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Review

A Review of Acoustic Emission Source Localization Techniques in Different Dimensions

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Abstract: Acoustic emission (AE) source localization technology, since the early application to one-dimensional structures, has been extended to a wide range of applications to two-dimensional (2D) structures, including isotropic and anisotropic materials, which are currently the most widely studied and the most mature. With the development of AE source localization technology, more and more significant challenges have arisen for three-dimensional (3D) structures, which are mostly anisotropic and have complex propagation paths. This paper summarizes and discusses the AE source localization methods in different dimensions as well as their applications, including the main methods for 2D AE source localization, such as the triangulation method, beam forming, strain rosette technique, modal AE, artificial neural network, optimization and the time reversal technique, as well as state-of-the-art AE source localization methods in isotropic and anisotropic structures utilizing these methods. Recent advances in AE source localization in complex 3D structures are also reviewed.

Keywords: acoustic emission; beam forming; source localization

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1. Introduction

Sound source localization refers to the process of recording and analyzing the acoustic signal of sound propagation through an elastic medium from a source that radiates sound waves to deduce the location of the sound source. Sound source localization technology is widely used in aerospace, military, medical, seismic, intelligent voice recognition and non-destructive testing applications. Sound source localization technology utilizes acoustic, signal detection, digital signal processing and many other technologies.

Acoustic emission (AE) source localization technology is an important part of structural health inspections. AE is a physical phenomenon in which a localized source in a material rapidly releases energy to produce elastic waves. AE is ubiquitous in daily life, since both fracture and deformation of materials can produce AE phenomena. Sources related to the fracture and deformation of materials are called AE sources, which include pipe leakage, friction, collision and combustion. Sources that are not related to the fracture and deformation of the material are called secondary AE sources. AE source signals contain important information about material deformation, crack extension and damage location and extent. The process of recording, processing and analyzing the AE signals and deducing the location of the AE source from the AE signals is known as AE localization technology.

This article mainly summarizes the methods of acoustic emission source localization in different dimensions and provides a detailed solution process for acoustic source localization using one-dimensional, two-dimensional and three-dimensional time difference methods. As dimensions increase, positioning becomes increasingly complex and difficult. The three-dimensional positioning method is currently a key research direction which

helps to apply acoustic emission source positioning technology to practical engineering. At present, there is no detailed review and comparison of the localization methods for three-dimensional structures in research. This article classifies the current three-dimensional sound source localization methods and compares the sound source localization methods for three-dimensional structures. Notes on this research direction are proposed at the end.

2. Sound Source Localization Methods for One-Dimensional (1D) Structures

The one-dimensional positioning method mainly utilizes time difference to locate the sound source (Figure 1).

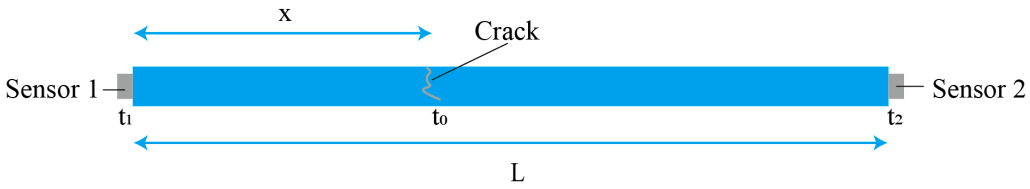


Figure 1. One-dimensional time difference methods.

$$t_1 - t_0 = \frac{x}{c}$$

$$t_2 - t_0 = \frac{L - x}{c}$$

$$x = \frac{L - (t_2 - t_1)c}{2}$$

x is the distance from the crack to sensor 1, where x represents the position of the acoustic emission source, L is the length of the detection section, c is the wave velocity, t_0 represents the time when the crack begins to form, t_1 represents the time when sensor 1 receives the signal and t_2 represents the time when sensor 2 receives the signal.

3. Sound Source Localization Methods for Two-Dimensional (2D) Structures

Research on AE source localization in planar materials was initiated as early as the last century. AE source localization for 2D planar surfaces is often applied in the aerospace industry for wing fuselage damage detection, and damage localization in civil and marine structures. Nowadays, acoustic emission damage localization is applied to many industries, such as the construction industry, geotechnical industry and materials industry. The main methods for 2D sound source localization (Figure 2) can be classified into the triangulation method, beam forming, strain rosette technique, modal AE (MAE), artificial neural networks, optimization and the time reversal technique. Many proposed new positioning methods are based on the above methods.

3.1. Triangulation Method

The triangulation method uses the time difference between the sound wave and different sensors to locate the sound source. It is an extension of the one-dimensional time difference positioning method, which essentially involves solving a system of equations, but two-dimensional methods require solving more systems of equations.

Since the 1960s, triangulation technology has been used for AE non-destructive testing of rocket motorcycles. Tobias [1], Sachse and Sancar [2] and others studied sound source localization technology in isotropic plates. For the triangular time difference localization method in an isotropic plate using the difference in the AE signal arrival times (TDOA) at the three sensors (Figure 3), obtain the sound emission source position S0 by calculating the difference between several matrices.

$$||X_S - X_{R,i}|| - ||X_S - X_{R,j}|| = c\,(t_i - t_j),\ \forall i,\ j\ [1,\ 2,\ \ldots,\ N]$$

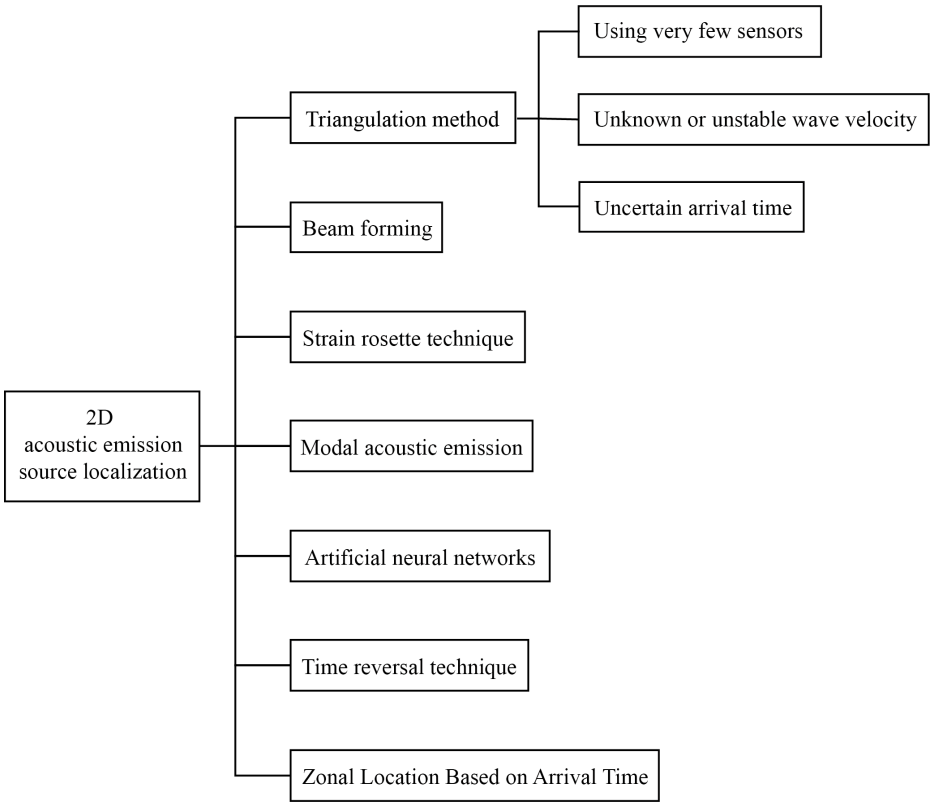


Figure 2. Method for 2D sound source localization.

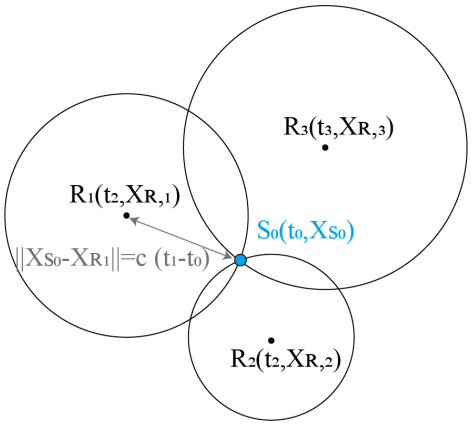


Figure 3. Triangular time difference localization method.

The triangulation method has the following requirements: (1) wave velocity is constant in the medium; (2) arrival of the wave signal can be caught perfectly; (3) a straight wave path; (4) sensor locations are accurately determined; and (5) it requires a lot of sensors.

By improving the above limitations, many scholars have also proposed new methods based on triangulation. We can classify the new methods based on the limitations of the improvements.

3.1.1. Triangular Positioning Method with Few Sensors

In order to save costs and improve efficiency, many scholars have proposed methods using fewer sensors for positioning.

Although at least three sensors and two sets of time differences can determine the two-dimensional coordinates of the acoustic emission source, in order to obtain a single accurate solution, four sensors and three sets of time differences are often used to locate the

acoustic emission source, such as in the four-probe rhombic localization method proposed by Shen et al. [3], and the planar square-triangle localization method, shown in Figure 4a,c. The normalized square localization method proposed by Ma et al. [4] is shown in Figure 4b. Although these acoustic emission source localization methods based on time difference require a small number of sensors, they are only applicable to materials with known constant velocity and isotropy.

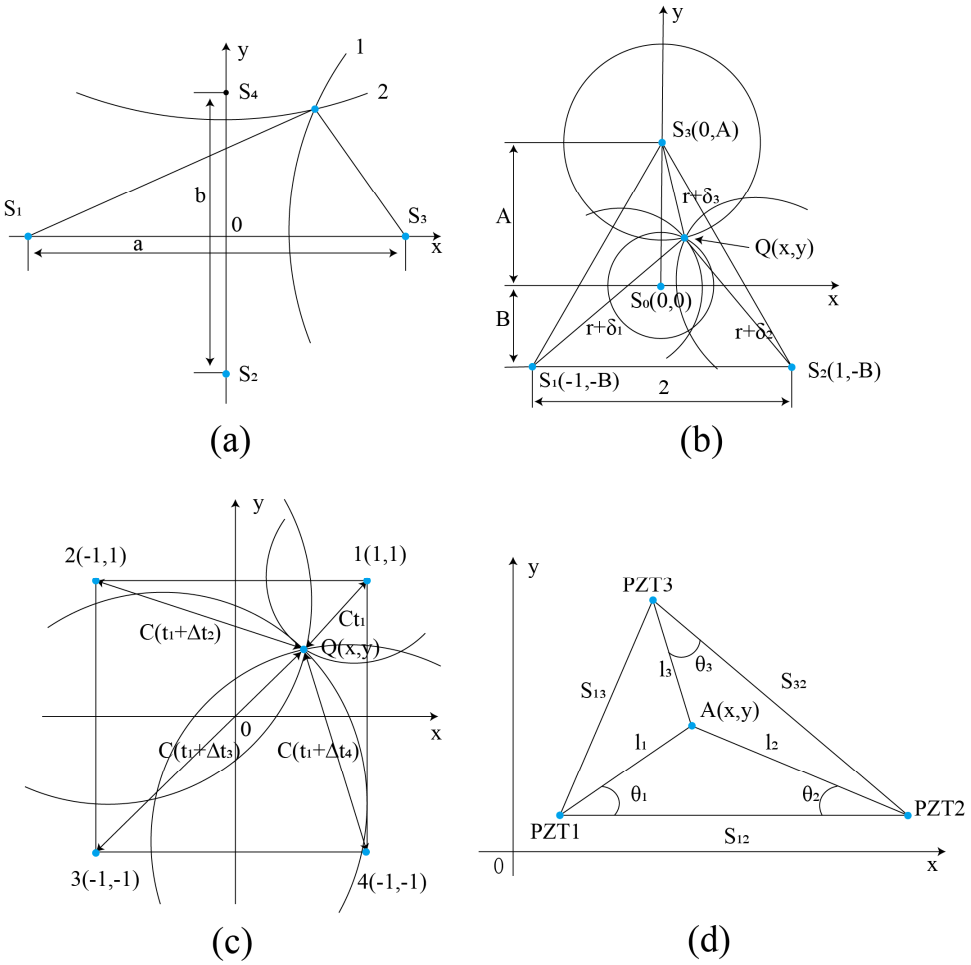


Figure 4. Positioning methods based on time difference method: (**a**) rhombic AE localization method [3]; (**b**) normalized square localization method [4]; (**c**) planar square–triangle localization method [3]; (**d**) triangular time-difference localization method with known velocity.

3.1.2. Triangular Positioning Method under Unknown or Unstable Wave Velocity

For anisotropic structures, the wave speed is not constant. Kundu et al. [5] first performed sound source localization by the improved time difference method in steel-reinforced metal plates and proposed an easy-to-implement method for estimating the location of sound sources in orthogonal anisotropic plates, which was based on the energy of the recorded signal.

Subsequently, Liang et al. [6] proposed a sound source localization method based on the triangular time difference method applied to anisotropic materials with known wave velocities, which solved a system of nonlinear equations to obtain the location of the sound source, as shown in Figure 4d.

Dong et al. [7] presented a multi-step localization method (MLM) which does not require the wave velocity to be known in advance for heterogeneous media. But this method requires more sensors.

Sen et al. [8] used a cluster of four closely positioned sensors forming the four vertices of a square and facing different directions. They proposed a formula for estimating the angle of incidence from the signals acquired by the square cluster. A method based on the shape of the wavefront can then be applied to estimate the sound source location.

Haywood-Alexander et al. [9] proposed a new method which used the Bayesian decomposition of single-source signals and required only a priori information about the surface displacements on the propagation path. The Bayesian decomposition method returned signals that contained only reflected waves and obtained parametric features to be used to assess damage.

Zhou et al. [10] proposed a new method for localization of sound sources, which required only six sensors to quickly predict the damage location in both isotropic and anisotropic materials with the help of the L-shaped coupled sensor clusters. Li et al. [11] presented a new approach to damage assessment based on empirical wavelet transform and long- and short-term wavelet decomposition.

Li et al. [11] used an AE source localization method based on empirical wavelet transform and long and short-term memory neural networks for crack monitoring in ortho-tropic anisotropic steel plates.

Since the traditional time difference method does not consider the structural complexity that may change the wave propagation path and velocity, Al-Jumaili [12] proposed a new and improved fully automated delta T mapping technique, where a clustering algorithm was used to automatically identify and select the highly correlated events at each grid point, while a minimum-difference method was adopted to determine the source location.

3.1.3. Triangular Positioning Method under Uncertain Arrival Time Difference of Sound Waves

Cantero-Chinchilla et al. [13] proposed a new fully probabilistic method for estimating time-of-flight based on a Bayesian inverse problem that provided a reliable estimate of the time-of-flight for each sensor independently. The prediction was then used as an input to the Bayesian inverse problem for damage localization.

Zhao et al. [14] proposed an improved AE-based damage source localization method for wind turbine blades and used five methods to determine the most reasonable TDOA to improve the accuracy of the damage source localization.

Jones et al. [15] proposed a Bayesian source localization strategy which was able to cope with complex situations. In this new framework, a Gaussian process was first used to model the relationship between the source location and the corresponding TDOA values for multiple sensor pairs. When an AE event of unknown origin was observed, a mapping was generated that quantified the likelihood of the emission location across the surface of the structure.

Zargar et al. [16] proposed an autonomous analysis of the wavefield for impact diagnostics based on computer vision, i.e., identifying the location of the impact and reconstructing the impact force time-course.

Hao et al. [17] proposed a machine-learning method for localizing composite panels within a five-peak narrowband modulated sinusoidal signal excitation source and a back propagation (BP) neural network. The idea was to use the arrival time of the first wave packet of the five-peak wave signals to locate the AE source.

Jang et al. [18] used the magnitude of fiber optic sensor signals to estimate the distance between each sensor and the impact location. To achieve a higher correlation between signal magnitude and distance, the former was calculated using a rough estimate of the signal near the arrival time. Then, the accuracy of estimating the signal magnitude distance was improved by neural network training. Finally, triangulation was used to localize the impact source.

Mirgal et al. [19] proposed a simplified and robust arrival-time-based iterative planar source (IPS) localization algorithm for identifying arbitrarily selected multiple damage source locations for rectangular, circular and sawtooth otoacoustic emission sensor network

arrangements. The outcomes of the proposed localization algorithm were then compared to the results of an evolutionary particle swarm optimization (PSO) algorithm for each sensor network arrangement to evaluate the performance of the AE source monitoring strategy.

Feng et al. [20] extracted the arrival time features at different frequencies from time domain signals by continuous wavelet transform, mutual correlation and Hilbert transform. Two techniques, namely, image fusion and artificial neural network, were proposed to fuse multi-frequency features to detect impact defects in large aerospace structures.

3.2. Beam Forming

Another classical method for sound source localization is beam forming. It is a wireless communication technology that employs a sophisticated strategy during data transmission. The core principle is that the transmitting end will weight the data to be sent and then form a focused narrow beam, which is like a laser beam and directly points towards the target receiving user. The main purpose of doing so is to enhance the signal strength sent to the target user, reduce signal attenuation during propagation and significantly improve the demodulation signal-to-noise ratio of the target user, especially for users located at the edge of the cell with relatively weak signals. This technology can significantly improve their data throughput.

The beam forming method has been successfully applied in multiple fields such as sonar, telecommunications, radar, sound source recognition and localization. Beam forming was first proposed by McLaskey for sound source localization.

The advantages of constraint formation technology are high positioning accuracy and robustness. The limitations are (1) that it requires a large number of sensor groups; (2) when comparing the shape of signals in beam forming, all sensors in the array should have similar amplitude and phase responses; and (3) to avoid spatial aliasing, the beam forming array needs to have a relatively small aperture.

McLaskey et al. [21] proposed an improved beam forming approach for civil engineering structures, as shown in Figure 5. He et al. [22] realized sound source localization in plate structures by improving the beam forming method, examined the effect of AE characteristics on the localization accuracy and proposed a method for determining the localization speed by combining the plate wave theory and wavelet transform, as shown in Figure 6a.

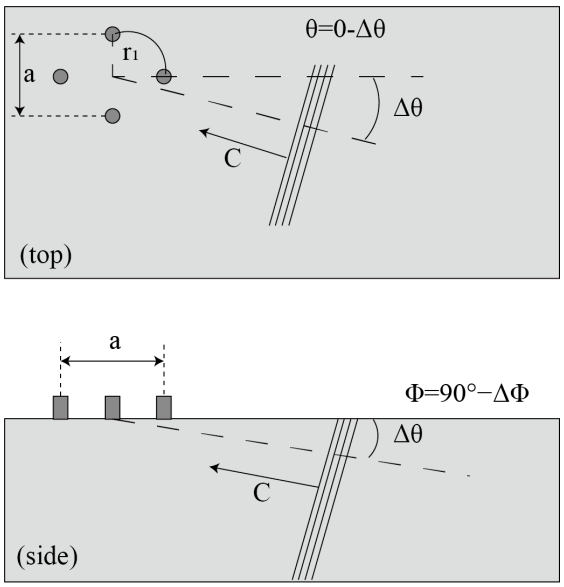


Figure 5. Four-sensor beam forming technique.

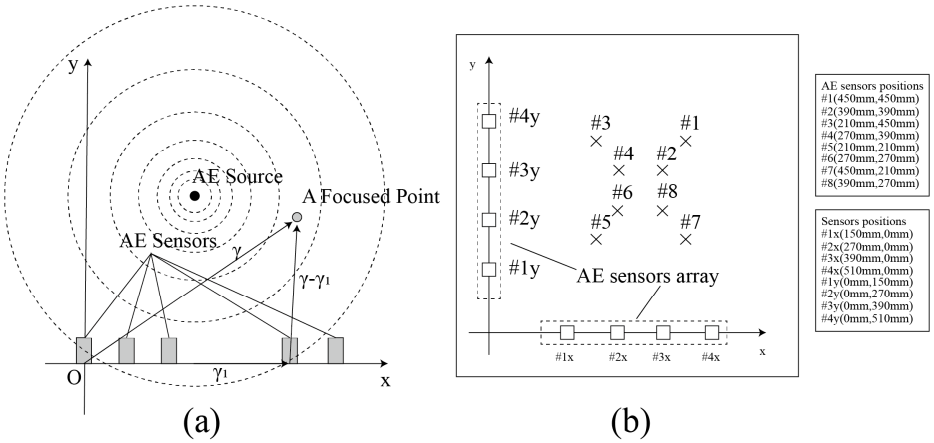


Figure 6. (**a**) Beam forming localization method [22]. (**b**) Beam forming localization method using L-shaped sensor array.

Hamid et al. [23] compared the execution time of various time-domain and frequency-domain beam forming techniques on general-purpose processors as well as their hardware requirements. Chen et al. [24] proposed a new method working in low-frequency combined with high-frequency secondary AE beam forming localization for internal defects in thin plates. The signal source position using high- and low-frequency bands was first determined by analyzing the main flap and sidelobe parameters with the maximum sidelobe level (MSL), then the low-frequency localization of the signal envelope was used to determine the range of the main flap and, finally, signal filtering was performed for high-frequency localization through the narrowing of the scanning scope by the determined range of the main flap. The results showed that the method avoided the beam formation of the main flap being wider and the existence of influence of the side flap, and the defects in thin plates were accurately localized, but it also solved the linear array perpendicular to the array direction of the localization of the problem of low resolution.

Han et al. [25] applied the beam forming technique to robotic sound source localization and used the minimum-variance distortion-free response adaptive beam forming algorithm for sound source localization, which provided a higher localization accuracy compared to the conventional beam forming algorithm. They proposed an improved cross-shaped microphone array data processing method to reduce the computational burden of the beam forming algorithm when used with the 2D microphone arrays. Liang et al. [26] proposed a virtual primitive localization method based on planar array beam formation, which symmetrically split a uniform square array into four subarrays projected into virtual primitives through subarray beam formation and constituting a four-primitive cross array. The direction of incoming waves was calculated by combining the estimated wave directions by the four-primitive cross arrays. The results obtained by this method are compared with the results obtained by the beam forming technique and large deviations are discarded; otherwise, they are used as the reference direction for the next ping data in an iterative loop improving the localization accuracy. Tai et al. [27] proposed a method to determine the position of a sound source in an anisotropic structure by using an L-shaped transducer array, as shown in Figure 6b.

3.3. Strain Rosette Technique

Another classical method for acoustic source localization is the rosette method, in which the transducer arrays are arranged in the shape of a flower and the intersection of the propagation directions determined by two rosette arrays gives the acoustic source location when the transducer array direction is in the same direction as the main strain.

The advantage of this technology is that it is not affected by noise and does not require the arrival time of waves. The limitation is that this technology is not applicable

to anisotropic plates, as it requires the principal strain direction to be consistent with the group velocity (or energy velocity) direction.

Matt et al. [28] proposed a method based on piezoelectric transducer rosette junctions for passive damage or impact localization in anisotropic or geometrically complex structures. A rosette junction consists of rectangular macro-fiber composite (MFC) transducers exhibiting a highly directional response to ultrasonic guided waves. Salamone et al. [29] proposed a method using MFC transducer arrays arranged in rosettes for fast impact localization in isotropic and composite aircraft panels. Each rosette utilized the directional response of three MFC transducers to determine the direction of the incident wave generated by the shock source as the principal strain angle. Two rosettes sufficed to determine the impact location from the intersection of incoming wave directions.

Langenberg et al. [30] achieved sound source localization in plates by arranging the sensors in a rosette array. This method requires the propagation direction to coincide with the main strain direction without knowing the wave velocity (Figure 7a). Ciampa et al. [31–33] measured the wave stress differences at six piezoelectric sensors, as shown in Figure 7b, used continuous wavelet transform to determine the bending Lamb wave arrival times, and then solved the nonlinear equations to obtain the coordinates of damage location and bending wave velocity by combining backtracking techniques related to global line search and local Newton iterative methods. Aljet et al. [34] achieved damage localization on carbon-fiber-reinforced composite panels by combining arrival times and wave mode analysis from the data acquired by three closely spaced sensors, as shown in Figure 7c. Jiang et al. [35] investigated the effect of various rosette configurations, including 45° rectangular, 135° rectangular, 60° delta and 120° delta, on the accuracy of wave propagation direction estimation. The results showed that the 135° triangle configuration provided the superior results and that the errors depended on the size and position of each sensor in the rosette.

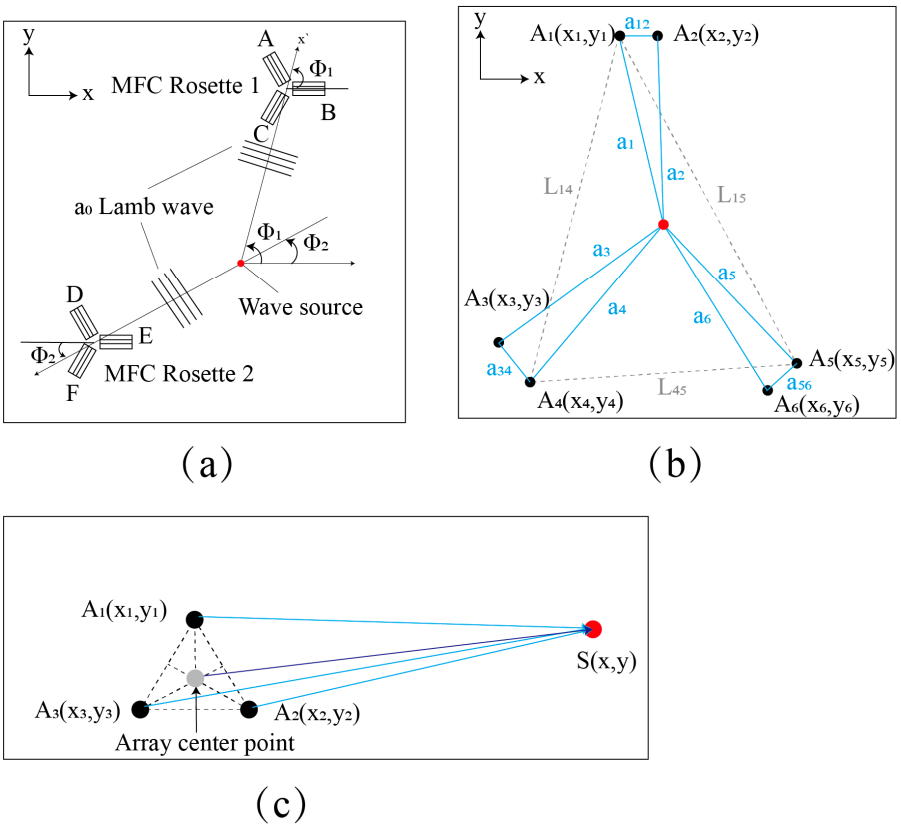


Figure 7. (**a**) Rosette array localization method. (**b**) Localization method using six sensors. (**c**) Three closely placed AE sensors for AE source localization.

Kundu et al. [36,37] proposed an acoustic source localization utilizing transducers arranged in an isosceles triangle, which utilized the arrival time difference. The method was not only applicable to damage detection in isotropic materials but also to anisotropic structures. The method's performance has been continuously improved [38–40] (Figure 8b).

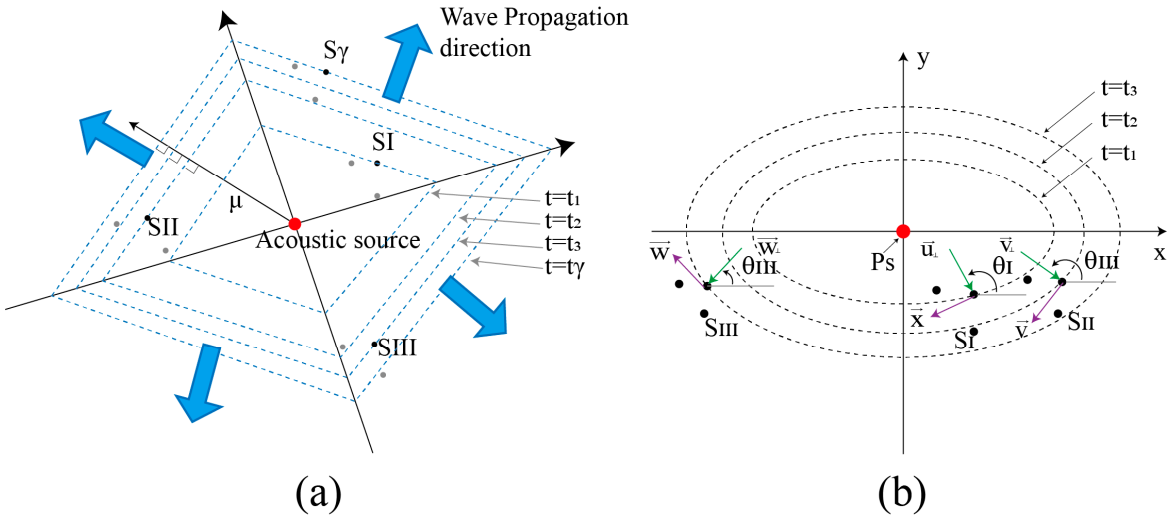


Figure 8. (**a**) AE source localization method with rhombic wavefront [41]. (**b**) AE source localization method with elliptical wavefront.

Park et al. [41] introduced a localization method for an AE source that produced a rhombic or elliptical wavefront surface, as shown in Figure 8a.

3.4. Modal Acoustic Emission (MAE)

Modal acoustic emission is a waveform analysis method. Common waveform analysis methods include Fourier transform, wavelet analysis, neural networks and full waveform analysis.

In 1991, the American scholar Gorman published a study on plate wave acoustic emission (PWAE), which deepened researchers' understanding of Lamb waves and applied this theory more to acoustic emission monitoring. After PWAE, it is also known as modal acoustic emission (MAE). The MAE theory combines the physical mechanism of the acoustic emission source with the plate wave theory. The results show that this method is suitable for monitoring acoustic emission signals of thin sheet metal materials and thin-walled long pipe corrosion. Due to the typical characteristics of extended waves and bending waves, the waveform features are significantly different from noise, making it easy to identify the waveform of the corrosion signal.

The advantage of modal acoustic emission is that it requires fewer sensors and can be located using a single sensor. The limitations are that (1) it is necessary to identify the arrival time of the stretching wave and bending wave modes (which is not easy), as well as (2) separation of wave reflection and multiple AE events.

Jiao et al. [42] introduced a single-sensor sound source localization technique, which firstly predicted the dispersion characteristics of elastic waves in a thin plate by analyzing the modes of propagating elastic waves. Then, the Gabor wavelets were applied. The results showed that the arrival times of different modes can be determined from the peaks of wavelet transform amplitudes.

Ebrahimkhanlou et al. [43] adopted multimodal edge reflections to identify AE sources by estimating the distance between the AE source and a single transducer using the continuous wavelet transform and dispersion curves of the fundamental Lamb wave modes. This step used the MAE method. Then, an analytical model was proposed to simulate the waves reflected from the edges using the estimated distance. Finally, the

correlation between the experimental and simulated waveforms was utilized to estimate the location of the AE source. The method was applied to isotropic plates.

Roy [44] proposed a method to minimize the effects of geometry, boundaries and edges. The method was based on identifying the front of the time–frequency representation (TFR) plot of the AE signal, i.e., the first few high-energy regions in the TFR, and then aligning these regions according to the contours of the group velocity profile of the Lamb mode.

Jiang et al. [45] used the MAE method to characterize damage in a carbon fiber composite pressure vessel. Mostafapour et al. [46] proposed a method for continuous leakage source localization in inflatable pipelines and noisy environments using a single transducer and wavelet analysis and modal localization theory. Wang et al. [47] applied an optimized microfiber coupler sensor (MFCS) to acoustic source localization using an MAE method to apply an optimized microfiber coupler sensor (MFCS) to sound source localization. Fu et al. [48] used an MFCS in an improved modal analysis method for source localization. The method employed the least square error to reduce the dependence of the localization results on frequency selection and to automate the localization process for contour threshold modal analysis.

Zhang et al. [49] studied complex damage mechanisms and challenging identification of damage AE signals in carbon-fiber-reinforced composites (CFRP). They proposed a classification algorithm based on the modal separation method for the identification of CFRP damage signals, which provided a modal characterization of CFRP damage AE signals.

Aljets et al. [50] developed a new AE source localization method for large slabs that utilized a combination of time-of-flight and modal source localization algorithms to evaluate the location of sound sources.

3.5. Artificial Neural Networks

An artificial neural network is an operational model composed of a large number of interconnected nodes (or neurons). Artificial neural networks abstract the neural network of the human brain from the perspective of information processing, establish a simple model and form different networks according to different connection methods.

An artificial neural network (ANN) is a highly effective method for AE source localization. Its advantage is that it does not require knowledge of wave velocity and can be applied to anisotropic materials, but its disadvantage is that it requires a large amount of data and high computational requirements.

Determining the position and size of the acoustic emission source from the displacement field is a reverse problem, and Sribar and Sachse [51] and Kosel et al. [52] used artificial neural networks and pattern recognition techniques to solve this inverse problem. This method can not only estimate its location, but also estimate the strength of the source, but it has high computational requirements and requires repeated training.

Kim et al. [53] attempted AE localization in anisotropic plates with nails and small holes and isotropic aluminum plate pairs using the least squares support vector machine. The AE source was generated by breaking a pencil lead. The dimensions of the tested aluminum plates with holes were 900×900 mm^2, 600×600 mm^2 and 600×600 mm^2, while those of the anisotropic plate with a willow nail and holes were 600×600 mm^2. The thickness was 11.88 mm. The errors varied between 9.8 mm and 1.9 mm. The advantages of the method were that it avoided local minima and could be used on small samples and in nonlinear conditions. The disadvantage was that the method required a large amount of data for training. Subsequently, Yan et al. [54] utilized a Bayesian approach to sound source localization in clamped aluminum panels. They introduced a data fusion scheme combining the identification results obtained from arrival time difference data at different frequencies. They also improved the prediction accuracy, achieving a mean error of 2.74%. The disadvantages of this method were that the prediction accuracy was affected by frequency and it required a large amount of data, making it computationally intensive. Boniface et al. [55] used artificial neural networks to localize the sound source and compared the results to those of the time-based arrival difference-based localization

method. They found that the localization accuracy was improved by a factor of six. By increasing the amount of data for training, the AE localization accuracy was improved. Fu et al. [56] used a backpropagation artificial neural network for AE source localization from the data collected by a prismatically arranged sensor matrix on an anisotropic carbon fiber polymer plate (300 mm × 300 mm × 1.8 mm). They arranged a sensor array on an isotropic aluminum plate (300 mm × 300 mm × 4 mm) for a sound source localization test to verify the effectiveness of the algorithm, the localization accuracy of the method. Among a total of 21 test points, the error was large for only 5. The maximum error was 10.6 mm. For the anisotropic carbon fiber polymer plate, the maximum error was only 4.3 mm, and the test point of the maximum error was 6.4 mm.

Hesser et al. [57] utilized convolutional neural networks and deep transfer learning to identify AE source types. A pencil core break and a steel ball impact were used to excite an aluminum plate and collect a large amount of data. An artificial neural network, Conv1D, Conv2D-TF and Conv2D-TF off were used and the AE source type recognition results were compared.

Mirgal et al. [19] firstly used a time-of-arrival-based in-plane source (IPS) localization algorithm for AE sources with rectangular, circular and sawtooth sensor arrangements. Then, the PSO algorithm was adopted to localize the AE sources, which were excited by a pencil lead fracture on a concrete slab (1000 mm × 1000 mm) and the two algorithms are compared. The computational time of PSO was 1.23 s, whereas that of the IPS algorithm was 0.9 s. The IPS algorithm was superior to PSO in terms of algorithmic consistency. A rectangular sensor array produced better localization results. The maximum localization error of the IPS algorithm was 125 mm. Hamdi et al. [58] studied the acoustic source localization method in large reinforced concrete slabs and proposed an algorithm using a combination of time-of-flight and MAE source localization. Most of the algorithms for acoustic source localization assume that the algorithm is independent of the nature of the propagation medium, assuming that the propagation path is a straight line between the transducer and the source. Gollob et al. [59] proposed a method for acoustic source localization called Fastway, which accounted for discontinuities in material, including cracks and voids, and considered the fastest wave propagation path between source and the transducer, instead of the shortest (straight) path. The experiments demonstrated that the Fastway method determined the location of the sound source more accurately.

3.6. Time Reversal Technique

Time reversal technique is a commonly used sound source localization method in complex structures. It is closely related to artificial neural network computing. The steps of using time reversal technology for sound source localization are as follows: (1) collecting a training dataset by mechanically impacting multiple points on the structure and measuring the corresponding impulse response function (IRF) through one or more surface mount sensors; (2) recording the actual impact event signal on the sensor; and (3) identifying the IRF in the training dataset, which provides the maximum correlation with the IRF generated by the actual impact event, in order to determine the corresponding mechanical impact point.

The advantage of time reversal technology is that it can be used for positioning in complex structures, but the disadvantage is that the positioning process is complex and requires high computational requirements.

Kiri et al. [60] and Ribay et al. [61] proposed a method for sound source localization in inhomogeneous structures called the time inversion technique. Grabec and Sachse [62] also proposed a similar method for source localization by inverting the impact response function and avoiding wave mechanics analysis.

Qiu et al. [63] proposed an impact imaging method based on the time inversion technique and validated it for an aircraft wing box with bolt holes and reinforcements. Ciampa et al. [64] used a passive transducer and a time inversion technique for detecting the impact source location in reverberant complex composite structures in real time.

Park et al. [65] proposed a new impact imaging technique using the time inversion concept with surface mounted piezoelectric transducers and scanning laser Doppler vibrometer to pinpoint the location of impact events in a complex structure.

Wang et al. [66] utilized the virtual time reversal (VTR) technique to locate a continuous acoustic source in a cylindrical shell structure and an imaging technique to extract the wavelet transform coefficients of the AE signals at a specific frequency to construct a transient abrupt feature of the signals for further processing. They also provided an algorithm to determine the shortest path between the AE source and a sensor.

3.7. Zonal Location Based on Arrival Time

Using this method requires many single component sensors. These sensors are installed in appropriate locations that can effectively detect acoustic emission/microseismic (AE/MS) activity [67]. Then, based on the observed arrival time, velocity model and sensor coordinates, an arrival time function is established for each sensor. The following is the simplest form of this function:

$$\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = v(t_i - t)$$

The equation represents arrival time functions that assume a constant velocity model. And (x, y, z) are the source coordinates, (x_i, y_i, z_i) are the coordinates of the ith transducer, t_i is the arrival time at the ith transducer, v is the stress wave propagation velocity and i = 1, 2, …, N, …, M. ($M \geq N$). d. When M = N, we can determine the unknown precisely; when M > N, the problem becomes overdetermined and a regression method must be used for the optimum solution.

4. Acoustic Emission Source Localization Techniques for Three-Dimensional (3D) Structures

The localization of sound sources in three-dimensional structures is relatively complex and can be roughly divided into the following methods, as shown in Figure 9. The summary of three-dimensional acoustic emission source localization methods is shown in Table 1.

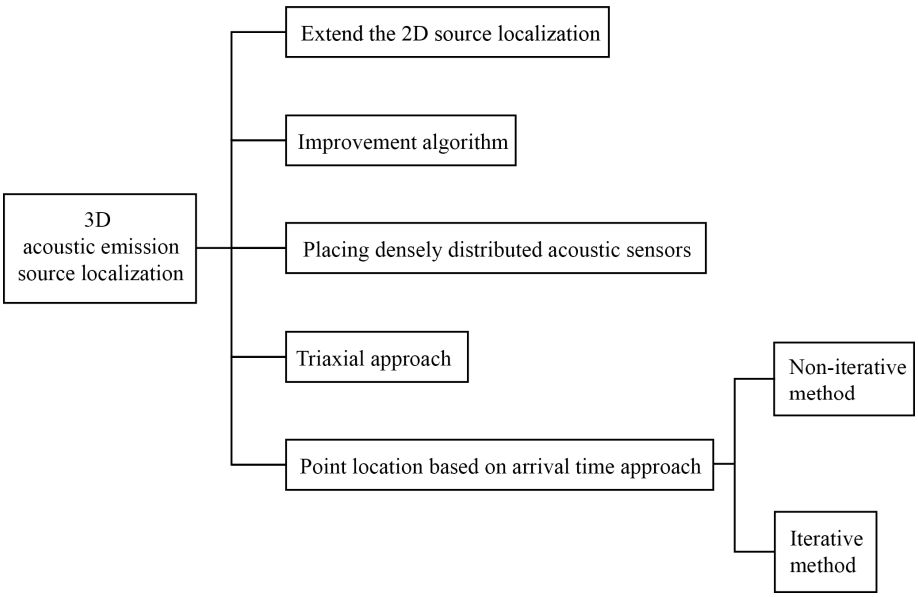


Figure 9. Method for 3D sound source localization.

4.1. Extend the Two-Dimensional Source Localization

The most classic two-dimensional positioning method is the time difference method. The time difference localization method in three-dimensional structures first assumes that the sound velocity is known and constant. By calculating the distance difference

between the sound source and each sensor, the spatial coordinates of the sound source are determined (Figure 10).

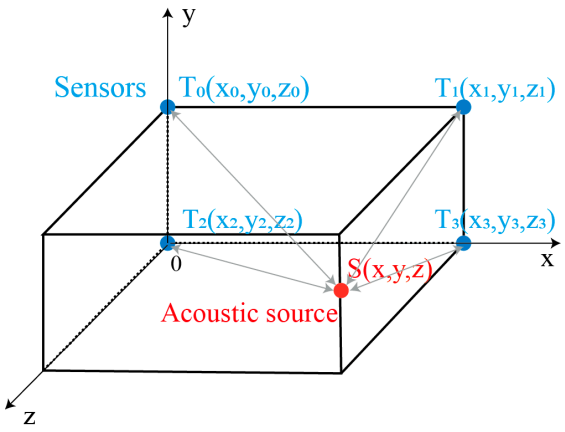


Figure 10. Time difference positioning method in three-dimensional structure.

Four sensors are located in the same plane (z = 0), and S is the position of the sound source. Assuming the coordinates of T_2 are (0, 0, 0), T_0 is $(x_0,\ y_0,\ z_0)$, T_1 is $(x_1,\ y_1,\ z_1)$, T_3 is $(x_3,\ y_3,\ z_3)$ and S is (x, y, z), the distance difference is:

$$\begin{aligned} |ST_0| - |ST_2| &= d_{02} \\ |ST_1| - |ST_2| &= d_{12} \\ |ST_3| - |ST_2| &= d_{32} \end{aligned}$$

Substitute the coordinates into the equation to obtain the system of Equation (1)

$$\begin{aligned} \sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} - \sqrt{x^2+y^2+z^2} &= d_{02} \\ \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - \sqrt{x^2+y^2+z^2} &= d_{12} \\ \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} - \sqrt{x^2+y^2+z^2} &= d_{32} \end{aligned}$$

Simplify to obtain Equation (2)

$$\begin{aligned} 2(x_0x+y_0y+z_0z) + 2d_{02}\sqrt{x^2+y^2+z^2} &= {x_0}^2+{y_0}^2+{z_0}^2-{d_{02}}^2 \\ 2(x_1x+y_1y+z_1z) + 2d_{12}\sqrt{x^2+y^2+z^2} &= {x_0}^2+{y_0}^2+{z_0}^2-{d_{12}}^2 \\ 2(x_3x+y_3y+z_3z) + 2d_{32}\sqrt{x^2+y^2+z^2} &= {x_0}^2+{y_0}^2+{z_0}^2-{d_{32}}^2 \end{aligned}$$

Obtain Equation (3) based on the distance formula between two points

$$\begin{aligned} {x_0}^2+{y_0}^2+{z_0}^2-{d_{02}}^2 &= 2d_0 \\ {x_1}^2+{y_1}^2+{z_1}^2-{d_{12}}^2 &= 2d_1 \\ {x_3}^2+{y_3}^2+{z_3}^2-{d_{32}}^2 &= 2d_3 \end{aligned}$$

Compare the two equations in Equation (2) and substitute Equation (3) into Equation (2) to obtain Equation (4)

$$\begin{aligned} \frac{x_0x+y_0y+z_0z-d_0}{x_1x+y_1y+z_1z-d_1} &= c_{01} \\ \frac{x_0x+y_0y+z_0z-d_0}{x_3x+y_3y+z_3z-d_3} &= c_{03} \end{aligned}$$

Simplify Equation (4) to obtain Equation (5)

$$\begin{aligned} (x_0-c_{01}x_1)x + (y_0-c_{01}y_1)y + (z_0-c_{01}z_1)z - d_0 + c_{01}d_1 &= 0 \\ (x_0-c_{03}x_3)x + (y_0-c_{03}y_3)y + (z_0-c_{03}z_3)z - d_0 + c_{03}d_3 &= 0 \end{aligned}$$

Substitute the initial condition z_0 = z1 = z_3 = 0 to obtain the coordinates of the sound source

$$x = \frac{(d_0 - c_{01}d_1)(y_0 - c_{03}y_3) - (d_0 - c_{03}d_3)(y_0 - c_{01}y_1)}{(x_0 - c_{01}x_1)(y_0 - c_{03}y_3) - (x_0 - c_{03}x_3)(y_0 - c_{01}y_1)}$$

$$y = \frac{(d_0 - c_{01}d_1)(x_0 - c_{03}x_3) - (d_0 - c_{03}d_3)(x_0 - c_{01}x_1)}{(y_0 - c_{01}y_1)(x_0 - c_{03}x_3) - (y_0 - c_{03}y_3)(x_0 - c_{01}x_1)}$$

$$z = \sqrt{\left[\frac{d_0 - (x_0 x + y_0 y)}{d_{02}}\right]^2 - (x^2 + y^2)}$$

A. Carpinteri et al. [68] used multiple sensors to localize the damage location in reinforced concrete beams was based on the time difference method, where the time difference recorded by multiple sensors was used to localize the damage location (Figure 11). Subsequently, an improved AIC method was proposed by A. Carpinteri et al. [69]. The improved AIC (Akaike Information Criterion) method was successfully applied to AE detection during a three-point bending test of a fiber-reinforced concrete beam to analyze the crack pattern. Experiments have shown that the deviations in the results obtained by the improved method ranged from 3% to 4% from the correct results (Figure 12).

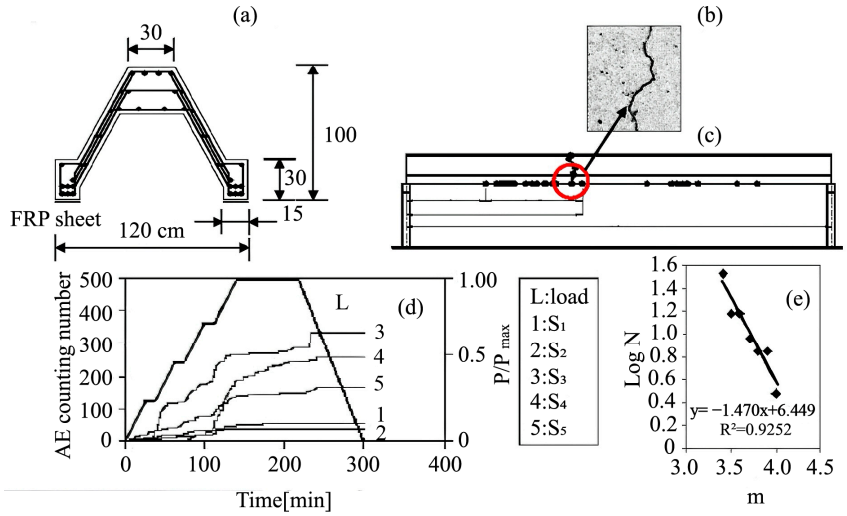


Figure 11. In situ retrofitted RC beam test. (**a**) Scheme of the beam cross-section. (**b**) Photo of a flexural crack in between transducers 3 and 4 (using an optical microscopy with magnification 100×). (**c**) Scheme of the beam indicating localized AE sources. (**d**) AE counting number for each sensor Si during the loading test. (**e**) The b-value during the loading test.

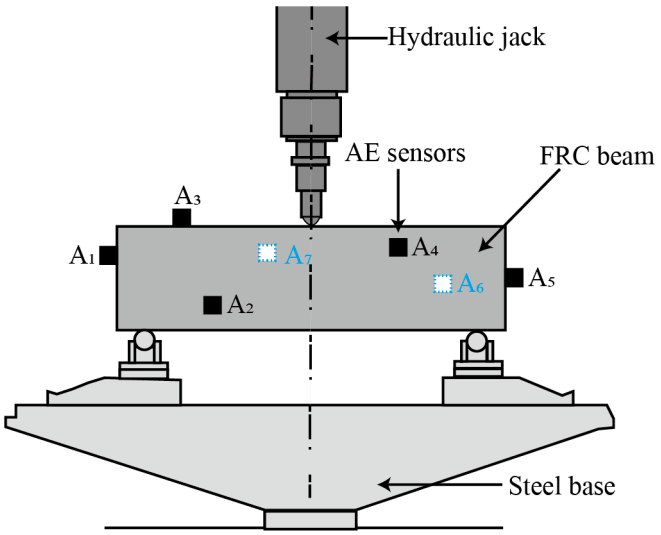


Figure 12. 3D structural sound source localization based on AIC.

Baxter, M. G. et al. [70] proposed a new method for locating artificial acoustic emission sources (named the H-N source [71]) based on the time difference method, called "Delta T" source location. This method does not require knowledge of the sensor location or wave spread. Compared with traditional TOA source location methods, this method had significant improvements, reducing the positioning error from 4.81% using traditional time of arrival (TOA) technology to 1.77% using "Delta T" location. Ting et al. [72] localized acoustic sources in cylindrical coal samples in this manner.

Dong and Li [73] simplified the source localization in three-dimensional bodies by placing sensors at selected corner points of a cube and then deriving an analytical expression for source localization (Figure 13).

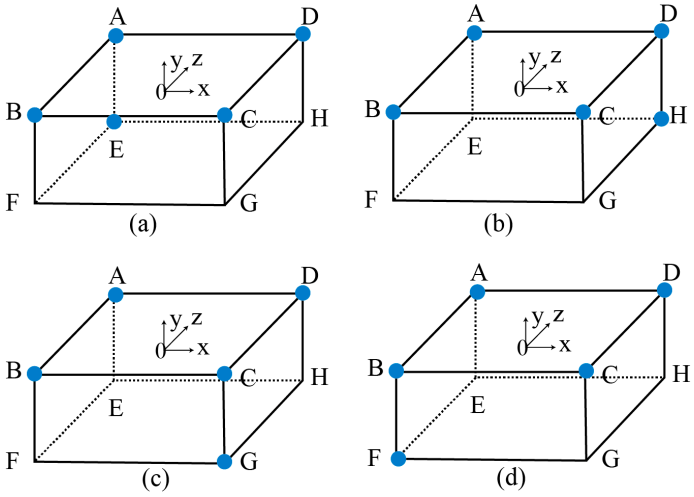


Figure 13. Schematic of three-dimensional location of cube monitoring network: (**a**) AE sensors at A, B, C, D, E; (**b**) AE sensors at A, B, C, D, H; (**c**) AE sensors at A, B, C, D, G; (**d**) AE sensors at A, B, C, D, F.

Yin et al. [74] proposed a positioning method for a right-angle tetrahedral sensor cluster. Combining the spatial information of the sensor cluster, the acoustic emission source was located by collecting the time difference of arrival of the first wave between different sensors. This method can be applied to anisotropic materials and requires fewer sensors.

There are also some two-dimensional methods that can be applied to three-dimensional positioning, for example, establishing the objective equation of the error function [75] for localization methods, using iterative algorithms to locate the acoustic emission source from the information collected by the sensor array [76,77], three-dimensional beam forming localization methods [78–84], etc.

Beam forming is a commonly used method in two-dimensional positioning. However, especially in the past few years, there has been an increasing trend in exploring the possibility of calculating beam forming results in three-dimensional space, but most of them are focused on locating noise sources in space [85–91]. These methods provide reference for the application of beam forming technology in three-dimensional acoustic emission source localization.

4.2. Improvement Algorithm

Gollob et al. [59] proposed a new acoustic source localization method, FastWay, which used the fastest rather than the shortest propagation path between the source and each sensor to localize the AE source. This algorithm performs sound source localization by improving the traditional Dijkstra algorithm (shortest path algorithm). The method was more accurate and reliable than the conventional acoustic source localization methods. This method requires 12 sensors and is suitable for anisotropic materials.

Kocur et al. [92] proposed a three-dimensional positioning method for reinforced concrete beams called time reverse modeling (TRM), and confirmed the accuracy of the results by obtaining three-dimensional crack distribution through X-ray computed tomography.

Kobayashi et al. [93] proposed a three-dimensional AE tomography algorithm for locating three-dimensional structures. The method was verified by numerical investigations.

Zhou et al. [94] proposed a new algorithm for three-dimensional sound source localization. According to sensor coordinates, the arrival time of acoustic waves, the velocities of acoustic waves in two kinds of media, the space–time relation equations of the AE source point and the measuring point were established by the precise coordinates of the AE source based on Snell's law.

4.3. Placing Densely Distributed Acoustic Sensors on the Structure

Bi [95] proposed a method that combines the analysis passive time reversal method (APTRM) with the equivalent sound source method (ESM) for locating sound sources in arbitrarily shaped shells. An experiment was conducted in a rectangular wooden cabinet using a spherical array of 48 microphones. This method can only locate sound sources with frequencies above 1000 Hz.

4.4. Triaxial Sensor Approach

The idea of this method is that if the spatial position of a point is known, then the spatial positioning of any other point can be represented by its relative distance and azimuth to the known point [96]. Source S is to be determined in terms of its relative distance, d, and its azimuth (α, β, γ).

The relative distance can be expressed as:

$$d = \frac{v_p v_s}{v_p - v_s}(t_s - t_p)$$
$$\alpha = (\cos l)^{-1},\ \beta = (\cos m)^{-1}, \gamma = (cos p)^{-1}$$
$$l = \frac{A_x}{A},\ m = \frac{A_y}{A}, p = \frac{A_z}{A}$$
$$A = \sqrt{{A_x}^2 + {A_y}^2 + {A_z}^2}$$

where d is the distance from the source to the sensor, v_p and v_s are the velocities of P-and S-waves, and t_p and t_s are the arrival times of P- and S-waves. The relative azimuth (α, β, γ) can be determined by the amplitude of the received signals, assuming that A_x, A_y and A_z are the amplitudes of three mutually orthogonal components of the signal, where l, m and p are the direction cosines of the signal relative to the sensor.

The triaxial sensor approach requires fewer sensors, and for deep applications it can reduce the number of boreholes, resulting in significant cost savings. This method has been used in various deep applications, such as rock burst research, the stability of oil reserve sites and geothermal engineering. This method also has two technical advantages. Firstly, as this method uses both P-waves and S-waves to reach, it improves the stability of the source position solutions for these external array events. Secondly, it allows people to analyze the ground motion status of sensor locations, which is crucial for studying event magnitude and source mechanisms.

The main technical issue with this method is the stability of the azimuth angle, as amplitude is more sensitive to material properties and structure than travel time.

4.5. Point Location Based on Arrival Time Approach

Using this method requires many single component sensors. These sensors are installed in appropriate locations that can effectively detect acoustic emission/microseismic (AE/MS) activity. Then, based on the observed arrival time, velocity model and sensor

coordinates, an arrival time function is established for each sensor. The following is the simplest form of this function:

$$\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = v(t_i - t) \quad (1)$$

where the unknowns, x, y and z are the coordinates of the source, t is the origin time of the event, x_i, y_i and z_i are the coordinates of the ith transducer, t_i is the arrival time at the ith transducer, v is stress wave propagation velocity and i = 1, 2, . . ., N, . . ., M.

When M > N, the problem becomes overdetermined and a regression method has to be used for the optimum solution.

When solving this nonlinear equation, it can be solved iteratively or non-iteratively. So, based on the type of equation being solved, point location can be divided into non-iterative methods and iterative methods.

Non iterative methods include USBM [97,98] and Inglada [99], while non-iterative methods include Geiger [100,101], Thurber [102] and Simplex [103]. Ge [67,77] provided a systematic review of iterative and non-iterative methods.

4.5.1. The USBM Method

This method was developed by researchers from the United States Bureau of Mines (USBM) in the early 1970s. The development of this method was part of the mining bureau's efforts to make acoustic emission/microseismic (AE/MS) technology an effective engineering tool for determining the stability of rock structures. This method was first published in 1970 and further revised in 1972 [97,98]. Since then, it has become the primary AE/MS source localization method used in North America for mines.

The algorithm is as follows:

Let D_i represent the distance from the source to the ith transducer,

$$D_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = v(t_i - t)$$
$$D_i - D_1 = v(t_i - t_1)$$

where i = 2, 3, . . ., m. Squaring and simplifying the above equation, this yields

$$d_i + \frac{e_i}{d_i} - \frac{2(a_i x + b_i y + c_i z)}{d_i} = -2D_i \quad (2)$$

$$a_i = x_1 - x_i$$
$$b_i = y_1 - y_i$$
$$c_i = z_1 - z_i$$
$$d_i = v(t_i - t_1)$$
$$e_i = {x_1}^2 + {y_1}^2 + {z_1}^2 - ({x_i}^2 + {y_i}^2 + {z_i}^2)$$

The non-linear system defined by (2) can be linearized by subtracting the second equation from the rest of them. This process yields

$$f_{i,1}x + f_{i,2}y + f_{i,3}z = h_i + g_i v^2 \quad (3)$$

where

$$f_{i,1} = 2(\tfrac{a_2}{t_2} - \tfrac{a_i}{t_i})$$
$$f_{i,2} = 2(\tfrac{b_2}{t_2} - \tfrac{b_i}{t_i})$$
$$f_{i,3} = 2(\tfrac{c_2}{t_2} - \tfrac{c_i}{t_i})$$
$$g_i = t_2 - t_i$$
$$h_i = \tfrac{e_2}{t_2} - \tfrac{e_i}{t_i}$$
$$i = 3,\ 4, \ldots, m.$$

Equation (3) defines a linear system.

In matrix notation, the linear system defined by Equation (3) can be written as

$$Ax = b$$

where

$$A = \begin{bmatrix} f_{3,1} & f_{3,2} & f_{3,3} \\ \vdots & & \vdots \\ f_{m,1} & f_{m,2} & f_{m,3} \end{bmatrix},\ x = \begin{bmatrix} x \\ y \\ z \end{bmatrix},\ b = \begin{bmatrix} h_3 + g_3 v^2 \\ \vdots \\ h_m + g_m v^2 \end{bmatrix}$$

4.5.2. Inglada's Method

This method is most suitable for simple source location problems, where the minimum number of sensors used can be assumed to be a constant velocity model [99].

The algorithm is as follows:

$$(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = v^2(t_i - t)^2 \tag{4}$$

for i = 1, 2, 3 and 4, and then the system is linearized by subtracting the first equation from the three remaining ones, which yields:

$$a_i x + b_i y + c_i z = e_i + f_i t \tag{5}$$

where

$$\begin{gathered} a_i = x_i - x_1 \\ b_i = y_i - y_1 \\ c_i = z_i - z_1 \\ e_i = 0.5({R_i}^2 - {R_1}^2 - v^2({t_i}^2 - {t_1}^2)) \\ f_i = v^2(t_i - t_1) \end{gathered}$$

And

$$\begin{gathered} {R_i}^2 = {x_i}^2 + {y_i}^2 + {z_i}^2 \\ {R_1}^2 = {x_1}^2 + {y_1}^2 + {z_1}^2 \end{gathered}$$

for i = 2, 3 and 4.

Three linear equations defined in (5) can be solved for x, y and z in terms of t by using Cramer's rule. The solution is as follows:

$$x = \frac{M_1 + N_1 t}{D},\ y = \frac{M_2 + N_2 t}{D},\ z = \frac{M_3 + N_3 t}{D} \tag{6}$$

where D is the determinant given by

$$D = \begin{bmatrix} a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \\ a_4 & b_4 & c_4 \end{bmatrix}$$

M_j and N_j, for j = 1, 2, 3, are also the determinants. They are similar to D, but with the jth column of D replaced by $(e_2,\ e_3,\ e_4)$ and $(f_2,\ f_3,\ f_4)$, respectively.

Substitute three equations defined in (6) back to one of the equations defined in (4). Since x, y and z in (6) are all expressed in terms of t, this back substitution yields a second order equation of t with the form

$$At^2 + Bt + C = 0 \tag{7}$$

where A, B and C are constants.

Equation (7) is a quadratic function of t and there are two solutions, say, t_{01} and t_{02}. Substituting t_{01} and t_{02} into Equation (6), the corresponding solutions are $(x_{01},\ y_{01},\ z_{01},\ t_{01})$ and $(x_{02},\ y_{02},\ z_{02},\ t_{02})$, respectively.

4.5.3. Geiger's Method

Geiger's method uses the first derivative to capture the nonlinear behavior of the arrival time function at the trial solution. Geiger's method was developed at the beginning of the last century and is a classic source localization method for all accounts [100,101]. In addition to its long history, this method is the most famous and widely used source localization method. In seismology, it is almost universally used for local earthquake localization.

4.5.4. Thurber's Method

Thurber's method is an important derivative method that uses information from the first and second derivatives to determine the correction vector [102]. Thurber's method is a more complex derivative method than Geiger's method because it utilizes a quadratic model for optimization.

4.5.5. Simplex Method

The simplex method is a sound source localization method that searches for the minimum value of a mathematical function through function comparison [103]. The starting point of the simplex method is that for a given arrival time related to a set of sensors, the error at any point can be calculated by comparing the observed and calculated arrival times.

The simplex method is an important source localization method. Due to its unique iterative method, divergence is impossible. This gives this method a significant advantage over derivative methods. Another major advantage of this method is its flexibility in handling complex velocity models. Unlike the derivative methods, which require the establishment of an arrival time function before analysis, the arrival time function used in the simplex method can be established during data processing, which is a necessary condition for dealing with many complex problems.

Table 1. Three-dimensional sound source localization methods.

Author	Methods/Models	Material	Number of Sensors	Performance Index (Unit)	Value
Carpinteri 2006 [68]	Measuring time delays	RC beam	5	—	—
Carpinteri 2012 [69]	Akaike Information Criterion (AIC)	Fiber RC beam	7	Location error (%)	3~4
Baxter 2007 [70]	"Delta T" source location	An aircraft component	4	Location error (%)	1.77
Dong and Li 2012 [73]	Analytical method	Rod of granite rock	5	Location error (m)	0.01–0.03
Yin 2020 [74]	Rapid acoustic source localization technique	Aluminum cubes and iron cubes	4	Mean error (%)	9.17
Gollob 2021 [59]	FastWay	Reinforced concrete beam	12	Average location error (mm)	4
Kocur 2012 [92]	The time reverse modeling (TRM)	Reinforced concrete beam	8	—	—
Kobayashi 2014 [93]	Ray-trace technique	Numerical investigations	8	Location error (%)	10
Zhou 2017 [94]	The spatiotemporal relationship equation of acoustic emission source	Granite and iron	4	Average absolute error (mm)	<1.5
Bi 2019 [95]	APTRM combined with ESM	A rectangular wooden cabinet	48	Location error (m)	0.05

5. Conclusions

Through the continuous efforts of several generations of researchers, the localization technology for acoustic emission sources has continuously improved and achieved many results.

It is worth mentioning that there are several directions worth noting in future research.

1. Research on sound source localization for two-dimensional anisotropic materials, as materials in practical engineering are often anisotropic.
2. Research on sound source localization in three-dimensional structures. Currently, there is not much research on three-dimensional sound emission source localization, mainly due to the complexity of three-dimensional structures, difficulties in localization work, the large computational complexity and the need for multiple sensors.
3. Paying attention to the processing of noise signals, as noise is the main cause of errors.
4. Machine learning and many existing algorithms in the field of computer science have enormous potential in three-dimensional sound source localization.

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References

1. Tobias, A. Acoustic-emission source location in two dimensions by an array of three sensors. *Non Destr. Test.* **1976**, *9*, 9–12. [CrossRef]
2. Sachse, W.; Sancar, S. Acoustic Emission Source Location on Plate-Like Structures Using a Small Array of Transducers. U.S. Patent No. 4,592,034, 27 May 1986.
3. Shen, Y. (Ed.) *Modern Nondestructive Testing Technology*; Xi'an Jiaotong University Press: Xi'an, China, 2012.
4. Ma, Y. Normalized square array acoustic emission localization method. *Eng. Exp.* **1983**.
5. Sen, N.; Kundu, T. A new signal energy-based approach to acoustic source localization in orthotropic plates: A numerical study. *Mech. Syst. Signal Process.* **2022**, *171*, 108843. [CrossRef]
6. Liang, D.; Yuan, S.; Liu, M. Distributed coordination algorithm for impact location of preciseness and real-time on composite structures. *Measurement* **2013**, *46*, 527–536. [CrossRef]
7. Hu, Q.; Dong, L. Acoustic Emission Source Location and Experimental Verification for Two-Dimensional Irregular Complex Structure. *IEEE Sens. J.* **2020**, *20*, 2679–2691. [CrossRef]
8. Sen, N.; Gawroński, M.; Packo, P. Square-shaped sensor clusters for acoustic source localization in anisotropic plates by wave front shape-based approach. *Mech. Syst. Signal Process.* **2021**, *153*, 107489. [CrossRef]
9. Haywood-Alexander, M.; Dervilis, N.; Worden, K. Informative Bayesian tools for damage localisation by decomposition of Lamb wave signals. *J. Sound Vib.* **2022**, *535*, 117063. [CrossRef]
10. Zhou, Z.; Cui, Z.; Yin, S. A rapid acoustic source localization technique for early warning of building material damage. *Constr. Build. Mater.* **2022**, *325*, 126840. [CrossRef]
11. Li, D.; Nie, J.-H.; Ren, W.-X. A novel acoustic emission source location method for crack monitoring of orthotropic steel plates. *Eng. Struct.* **2022**, *253*, 113717. [CrossRef]
12. Al-Jumaili, S.K.; Pearson, M.R.; Holford, K.M. Acoustic emission source location in complex structures using full automatic delta T mapping technique. *Mech. Syst. Signal Process.* **2016**, *72–73*, 513–524. [CrossRef]
13. Cantero-Chinchilla, S.; Chiachío, J.; Chiachío, M. A robust Bayesian methodology for damage localization in plate-like structures using ultrasonic guided-waves. *Mech. Syst. Signal Process.* **2019**, *122*, 192–205. [CrossRef]
14. Zhao, Z.; Chen, N.-Z. Acoustic emission based damage source localization for structural digital twin of wind turbine blades. *Ocean Eng.* **2022**, *265*, 112552. [CrossRef]
15. Jones, M.R.; Rogers, T.J.; Worden, K.A. Bayesian methodology for localising acoustic emission sources in complex structures. *Mech. Syst. Signal Process.* **2022**, *163*, 108143. [CrossRef]

16. Zargar, S.A.; Yuan, F.-G. Impact diagnosis in stiffened structural panels using a deep learning approach. *Struct. Health Monit.* **2021**, *20*, 681–691. [CrossRef]
17. Hao, W.; Huang, Y.; Zhao, G. Acoustic sources localization for composite pate using arrival time and BP neural network. *Polym. Test.* **2022**, *115*, 107754. [CrossRef]
18. Jang, B.-W.; Kim, C.-G. Impact localization of composite stiffened panel with triangulation method using normalized magnitudes of fiber optic sensor signals. *Compos. Struct.* **2019**, *211*, 522–529. [CrossRef]
19. Mirgal, P.; Pal, J.; Banerjee, S. Online acoustic emission source localization in concrete structures using iterative and evolutionary algorithms. *Ultrasonics* **2020**, *108*, 106211. [CrossRef]
20. Feng, B.; Ribeiro, A.L.; Pasadas, D.J. Locating Low Velocity Impacts on a Composite Plate Using Multi-Frequency Image Fusion and Artificial Neural Network. *J. Nondestruct. Eval.* **2022**, *41*, 34. [CrossRef]
21. McLaskey, G.C.; Glaser, S.D.; Grosse, C.U. Beamforming array techniques for acoustic emission monitoring of large concrete structures. *J. Sound Vib.* **2010**, *329*, 2384–2394. [CrossRef]
22. He, T.; Xiao, D.; Pan, Q. Analysis on accuracy improvement of rotor–stator rubbing localization based on acoustic emission beamforming method. *Ultrasonics* **2014**, *54*, 318–329. [CrossRef]
23. Hamid, U.; Qamar, R.A.; Waqas, K. Performance Comparison of Time-Domain and Frequency-Domain Beamforming Techniques for Sensor Array Processing. In Proceedings of the 11th International Bhurban Conference on Applied Sciences & Technology (IBCAST), Islamabad, Pakistan, 14–18 January 2014.
24. Chen, B.; Wang, G.; Liu, X. Acoustic emission beam forming defect localization of thin plate parts of mechanical equipment. *Agric. Equip. Veh. Eng.* **2023**, *61*, 64–68+74.
25. Han, Z. *Research on Robot Sound Source Localization Method Based on Beamformation*; Tongfang Knowledge Network (Beijing) Technology Co., Ltd.: Beijing, China, 2022.
26. Liang, T.; Yang, B.; Zhu, M. Uniform square matrix virtual primitive localization method based on beam forming. *J. Instrum.* **2021**, *42*, 266–274.
27. Tai, J.; He, T.; Pan, Q. A fast beamforming method to localize an acoustic emission source under unknown wave speed. *Materials* **2019**, *12*, 735. [CrossRef]
28. Matt, H.M.; di Scalea, F.L. Macro-fiber composite piezoelectric rosettes for acoustic source location in complex structures. *Smart Mater. Struct.* **2007**, *16*, 1489. [CrossRef]
29. 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]
30. Langenberg, K.J.; Berger, M.; Kreutter, T.; Mayer, K.; Schmitz, V. Synthetic aperture focusing technique signal processing. *NDT Int.* **1986**, *19*, 177–189. [CrossRef]
31. Ciampa, F.; Meo, M. A new algorithm for acoustic emission localization and flexural group velocity determination in anisotropic structures. *Compos. Part A Appl. Sci. Manuf.* **2010**, *41*, 1777–1786. [CrossRef]
32. Ciampa, F.; Meo, M.; Barbieri, E. Impact localization in composite structures of arbitrary cross section. *Struct. Health Monit.* **2012**, *11*, 643–655. [CrossRef]
33. 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]
34. Aljets, D.; Chong, A.; Wilcox, S. Acoustic Emission Source Location in Plate-Like Structures Using A Closely Arranged Triangular Sensor Array. *J. Acoust. Emiss.* **2010**, *28*, 85–98.
35. Jiang, S.; Shen, Y.; Wang, S. The Effect of Piezoelectric Fiber Rosette Configurations on Lamb Wave Direction Detection for Damage Localization. *J. Sens.* **2021**, *2021*, 9918049. [CrossRef]
36. Kundu, T. A new technique for acoustic source localization in an anisotropic plate without knowing its material properties. In Proceedings of the 6th European Workshop on Structural Health Monitoring, Dresden, Germany, 3–6 July 2012.
37. Kundu, T.; Nakatani, H.; Takeda, N. Acoustic source localization in anisotropic plates. *Ultrasonics* **2012**, *52*, 740–746. [CrossRef] [PubMed]
38. Kundu, T.; Yang, X.; Nakatani, H. A two-step hybrid technique for accurately localizing acoustic source in anisotropic structures without knowing their material properties. *Ultrasonics* **2015**, *56*, 271–278. [CrossRef] [PubMed]
39. Nakatani, H.; Kundu, T.; Takeda, N. Improving accuracy of acoustic source localization in anisotropic plates. *Ultrasonics* **2014**, *54*, 1776–1788. [CrossRef]
40. Koabaz, M.; Hajzargarbashi, T.; Kundu, T. Locating the acoustic source in an anisotropic plate. *Struct. Health Monit.* **2012**, *11*, 315–323. [CrossRef]
41. Park, W.; Packo, P.; Kundu, T. Acoustic source localization in an anisotropic plate without knowing its material properties: A new approach. In Proceedings of the SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, Las Vegas, NV, USA, 20–24 March 2016.
42. Jiao, J.; He, C.; Wu, B.; Fei, R.; Wang, X. Application of wavelet transform on modal acoustic emission source location in thin plates with one sensor. *Int. J. Press. Vessel. Pip.* **2004**, *81*, 427–431. [CrossRef]
43. Ebrahimkhanlou, A.; Salamone, S. Acoustic emission source localization in thin metallic plates: A single-sensor approach based on multimodal edge reflections. *Ultrasonics* **2017**, *78*, 134–145. [CrossRef]

44. Roy, P.; Datta, A.K.; Topdar, P. A study on the efficacy of modal acoustic emission technique for health monitoring of structures with different geometries. *Nondestruct. Test. Eval.* **2023**, *39*, 846–885. [CrossRef]
45. Jiang, P.; Liu, X.; Li, W.; Guo, F.; Hong, C.; Liu, Y.; Yang, C. Damage Characterization of Carbon Fiber Composite Pressure Vessels Based on Modal Acoustic Emission. *Materials* **2022**, *15*, 4783. [CrossRef]
46. Mostafapour, A.; Davoodi, S. Continuous leakage location in noisy environment using modal and wavelet analysis with one AE sensor. *Ultrasonics* **2015**, *62*, 305–311. [CrossRef]
47. Wang, L.; Liu, Y.; Fu, W.; Li, F.; Zhao, Z.; Yu, K. Source location using an optimized microfiber coupler sensor based on modal acoustic emission method. *Struct. Control Health Monit.* **2017**, *24*, e2011. [CrossRef]
48. Fu, W.; Liu, Y.; Wang, L.; Wang, X. Minimum Squared Error Method based on Modal Analysis for Acoustic Emission Source Location using Microfiber Coupler Sensor. *Measurement* **2023**, *220*, 113406. [CrossRef]
49. Zhang, H.; Jiang, P.; Song, J. Identification of damage mechanisms in carbon fiber reinforced composites based on modal acoustic emission. *Compos. Sci. Eng.* **2021**, 11–17.
50. Aljets, D.; Chong, A.; Wilcox, S.; Holford, K. Acoustic emission source location on large plate-like structures using a local triangular sensor array. *Mech. Syst. Signal Process.* **2012**, *30*, 91–102. [CrossRef]
51. Sribar, R.; Sachse, W. An experimental investigation of the AE source location and magnitude on 2-D frame structures using intelligent signal processing. *J. Acoust. Soc. Am.* **1993**, *93 Pt 2*, 2279. [CrossRef]
52. Kosel, T.; Grabec, I.; Muzic, P. Location of acoustic emission sources generated by air flow. *Ultrasonics* **2000**, *38*, 824–826. [CrossRef]
53. Kim, K.-R.; Lee, Y.-S. Acoustic emission source localization in plate-like structures using least-squares support vector machines with delta t feature. *J. Mech. Sci. Technol.* **2014**, *28*, 3013–3020. [CrossRef]
54. Yan, G.; Tang, J. A Bayesian Approach for Localization of Acoustic Emission Source in Plate-Like Structures. *Math. Probl. Eng.* **2015**, *2015*, 247839. [CrossRef]
55. Boniface, A.; Saliba, J.; Sbartaï, Z.M. Evaluation of the acoustic emission 3D localisation accuracy for the mechanical damage monitoring in concrete. *Eng. Fract. Mech.* **2020**, *223*, 106742. [CrossRef]
56. Fu, T.; Zhang, Z.; Liu, Y.; Leng, J. Development of an artificial neural network for source localization using a fiber optic acoustic emission sensor array. *Struct. Health Monit.* **2015**, *14*, 168–177. [CrossRef]
57. Hesser, D.F.; Mostafavi, S.; Kocur, G.K.; Markert, B. Identification of acoustic emission sources for structural health monitoring applications based on convolutional neural networks and deep transfer learning. *Neurocomputing* **2021**, *453*, 1–12. [CrossRef]
58. Hamdi, S.E.; Sbartaï, Z.M.; Boniface, A.; Saliba, J.; Henault, J.M. Pressure-induced damage monitoring in prestressed concrete of nuclear containment wall segments using acoustic emission technique—Application to VeRCoRs containment building. *Eng. Fract. Mech.* **2023**, *281*, 109089. [CrossRef]
59. Gollob, S.; Kocur, G.K.; Schumacher, T.; Mhamdi, L.; Vogel, T. A novel multi-segment path analysis based on a heterogeneous velocity model for the localization of acoustic emission sources in complex propagation media. *Ultrasonics* **2017**, *74*, 48–61. [CrossRef]
60. Kiri, R.; Quieffin, N.; Catheline, S.; Fink, M. In solid localization of finger impacts using acoustic time-reversal process. *Appl. Phys. Lett.* **2005**, *87*, 204104.
61. Ribay, G.; Catheline, S.; Clorennec, D.; Ing, R.K.; Quieffin, N.; Fink, M. Acoustic impact localization in plates: Properties and stability to temperature variation. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2007**, *54*, 378–385. [CrossRef]
62. Grabec, I.; Sachse, W. Application of an intelligent signal processing system to acoustic emission analysis. *J. Acoust. Soc. Am.* **1989**, *85*, 1226–1235. [CrossRef]
63. Qiu, L.; Yuan, S.; Zhang, X.; Wang, Y. A time reversal focusing based impact imaging method and its evaluation on complex composite structures. *Smart Mater. Struct.* **2011**, *20*, 105014. [CrossRef]
64. Ciampa, F.; Meo, M. Impact detection in anisotropic materials using a time reversal approach. *Struct. Health Monit.* **2011**, *11*, 43–49. [CrossRef]
65. Park, B.; Sohn, H.; Olson, S.E.; DeSimio, M.P.; Brown, K.S.; Derriso, M.M. Impact localization in complex structures using laser-based time reversal. *Struct. Health Monit.* **2012**, *11*, 577–588. [CrossRef]
66. Wang, S.; Wang, H.; Wang, D.; Wang, J.; Zhang, W.; Hong, J.; Gao, L. AE source localization and imaging on cylindrical shell structures based on six-AE-sensor monitoring network and VTR focusing imaging. *Nondestruct. Test. Eval.* **2021**, *36*, 35–61. [CrossRef]
67. Ge, M. Analysis of Source Location Algorithms, Part I: Overview and Non-Iterative Methods. *J. Acoust. Emiss.* **2003**, *21*, 14–28.
68. Carpinteri, A.; Lacidogna, G.; Niccolini, G. Critical behaviour in concrete structures and damage localization by acoustic emission. *Key Eng. Mater.* **2006**, *312*, 305–310. [CrossRef]
69. Carpinteri, A.; Xu, J.; Lacidogna, G.; Manuello, A. Reliable onset time determination and source location of acoustic emissions in concrete structures. *Cem. Concr. Compos.* **2012**, *34*, 529–537. [CrossRef]
70. Baxter, M.G.; Pullin, R.; Holford, K.M.; Evans, S.L. Delta T source location for acoustic emission. *Mech. Syst. Signal Process.* **2007**, *21*, 1512–1520. [CrossRef]
71. Hsu, N.N.; Brecknbridge, F.R. Characterization and calibration of acoustic emission sensors. *Mater. Eval.* **1979**, *39*, 60–68.

72. Ting, A.; Ru, Z.; Jianfeng, L.; Li, R. Space–time evolution rules of acoustic emission location of unloaded coal sample at different loading rates. *Int. J. Min. Sci. Technol.* **2012**, *22*, 847–854. [CrossRef]
73. Dong, L.-J.; Li, X.-B. Three-dimensional analytical solution of acoustic emission or microseismic source location under cube monitoring network. *Trans. Nonferrous Met. Soc. China* **2012**, *22*, 3087–3094. [CrossRef]
74. Yin, S.; Xiao, H.; Cui, Z.; Kundu, T. Rapid localization of acoustic source using sensor clusters in 3D homogeneous and heterogeneous structures. *Struct. Health Monit.* **2020**, *20*, 1145–1155. [CrossRef]
75. Kundu, T. Acoustic source localization. *Ultrasonics* **2014**, *54*, 25–38. [CrossRef]
76. So, H.C. *Source Localization: Algorithms and Analysis*; Zekavat, R., Buehrer, R.M., Eds.; The Institute of Electrical and Electronics Engineers, Inc.: Piscataway, NJ, USA, 2019.
77. Ge, M. Analysis of source location algorithms: Part II. Iterative Methods. *J. Acoust. Emiss.* **2003**, *21*, 29–51.
78. Song, H.C.; Cho, C. Array invariant-based source localization in shallow water using a sparse vertical array. *J. Acoust. Soc. Am.* **2017**, *141*, 183–188. [CrossRef] [PubMed]
79. Chen, J.C.; Yao, K.; Hudson, R.E. Acoustic Source Localization and Beamforming: Theory and Practice. *EURASIP J. Adv. Signal Process.* **2003**, *2003*, 926837. [CrossRef]
80. Dmochowski, J.P.; Benesty, J. Steered Beamforming Approaches for Acoustic Source Localization. In *Speech Processing in Modern Communication*; Springer: Berlin/Heidelberg, Germany, 1970.
81. Castellini, P.; Sassaroli, A. Acoustic source localization in a reverberant environment by average beamforming. *Mech. Syst. Signal Process.* **2010**, *24*, 796–808. [CrossRef]
82. Yu, H.; Xiao, D.; Ma, X.; He, T. Near-field beamforming performance analysis for acoustic emission source localization. *J. Vibroeng.* **2014**, *16*, 2035–2046.
83. Tian, H.; Qiang, P.; Xiandong, L.; Yingchun, S. AE beamforming method for damage inspection of aircraft structures. *Int. Symp. Aircr. Airworth.* **2011**, *17*, 297–302. [CrossRef]
84. Chiariotti, P.; Martarelli, M.; Castellini, P. Acoustic beamforming for noise source localization—Reviews, methodology and applications. *Mech. Syst. Signal Process.* **2019**, *120*, 422–448. [CrossRef]
85. Brooks, T.; Humphreys, W. Three-Dimensional Applications of DAMAS Methodology for Aeroacoustic Noise Source Definition. In Proceedings of the 11th AIAA/CEAS Aeroacoustics Conference, American Institute of Aeronautics and Astronautics, Monterey, CA, USA, 23–25 May 2005.
86. Dougherty, R.P. Jet Noise Beamforming with Several Techniques. In Proceedings of the 3rd Berlin Beamforming Conference—3rd BeBeC, Berlin, Germany, 24–25 February 2010.
87. Legg, M.; Bradley, S. Comparison of CLEAN-SC for 2D and 3D scanning surfaces. In Proceedings of the 4th Berlin Beamforming Conference—4th BeBeC, Berlin, Germany, 22–23 February 2012.
88. Geyer, T.; Sarradj, E.; Giesler, J. Application of a beamforming technique to the measurement of airfoil leading edge noise. *Adv. Acoust. Vib.* **2012**, *2012*, 905461. [CrossRef]
89. Sarradj, E. Three-dimensional acoustic source mapping. In Proceedings of the 4th Berlin Beamforming Conference—4th BeBeC, Berlin, Germany, 22–23 February 2012.
90. Sarradj, E. Three-dimensional acoustic source mapping with different beamforming steering vector formulations. *Adv. Acoust. Vib.* **2012**, *2012*, 292695. [CrossRef]
91. Porteous, R.; Prime, Z.; Doolan, C.J.; Moreau, D.J.; Valeau, V. Three-dimensional beamforming of dipolar aeroacoustic sources. *J. Sound Vib.* **2015**, *355*, 117–134. [CrossRef]
92. Kocur, G.K.; Saenger, E.H.; Grosse, C.U.; Vogel, T. Time reverse modeling of acoustic emissions in a reinforced concrete beam. *Ultrasonics* **2016**, *65*, 96–104. [CrossRef]
93. Kobayashi, Y.; Shiotani, T.; Oda, K. System identification for three-dimensional AE-tomography with Kalman filter. In Proceedings of the 31st European Working Group on Acoustic Emission, Dresden, Germany, 3–5 September 2014; pp. 3–5.
94. Zhou, Z.L.; Zhou, J.; Dong, L.J.; Cai, X.; Rui, Y.C.; Ke, C.T. Experimental study on the location of an acoustic emission source considering refraction in different media. *Sci. Rep.* **2017**, *7*, 7472. [CrossRef] [PubMed]
95. Bi, C.X.; Li, Y.C.; Zhang, Y.B.; Zhou, R. Analytical Passive Time Reversal Method Combined With Equivalent Source Method for Sound Source Localization in an Enclosure. *J. Vib. Acoust.* **2019**, *141*, 031014. [CrossRef]
96. Hardy, H.R. Source location velocity models for AE/MS field studies in geologic materials. In Proceedings of the 8th International Acoustic Emission Symposium, Tokyo, Japan, 21–24 October 1986.
97. Leighton, F.; Blake, W. *Rock Noise Source Location Techniques*; United States Bureau of Mines: Washington, DC, USA, 1970.
98. Leighton, F.; Duvall, W.I. *A Least Squares Method for Improving Rock Noise Source Location Techniques*; United States Bureau of Mines: Washington, DC, USA, 1972.
99. Inglada, V. Die berechnung der herdkoordinated eines nahbebens aus den eintrittszeiten der in einingen benachbarten stationen aufgezeichneten P-oder P-wellen. *Gerlands Beitr. Zur Geophys.* **1928**, *19*, 73–98.
100. Geiger, L. Herbsetimmung bei Erdbeben aus den Ankunfzeiten. *Nachrichten Ges. Wiss. Zu Göttingen Math.-Phys. Kl.* **1910**, *1910*, 331–349.
101. Geiger, L. Probability method for the determination of earthquake epicentres from the arrival time only. *Bull. St. Louis Univ.* **1912**, *8*, 60–71.

102. Thurber, C.H. Nonlinear earthquake location: Theory and examples. *Bull. Seism. Soc. Am.* **1985**, *75*, 779–790. [CrossRef]
103. Nelder, J.A.; Mead, R. A simplex method for function minimization. *Comput. J.* **1965**, *7*, 308–313. [CrossRef]

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