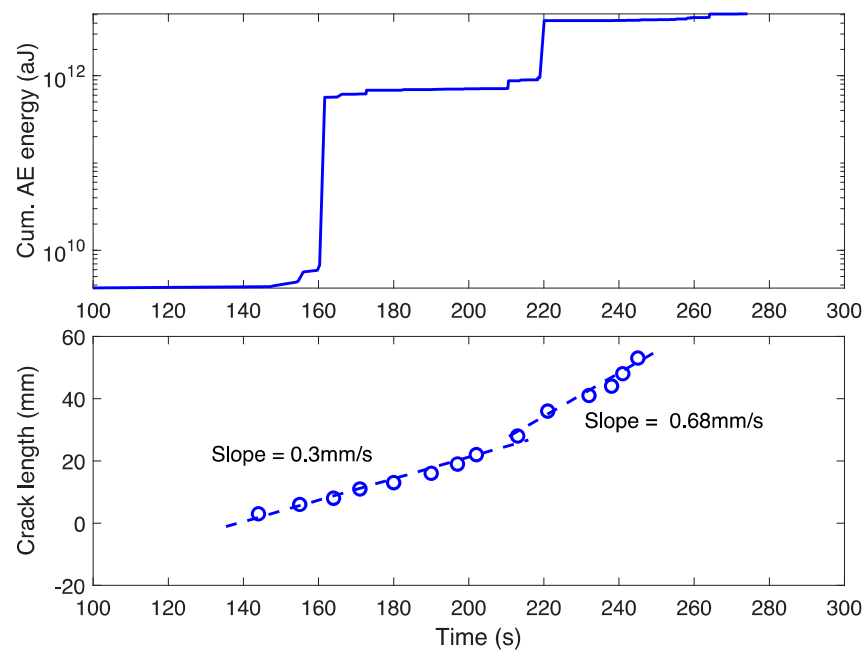


Figure 10. Evolution of the cumulated AE energy and the crack length velocity as a function of time.

5.2. EKF-Based Analysis of AE Data

As previously described, the CWT of complex Morlet wavelet is applied to determine the arrival time, dominant frequency, and uncertainties corresponding to all AE events. Figure 11 illustrates the time and frequency characteristics of the AE signals detected by the four AE sensors at the end of the first stage of the crack growth ($t = 201.84$ s). Time domain signals show that for the same AE event, the AE signals do not have apparently the same characteristics. More details are given by the time–frequency representation of the same signals. The 2D scalogram of the CWT shows that the energy distribution of the same AE event can be different from one sensor to another. The energy density of the AE signal is not a uniformly distributed function as it can be seen on Figure 11. For instance, the AE signal has the maximum energy (the deepest red color) in the frequency range [180–350 kHz].

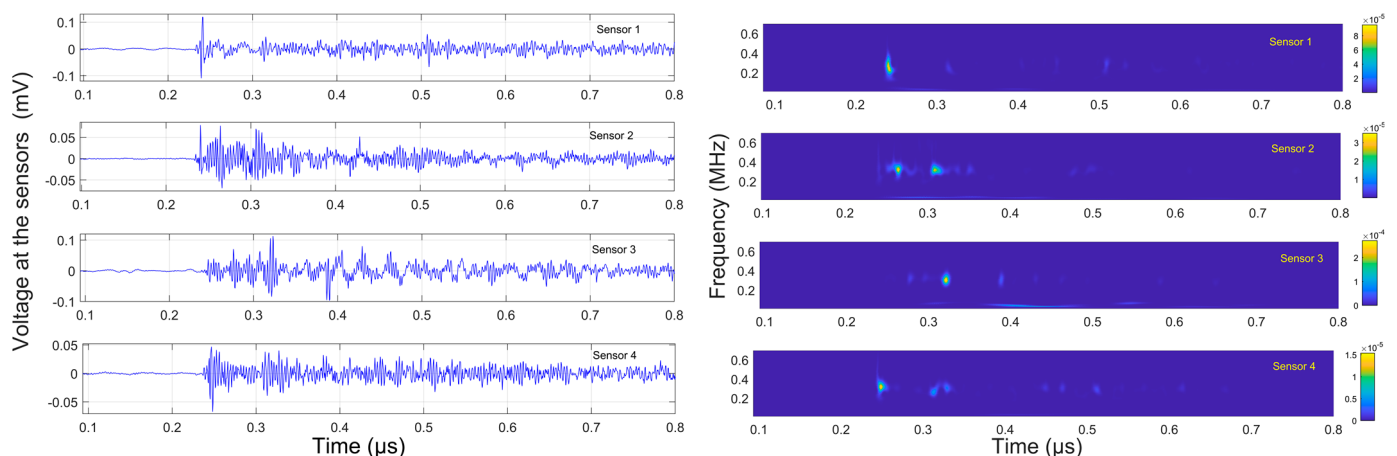


Figure 11. Time domain signals and their CWT characteristics corresponding to the same AE event as detected by the four AE sensors at the end of the first stage ($t = 201.84$ s).

Under the abovementioned considerations, we can project on the time domain the average dominant frequency component in order to determine the arrival time of the involved Lamb wave. Figure 12 illustrates the applied procedure for extracting the TOA

and their average frequency $\bar{f} = 283.3$ kHz. We note that during the mechanical test, the scalogram maxima coefficients resulted slightly different depending on the transducer position. However, the associated frequencies were approximately the same.

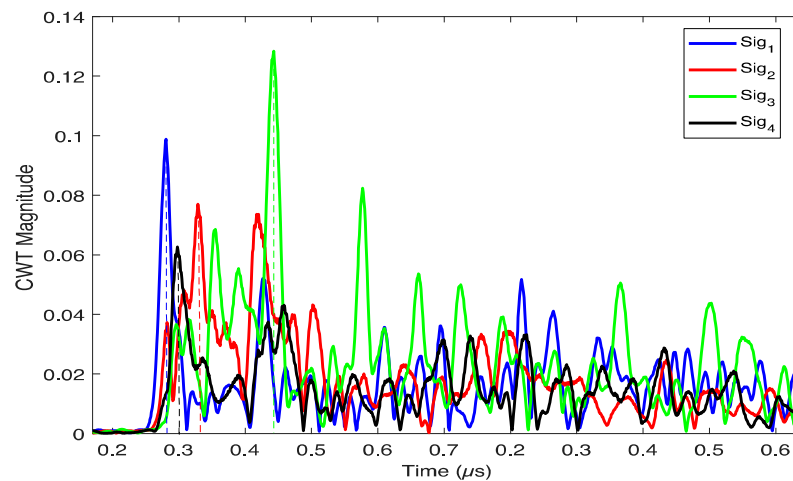


Figure 12. Identification of the time of arrival using the line profile of the scalogram at the average frequency $\bar{f} = 283.3$ kHz.

In order to locate the AE sources, the group velocity of the involved elastic guided waves must be known for each frequency. The frequency corresponding to AE hits emitted during the quasi-static tensile test of the aluminum plate were within [10–500 kHz]. According to the group velocity dispersion curve (see Figure 2), the involved Lamb modes within this frequency domain are A0 and S0. During the tensile test, it remains difficult to know a priori the mode generated by the cracks. The performed analyses showed that, depending on the detected AE hit, some of the sensors received A0 and S0 modes (as well as their reflections) and some other ones received only one mode, namely A0 mode (as well as its reflections). In order to locate the AE source position correctly, it remains important to use the same propagating mode which could be either extensional or flexural [65]. Recorded data revealed that the flexural mode A0 is always detected by all the sensors and contains at the same time the maximum energy of the detected AE hits. Depending on the involved frequency, group velocities corresponding to the detected A0 modes were between ~2200 m/s and ~3400 m/s. Here, it is important to note that under the multimodal condition, the EKF-based method should be adapted before carrying out the localization of the AE sources. The adapted EKF-based method is presented in the appendix. Once the group velocity and the time difference of arrival (TDOA) between the sensors and the master sensor are obtained, the adapted EKF-based method is applied to estimate the location and the propagation of the AE sources. Figure 13 shows the located AE sources using the proposed EKF-based method and the AE system. Both results show that the macro-crack is located inside the domain defined by the four sensors starting from the notch. However, when we superimpose these results to the crack path (obtained according to Figure 9c) we can see that the results obtained with the EKF method are closer to the crack than those obtained with the AE system. This is mainly related to the monitoring of the evolution of the group velocity (V_g), whose value changes during loading. The AE system does not update V_g and keeps the initial value to locate the different AE sources. In order to determine the space distribution of the localized AE sources, we have used an approach which consists in dividing the specimen into an array of rectangular elements within which a count of the number of AE hits is performed [66]. The size of the grid elements should be large enough to have a sufficient number of AE hits per element. At the same time, it should not be smaller than the accuracy of the proposed AE localization method. Under these conditions and according to [67], the width of the damage zone can be determined by drawing 80 % of the located AE hits. Indeed, it can be seen from Figure 14 that AE hits

are mainly concentrated around the damaged zone. The 80% criterion associated to the previously applied EKF method allow to have a very good estimation of the crack creation and propagation when the material is under test.

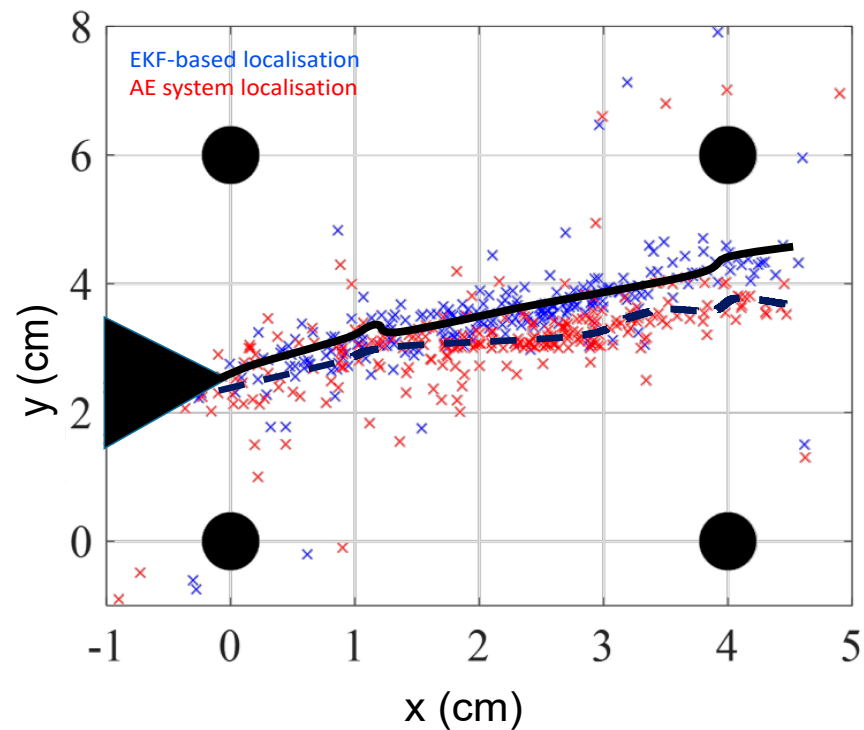


Figure 13. Comparison of the AE source localizations performed with the AE system and the EKF method during the mechanical test. The path of the crack is obtained according to Figure 9c (solid). Approximate crack path is also plotted based on the AE system localization (dashed).

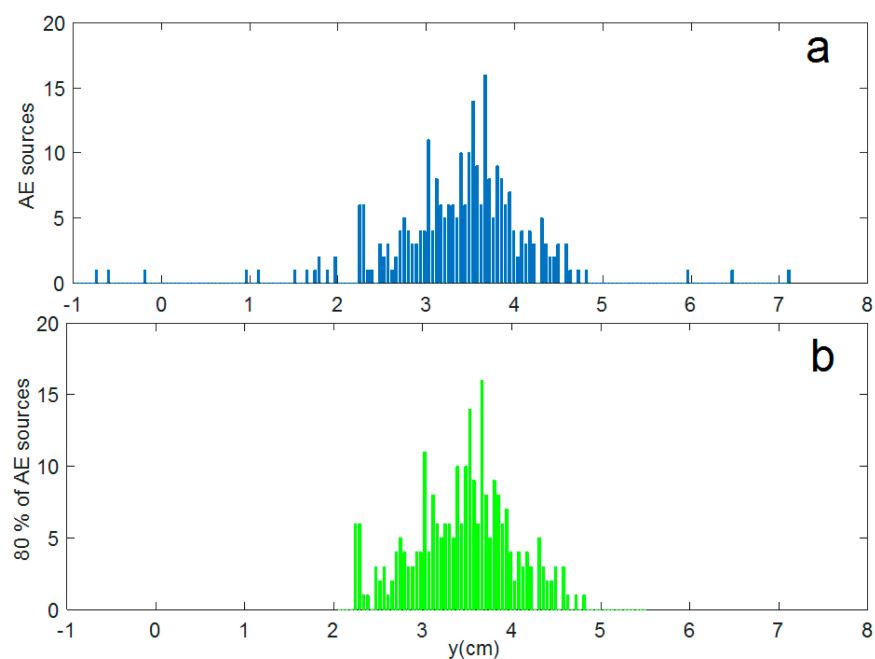


Figure 14. Histogram of the AE events detected in the aluminum plate before (a) and after (b) the application the 80% criterion.

6. Discussion

The proposed algorithm considers three unknown parameters: the group velocity and the in-plane coordinates of the AE sources. The method chosen to define the starting value of the group velocity is performed by the Monte Carlo simulation. The algorithm based on EKF allows the convergence between the initial values as well as the differences in time of arrival of the signals detected by the different sensors. This approach represents an advantage compared to the one proposed in a classical AE system. In the latter, damage or impact location is based on the triangulation method, which involves the time-of-arrival (TOA) taken at multiple receiving points. The classical AE system gives very good results when the wave velocity (V_g) of the considered Lamb wave and the TOA are known. However, TOA and wave velocity are two uncertain parameters. In general, uncertainties can be caused by random and systematic errors. The random errors are caused by unknown and unpredictable changes in the TOA measurements, including instrumentation noise, temperature changes etc. [14–19]. Systematic errors are mostly caused by the digital signal processing technique used for analyzing the AE waveforms [20]. In real operational and environmental conditions (noise, stress state, temperature changes, different impact scenarios, etc.), measurement errors are known to influence the propagating mode in terms of velocity and attenuation. In the case of our experiment, the attenuation can be considered as unchanged. However, the group velocity will change especially as a function of the stress conditions to which the material is subjected (i.e., acoustoelastic effect). If the velocity changes, the classical AE system will not be able to perform an automatic update. The positions of AE sources indicated by the classical AE system will be therefore erroneous. In that sense, the method proposed in this contribution comes to complete this insufficiency. The spatial convergence of the proposed algorithm, shown in Figure 7, is performed in just six iterations. Locations are determined with a good accuracy for PLB performed away from the edges of the specimen (i.e., less than 4% in both x and y coordinates). In such a case, the maximum error to estimate the coordinates of the different locations did not exceed ~5 mm. We also performed PLB measurements close to the edges of the specimen and outside the domain defined by the four sensors. In this case, signals are naturally more affected by reflections from the lateral edges. The accuracy of the location and the maximum error does not exceed ~15 mm (Figure 7).

The case where the source location is not a priori known is not very different from the case studied during the mechanical test. Indeed, it is expected from a material such as aluminum, that AE originates both from fracture of particles and from dislocation related sources. The creation and propagation of a crack in metals is accompanied by plastic deformation at the crack tip [68]. It was also found that the maximum plastic zone is situated in the interior but closer to the surface than to the mid plane [69–75]. Therefore, the plastic zone, which is also a source of AE signals, is surrounding the propagating crack and contributes significantly to the scattering of locations, as can be seen in Figure 13.

Finally, we note that in real experimental conditions the presence of noise and multiple crack detection are inevitable. The use of time filters namely the hit definition time (HDT), the hit lockout time (HLT), and the peak definition time (PDT), helps to separate AE signals and significantly limits their overlap. In our tensile experiments, we note that despite the calibration of the time filters, some AE hits still overlap but their number remains limited (less than 10%). The presence of noise requires some considerations. In general, threshold should be ~4 dB above noise level. If the threshold is high, a significant loss of AE signals might occur. The threshold could be either fixed during the test (in the case of a stationary noise), or floating (in the case of a varying background noise) [76,77]. In our experiments, the preamplification level was fixed at 40dB. The detected AE signals have a high signal-to-noise ratio (more than 50dB). Under these low noisy environment conditions, the AE signals received by the four channels are not affected by a possible saturation (low amplification) or loss in amplitude (they fall below threshold). However, in the case of a noisy environment, raw AE signals can be denoised using a wavelet analysis before performing the hit detection according to a suitable parameterization [78,79]. Finally,

note that if the noise level is unknown, a soft thresholding method can be adopted based on the wavelet coefficients, and by considering a non-white noise model [80].

7. Conclusions

The aim of this research is to propose a probabilistic method for localizing and tracking AE sources in a plate-like structure submitted to a tensile loading, based on continuous wavelet transform, unscented transform, and the EKF method. During mechanical tests, acoustic emission from the sample is recorded. The AE waves are measured by four acoustic emission PZT sensors. The Continuous Wavelet Transform (CWT) scalogram, which guarantees high accuracy in the time–frequency analysis of the acoustic waves, was employed to identify the arrival time (TOA) and the dominant frequency. The coordinates of the AE source location were obtained by solving a set of nonlinear equations through an adapted EKF iterative method. The proposed method, in contrast to triangulation algorithm, does not require a priori knowledge of the group velocity of the AE waveforms. By considering the common Lamb mode detected by all the different sensors (A0 in our case), the group velocity is obtained from the dispersion curves at the average frequency. The latter is calculated by considering the frequency of the largest wavelet amplitude determined at each sensor position. To validate and calibrate this method, experimental location tests were conducted on an aluminum plate. The source location was achieved with a good accuracy, where the maximum error in estimation of AE location was ~ 5 mm during the calibration stage. Mechanical tests showed that AE events increase significantly as damage progresses, where the concentration of acoustic events around the cracking zone revealed to be important. Furthermore, this work has shown the good agreement existing between the evolution of AE events in space and time and the crack propagation. Future development will be focused on the application of the proposed method and the improvement of its accuracy in the case where the number of sensors decreases or faulty sensors.

Author Contributions: Conceptualization, M.B., R.D. and A.E.M.; Methodology, E.y.D., M.B. and A.E.M.; Software, E.y.D. and M.B.; Validation, E.y.D., M.B. and R.D.; Formal analysis, E.y.D. and M.B.; Investigation, E.y.D. and M.B.; Resources, M.B. and A.E.M.; Data curation, E.y.D., M.B. and A.E.M.; Writing – original draft, E.y.D. and M.B.; Writing – review & editing, E.y.D. and M.B.; Visualization, M.B.; Supervision, M.B. and R.D.; Project administration, R.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: Not Applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1 Group Velocity Calculation Method of the AE Signal at the Dominant Frequency

The group wave velocity $\hat{V}_{gA0}$ and its variance $\hat{\sigma}_{V_{gA0}}^2$ can be calculated by determining the relationship between the probability distributions of the two random variables f and V_{gA0} when they are related by $V_{gA0} = F(fd)$. In view of the complex resolution of the nonlinear system of equations, we propose in this work an unscented transformation, which calculates the statistics of a random variable that undergoes a nonlinear transformation [70]. Assuming the random variable “ fd ” with a mean value “ $\bar{fd}$ ” and variance “ σ_{fd}^2 ”, three

weighted sigma points are necessary to calculate the statistics of V_{gA0} . These points are given by:

$$\begin{cases} \mathcal{X}0 = \bar{f}d \\ \mathcal{X}1 = \bar{f}d + \left(\sqrt{(1+k)\sigma_{fd}^2} \right) \\ \mathcal{X}2 = \bar{f}d - \left(\sqrt{(1+k)\sigma_{fd}^2} \right) \\ \mathcal{W}_0 = k/(1+k) \\ \mathcal{W}_1 = 1/2(1+k) \\ \mathcal{W}_2 = 1/2(1+k) \end{cases} \quad (A1)$$

where $\mathcal{W}_i$ is the weight associated with the i th point and k is an arbitrary number. By setting $k = 0$, Equation (A1) becomes:

$$\begin{cases} \mathcal{X}0 = \bar{f}d \\ \mathcal{X}1 = \bar{f}d + |\sigma_{fd}| \\ \mathcal{X}2 = \bar{f}d - |\sigma_{fd}| \\ \mathcal{W}_0 = 0 \\ \mathcal{W}_1 = 1/2 \\ \mathcal{W}_2 = 1/2 \end{cases} \quad (A2)$$

Given the set of sigma points calculated by Equation (A1), the transformation of the Gaussian probability density function of the random variable “ fd ” to the approximated Gaussian distribution of V_{gA0} is summarized in the following steps.

1. Calculate the group velocity corresponding to each sigma point according to the dispersion curves:

$$\mathcal{Y}_i = F(\mathcal{X}i) \quad i = 0, 1, 2 \quad (A3)$$

2. The mean of random variable $\bar{V}_{gA0}$ can be calculated as:

$$\bar{V}_{gA0} = \sum_{i=0}^2 \mathcal{W}_i \mathcal{Y}_i \quad (A4)$$

which gives in our case:

$$\hat{V}_{gA0} = \bar{V}_{gA0} = \sum_{i=1}^2 \frac{1}{2} \mathcal{Y}_i = \frac{1}{2} (\mathcal{Y}_1 + \mathcal{Y}_2) \quad (A5)$$

3. The variance of random variable V_{g0} can be determined by:

$$\sigma_{\bar{V}_{gA0}}^2 = \sum_{i=0}^2 \mathcal{W}_i (\mathcal{Y}_i - \bar{V}_{gA0}) (\mathcal{Y}_i - \bar{V}_{gA0})^T \quad (A6)$$

In our case these parameters are scalar and $\sigma_{\bar{V}_{gA0}}^2$ rewritten as:

$$\sigma_{\bar{V}_{gA0}}^2 = \frac{1}{2} (\mathcal{Y}_1 - \hat{V}_{gA0})^2 + \frac{1}{2} (\mathcal{Y}_2 - \hat{V}_{gA0})^2 \quad (A7)$$

Appendix A.2 Initiation of Location and Group Velocity

We consider the coordinates of the AE source initial location, $\hat{x}_{s0}$ and $\hat{y}_{s0}$ as uniformly distributed random variables. Their means and variances are expressed below and are calculated based on geometrical considerations [13,37]:

$$\hat{x}_{s0} = \frac{(\mathcal{X}_{sU} + \mathcal{X}_{sL})}{2}, \quad \hat{y}_{s0} = \frac{(\mathcal{Y}_{sU} + \mathcal{Y}_{sL})}{2} \quad (A8)$$

$$\sigma_{\hat{x}_{s0}}^2 = \frac{1}{12} (\mathcal{X}_{sU} - \mathcal{X}_{sL})^2, \quad \sigma_{\hat{y}_{s0}}^2 = \frac{1}{12} (\mathcal{Y}_{sU} - \mathcal{Y}_{sL})^2 \quad (A9)$$

$\mathcal{X}_{sL}$ and $\mathcal{Y}_{sL}$ represent the location of the master sensor (sensor 1) located at the origin of the coordinate system (the lower bound). $\mathcal{X}_{sU}$ and $\mathcal{Y}_{sU}$ represent the location of sensor 3 (the upper bound).

The starting estimates of the group wave velocity $\hat{V}_{g0}$ and its corresponding variance $\hat{\sigma}_{V_{g0}}^2$ are calculated using the Monte Carlo simulation. This is performed by assuming that the functional form $V_g = F(\bar{f}d)$ is known and deterministic. The frequency $\bar{f}$ is assumed as a Gaussian random variable of mean and variance defined in Equations (10) and (12), respectively. Recall that we are interested in determining the probability density of V_{g0} given the probability density of $\bar{f}d$, where d represents half the thickness of the plate ($d = e/2$). Once the dominant Lamb wave mode is determined, the Monte Carlo simulation is performed by randomly generating 150,000 samples of the random variable $\bar{f}d$ [37].

References

- Kundu, T. Acoustic source localization. *Ultrasonics* **2014**, *54*, 25–38. [\[CrossRef\]](#) [\[PubMed\]](#)
- Yu, L.; Momeni, S.; Godinez, V.; Giurgiutiu, V.; Ziehl, P.; Yu, J. Dual Mode Sensing with Low-Profile Piezoelectric Thin Wafer Sensors for Steel Bridge Crack Detection and Diagnosis. *Adv. Civ. Eng.* **2012**, *2012*, 402179. [\[CrossRef\]](#)
- Ebrahimkhanlou, A.; Dubuc, B.; Salamone, S. Damage localization in metallic plate structures using edge-reflected lamb waves. *Smart Mater. Struct.* **2016**, *25*, 085035. [\[CrossRef\]](#)
- Zhang, X.; Chen, Y.; Hu, J. Recent advances in the development of aerospace materials. *Prog. Aerosp. Sci.* **2018**, *97*, 22–34. [\[CrossRef\]](#)
- Starke, E.A.; Staley, J.T. Application of modern aluminum alloys to aircraft. *Prog. Aerosp. Sci.* **1996**, *32*, 131–172. [\[CrossRef\]](#)
- Rezaul Karim, M.; Kadau, K.; Narasimhachary, S.; Radaelli, F.; Amann, C.; Dayal, K.; Silling, S.; Germann, T.C. Crack nucleation from non-metallic inclusions in aluminum alloys described by peridynamics simulations. *Int. J. Fatigue* **2021**, *153*, 106475. [\[CrossRef\]](#)
- Zerbst, U.; Madia, M.; Klinger, C.; Bettge, D.; Murakami, Y. Defects as a root cause of fatigue failure of metallic components. II: Non-metallic inclusions. *Eng. Fail. Anal.* **2019**, *98*, 228–239. [\[CrossRef\]](#)
- Stawiarski, A.; Barski, M.; Pająk, P. Fatigue crack detection and identification by the elastic wave propagation method. *Mech. Syst. Signal Process.* **2017**, *89*, 119–130. [\[CrossRef\]](#)
- Das, A.K.; Leung, C.K. A fundamental method for prediction of failure of strain hardening cementitious composites without prior information. *Cem. Concr. Compos.* **2020**, *114*, 103745. [\[CrossRef\]](#)
- Kundu, T.; Das, S.; Jata, K.V. Point of impact prediction in isotropic and anisotropic plates from the acoustic emission data. *J. Acoust. Soc. Am.* **2007**, *122*, 2057–2066. [\[CrossRef\]](#) [\[PubMed\]](#)
- Salamone, S.; Bartoli, I.; Di Leo, P.; Lanza Di Scala, F.; Ajovalasit, A.; D’Acquisto, L.; Rhymer, J.; Kim, H. High-velocity Impact Location on Aircraft Panels Using Macro-fiber Composite Piezoelectric Rosettes. *J. Intell. Mater. Syst. Struct.* **2010**, *21*, 887–896. [\[CrossRef\]](#)
- Kundu, T.; Nakatani, H.; Takeda, N. Acoustic source localization in anisotropic plates. *Ultrasonics* **2012**, *52*, 740–746. [\[CrossRef\]](#) [\[PubMed\]](#)
- Dehghan Niri, E.; Salamone, S. A probabilistic framework for acoustic emission source localization in plate-like structures. *Smart Mater. Struct.* **2012**, *21*, 035009. [\[CrossRef\]](#)
- Nakatani, H.; Kundu, T.; Takeda, N. Improving accuracy of acoustic source localization in anisotropic plates. *Ultrasonics* **2014**, *54*, 1776–1788. [\[CrossRef\]](#) [\[PubMed\]](#)
- Mostafapour, A.; Davoodi, S.; Ghareaghaji, M. Acoustic emission source location in plates using wavelet analysis and cross time frequency spectrum. *Ultrasonics* **2014**, *54*, 2055–2062. [\[CrossRef\]](#)
- Kundu, T.; Yang, X.; Nakatani, H.; Takeda, N. A two-step hybrid technique for accurately localizing acoustic source in anisotropic structures without knowing their material properties. *Ultrasonics* **2015**, *56*, 271–278. [\[CrossRef\]](#)
- Kabir, M.; Saboonchi, H.; Ozevin, D. Accurate Source Localization Using Highly Narrowband and Densely Populated MEMS Acoustic Emission Sensors. In *Structural Health Monitoring 2015*; Stanford University: Stanford, CA, USA, 2015. [\[CrossRef\]](#)
- Zahedi, F.; Yao, J.; Huang, H. A passive wireless ultrasound pitch-catch system. *Smart Mater. Struct.* **2015**, *24*, 085030. [\[CrossRef\]](#)
- Hoseini Sabzevari, S.A.; Moavenian, M. Locating the acoustic source in thin glass plate using low sampling rate data. *Ultrasonics* **2016**, *70*, 1–11. [\[CrossRef\]](#)
- Park, W.H.; Packo, P.; Kundu, T. Acoustic source localization in an anisotropic plate without knowing its material properties—A new approach. *Ultrasonics* **2017**, *79*, 9–17. [\[CrossRef\]](#) [\[PubMed\]](#)
- Grabowski, K.; Gawronski, M.; Baran, I.; Spychalski, W.; Staszewski, W.J.; Uhl, T.; Kundu, T.; Packo, P. Time-distance domain transformation for Acoustic Emission source localization in thin metallic plates. *Ultrasonics* **2016**, *68*, 142–149. [\[CrossRef\]](#)
- Johnson, E.A.; Lam, H.F.; Katafygiotis, L.S.; Beck, J.L. Phase I IASCE-ASCE Structural Health Monitoring Benchmark Problem Using Simulated Data. *J. Eng. Mech.* **2004**, *130*, 3–15. [\[CrossRef\]](#)

23. Yang, J.N.; Lei, Y.; Lin, S.; Huang, N. Hilbert-Huang Based Approach for Structural Damage Detection. *J. Eng. Mech.* **2004**, *130*, 85–95. [\[CrossRef\]](#)
24. Seydel, R.; Chang, F.K. Impact identification of stiffened composite panels: I. System development. *Smart Mater. Struct.* **2001**, *10*, 354–369. [\[CrossRef\]](#)
25. Ciampa, F.; Meo, M. Acoustic emission source localization and velocity determination of the fundamental mode A0 using wavelet analysis and a Newton-based optimization technique. *Smart Mater. Struct.* **2010**, *19*, 045027. [\[CrossRef\]](#)
26. Gaul, L. Identification of the impact location on a plate using wavelets. *Mech. Syst. Signal Process.* **1998**, *12*, 783–795. [\[CrossRef\]](#)
27. Gaul, L.; Hurlbauss, S.; Jacobs, L. Localization of a synthetic acoustic emission source on the surface of a fatigue specimen. *Res. Nondestruct. Eval.* **2001**, *13*, 105–117. [\[CrossRef\]](#)
28. Dong, L.; Zou, W.; Li, X.; Shu, W.; Wang, Z. Collaborative localization method using analytical and iterative solutions for microseismic/acoustic emission sources in the rockmass structure for underground mining. *Eng. Fract. Mech.* **2019**, *210*, 95–112. [\[CrossRef\]](#)
29. Zhou, Z.; Lan, R.; Rui, Y.; Dong, L.; Cai, X. A New Algebraic Solution for Acoustic Emission Source Localization without Pre-measuring Wave Velocity. *Sensors* **2021**, *21*, 459. [\[CrossRef\]](#)
30. Liu, Z.H.; Peng, Q.; Li, X.; He, C.F.; Wu, B. Acoustic Emission Source Localization with Generalized Regression Neural Network Based on Time Difference Mapping Method. *Exp. Mech.* **2020**, *60*, 679–694. [\[CrossRef\]](#)
31. Kurz, J.H. New approaches for automatic three-dimensional source localization of acoustic emissions—Applications to concrete specimens. *Ultrasonics* **2015**, *63*, 155–162. [\[CrossRef\]](#)
32. Das, A.K.; Lai, T.T.; Chan, C.W.; Leung, C.K. A new non-linear framework for localization of acoustic sources. *Struct. Health Monit.* **2019**, *18*, 590–601. [\[CrossRef\]](#)
33. Hassan, F.; Mahmood, A.K.B.; Yahya, N.; Saboor, A.; Abbas, M.Z.; Khan, Z.; Rimsan, M. State-of-the-Art Review on the Acoustic Emission Source Localization Techniques. *IEEE Access* **2021**, *9*, 101246–101266. [\[CrossRef\]](#)
34. Yang, K.; An, J.; Bu, X.; Sun, G. Constrained Total Least-Squares Location Algorithm Using Time-Difference-of-Arrival Measurements. *IEEE Trans. Veh. Technol.* **2010**, *59*, 1558–1562. [\[CrossRef\]](#)
35. Smyth, A.W.; Masri, S.F.; Kosmatopoulos, E.B.; Chassiakos, A.G.; Caughey, T.K. Development of adaptive modeling techniques for non-linear hysteretic systems. *Int. J. Non-Linear Mech.* **2002**, *37*, 1435–1451. [\[CrossRef\]](#)
36. Sen, S.; Bhattacharya, B. Progressive damage identification using dual extended Kalman filter. *Acta Mech.* **2016**, *227*, 2099–2109. [\[CrossRef\]](#)
37. Dris, E.Y.; Draï, R.; Bentahar, M.; Berkani, D. Adaptive Algorithm for Estimating and Tracking the Location of Multiple Impacts on a Plate-Like Structure. *Res. Nondestruct. Eval.* **2020**, *31*, 1–23. [\[CrossRef\]](#)
38. Lu, Y.; Michaels, J.E. A methodology for structural health monitoring with diffuse ultrasonic waves in the presence of temperature variations. *Ultrasonics* **2005**, *43*, 717–731. [\[CrossRef\]](#)
39. Sarrafi, A.; Mao, Z. Probabilistic uncertainty quantification of wavelet-transform-based structural health monitoring features. In Proceedings of the SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, Las Vegas, NE, USA, 1 April 2016; Kundu, T., Ed.; 2016; p. 98051N. [\[CrossRef\]](#)
40. Lanza di Scalea, F.; Salamone, S. Temperature effects in ultrasonic Lamb wave structural health monitoring systems. *J. Acoust. Soc. Am.* **2008**, *124*, 161–174. [\[CrossRef\]](#)
41. Salamone, S.; Bartoli, I.; Lanza Di Scalea, F.; Coccia, S. Guided-wave Health Monitoring of Aircraft Composite Panels under Changing Temperature. *J. Intell. Mater. Syst. Struct.* **2009**, *20*, 1079–1090. [\[CrossRef\]](#)
42. Clarke, T.; Simonetti, F.; Cawley, P. Guided wave health monitoring of complex structures by sparse array systems: Influence of temperature changes on performance. *J. Sound Vib.* **2010**, *329*, 2306–2322. [\[CrossRef\]](#)
43. LeClerc, J.R.; Worden, K.; Staszewski, W.J.; Haywood, J. Impact detection in an aircraft composite panel—A neural-network approach. *J. Sound Vib.* **2007**, *299*, 672–682. [\[CrossRef\]](#)
44. Kundu, T.; Das, S.; Jata, K.V. Detection of the point of impact on a stiffened plate by the acoustic emission technique. *Smart Mater. Struct.* **2009**, *18*, 035006. [\[CrossRef\]](#)
45. Hajzargerbashi, T.; Kundu, T.; Bland, S. An improved algorithm for detecting point of impact in anisotropic inhomogeneous plates. *Ultrasonics* **2011**, *51*, 317–324. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Ebrahimkhanlou, A.; Salamone, S. A probabilistic framework for single-sensor acoustic emission source localization in thin metallic plates. *Smart Mater. Struct.* **2017**, *26*, 095026. [\[CrossRef\]](#)
47. Dris, E.Y.; Draï, R.; Bentahar, M.; Berkani, D.; Benammar, A. Comparative study between EKF and Geometrical methods for the Acoustic Emission source localization. *Procedia Comput. Sci.* **2019**, *148*, 438–447. [\[CrossRef\]](#)
48. Dris, E.Y.; Draï, R.; Dahou, Z.; Berkani, D. 2019. EKF and UKF methods for the Acoustic Emission source localization in Concrete. In Proceedings of the 2019 Third International Conference on Intelligent Computing in Data Sciences (ICDS), Marrakech, Morocco, 28–30 October 2019; pp. 1–6. [\[CrossRef\]](#)
49. Moon, Y.-S.; Lee, S.-K.; Shin, K.; Lee, Y.-S. Identification of Multiple Impacts on a Plate Using the Time-Frequency Analysis and the Kalman Filter. *J. Intell. Mater. Syst. Struct.* **2011**, *22*, 1283–1291. [\[CrossRef\]](#)
50. Lamb, H. On the Flexure of an Elastic Plate. *Proc. Lond. Math. Soc.* **1889**, *1*, 70–91. [\[CrossRef\]](#)
51. Lamb, H. On waves in an elastic plate. *Proc. R. Soc. Lond. Ser. Contain. Pap. Math. Phys.* **1917**, *93*, 114–128. [\[CrossRef\]](#)

52. Achenbach, J.D. *Wave Propagation in Elastic Solids*, 7th ed.; North Holland Series in Applied Mathematics and Mechanics; Elsevier: Amsterdam, The Netherlands, 1999.
53. Auld, B.A. *Acoustic Fields and Waves in Solids*; Wiley: New York, NY, USA, 1973; Volume 1.
54. Rose, J.L. *Ultrasonic Guided Waves in Solid Media*; Cambridge University Press: New York, NY, USA, 2014. [[CrossRef](#)]
55. Dris, E.Y.; Draï, R.; Benammar, A.; Berkani, D. Acoustic Emission Source Localization in Plate-Like Structure. In Proceedings of the 2017 European Conference on Electrical Engineering and Computer Science (E ECS), Bern, Switzerland, 17–19 November 2017; pp. 193–197. [[CrossRef](#)]
56. Kim, Y.Y.; Kim, E.-H. Effectiveness of the continuous wavelet transform in the analysis of some dispersive elastic waves. *J. Acoust. Soc. Am.* **2001**, *110*, 86–94. [[CrossRef](#)]
57. Satour, A.; Montrésor, S.; Bentahar, M.; Boubenider, F. Wavelet Based Clustering of Acoustic Emission Hits to Characterize Damage Mechanisms in Composites. *J. Nondestruct. Eval.* **2020**, *39*, 37. [[CrossRef](#)]
58. Hsu, N.N. Acoustic Emissions Simulator. U.S. Patent No 4,018,084, 1977.
59. Tekoğlu, C.; Çelik, Ş.; Duran, H.; Efe, M.; Nielsen, K.L. Experimental Investigation of Crack Propagation Mechanisms in Commercially Pure Aluminium Plates. *Procedia Struct. Integr.* **2019**, *21*, 2–11. [[CrossRef](#)]
60. Lecarme, L.; Tekoglu, C.; Pardoen, T. Void growth and coalescence in ductile solids with stage III and stage IV strain hardening. *Int. J. Plast.* **2011**, *27*, 1203–1223. [[CrossRef](#)]
61. Pardoen, T.; Scheyvaerts, F.; Simar, A.; Tekoğlu, C.; Onck, P.R. Multiscale modeling of ductile failure in metallic alloys. *Comptes Rendus Phys.* **2010**, *11*, 326–345. [[CrossRef](#)]
62. Scheyvaerts, F.; Onck, P.R.; Tekoglu, C.; Pardoen, T. The growth and coalescence of ellipsoidal voids in plane strain under combined shear and tension. *J. Mech. Phys. Solids* **2011**, *59*, 373–397. [[CrossRef](#)]
63. El-Naaman, S.A.; Nielsen, K.L. Observations on Mode I ductile tearing in sheet metals. *Eur. J. Mech.-A Solids* **2013**, *42*, 54–62. [[CrossRef](#)]
64. Pardoen, T.; Hachez, F.; Marchioni, B.; Blyth, P.H.; Atkins, A.G. Mode I fracture of sheet metal. *J. Mech. Phys. Solids* **2004**, *52*, 423–452. [[CrossRef](#)]
65. Jeong, H.; Jang, Y.S. Fracture source location in thin plates using the wavelet transform of dispersive waves. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2000**, *47*, 612–619. [[CrossRef](#)]
66. Haidar, K. Correlations between the internal length, the fracture process zone and size effect in mortar and model materials. *Mater. Struct.* **2005**, *38*, 201–210. [[CrossRef](#)]
67. Rossi, P.; Robert, J.L.; Gervais, J.P.; Bruhat, D. The use of acoustic emission in fracture mechanics applied to concrete. *Eng. Fract. Mech.* **1990**, *35*, 751–763. [[CrossRef](#)]
68. Yudin, A.A.; Ivanov, V.I. Acoustic emission in plastic deformation of metals (review). Report 1. *Strength Mater* **1985**, *17*, 842–851. [[CrossRef](#)]
69. Julier, S.; Uhlmann, J.; Durrant-Whyte, H.F. Durrant-whyte. A new method for the nonlinear transformation of means and covariances in filters and estimators. *IEEE Trans. Autom. Control* **2000**, *45*, 477–482. [[CrossRef](#)]
70. Sutton, M.A.; Orteu, J.J.; Schreier, H. *Image Correlation for Shape, Motion and Deformation Measurements*; Springer: New York, NY, USA, 2009. [[CrossRef](#)]
71. Tai, Y.H.; Zanganeh, M.; Asquith, D.; Yates, J.R. Characterization of full-field deformation behavior using digital imaging techniques. *Appl. Mech. Mater.* **2010**, *24–25*, 141–146. [[CrossRef](#)]
72. Vasco-Olmo, J.M.; James, M.N.; Christopher, C.J.; Patterson, E.A.; Díaz, F.A. Assessment of crack tip plastic zone size and shape and its influence on crack tip shielding. *Fatigue Fract. Eng. Mater. Struct.* **2016**, *39*, 1–12. [[CrossRef](#)]
73. Lopez-Crespo, P.; Steuwer, A.; Buslaps, T.; Tai, Y.H.; Lopez Moreno, A.; Yates, J.R.; Withers, P.J. Measuring overload effects during fatigue crack growth in bainitic steel by synchrotron X-ray diffraction. *Int. J. Fatigue* **2015**, *71*, 11–16. [[CrossRef](#)]
74. Lopez-Crespo, P.; Mostafavi, M.; Steuwer, A.; Kelleher, J.F.; Buslaps, T.; Withers, P.J. Characterization of overloads in fatigue by 2D strain mapping at the surface and in the bulk. *Fatigue Fract. Eng. Mater. Struct.* **2016**, *39*, 1040–1048. [[CrossRef](#)]
75. Lopez-Crespo, P.; Camas, D.; Antunes, F.V.; Yates, J.R. A study of the evolution of crack tip plasticity along a crack front. *Theor. Appl. Fract. Mech.* **2018**, *98*, 59–66. [[CrossRef](#)]
76. Barat, V.; Borodin, Y.; Kuzmin, A. Intelligent AE signal filtering methods. *J. Acoust. Emiss.* **2010**, *28*, 109–119.
77. Barat, V.; Grishin, D.; Rostovtsev, M. Detection of AE signals against background friction noise. *J. Acoust. Emiss.* **2011**, *29*, 133–141.
78. Donoho, D.L.; Johnstone, J.M. Ideal spatial adaptation by wavelet shrinkage. *Biometrika* **1994**, *81*, 425–455. [[CrossRef](#)]
79. Satour, A.; Montrésor, S.; Bentahar, M.; El guerjouma, R.; Boubenider, F. Acoustic emission signal de-noising to improve damage analysis in glass fiber reinforced composites. *Non-Destr. Test. Eval.* **2014**, *29*, 65–79. [[CrossRef](#)]
80. Donoho, D.L. De-noising by soft-thresholding. *IEEE Trans. Inf. Theory* **1995**, *41*, 613–627. [[CrossRef](#)]