Acoustic Emission Source Location in Plate-Like Structures using a closely arranged Triangular Sensor Array

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Abstract

In order to identify the location of Acoustic Emission (AE) sources in large plate-like structures it typically requires the use of at least three widely spaced sensors. The distance between these sensors is defined by, for example, expected AE intensity and attenuation of the signals. This work will present a novel configuration of the three sensors, which are installed in a closely arranged triangular array with the sensors just a few centimetres apart. The algorithm locates AE sources by determining the direction from which the wave is approaching the array using the time of arrival and the distance the wave has travelled using the wave mode separation. Tests were conducted on a composite (CFRP) plate with anisotropic lay-up. In this work it is shown that the technique is able to accurately identify the source location. The technique is particularly suitable for Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) applications where the close positioning of the sensors allows the array to be installed in one housing to simplify mounting and wiring. It is expected that this sensor arrangement could reduce the number of sensors needed to monitor large plate-like structures compared to more conventional AE source location methods.

Introduction

Source location of Acoustic Emission events has become an important tool for Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM) research and field applications. Localising the exact origin of an AE wave in a structure can help to determine the source type, for example crack propagation from a drill hole or rivet, impact damage or even just friction between different parts of the structure. This information can be used to evaluate the severity of the damage for the structure and can also help to understand the damage mechanism and propagation.

Many different source location methods have been developed in the past with a variety of applications and accuracies. The simplest method is the “first hit” method or zone location where the sensor with the first arrival or the highest amplitude of the wave is said to be the closest to the source [1]. This is adequate when the sensor spacing or the area to be monitored is small or the damage initiation point is known (for instance a bolt or notch). Other source location methods use the time of arrival of the AE wave at the different sensors. This method is often referred to as Time of Arrival (TOA) [2]. Two sensors can be used for linear source location between the sensors. At least three sensors are necessary to pinpoint a source on a plate. The source must be located inside or near the sensor array to give an adequate result and the wave velocity must be known.

Recent papers are increasingly using the modal nature of AE waves for source location purposes [3, 4, 5]. Acoustic Emission in thin structures propagates in two fundamental wave packages. The first, usually faster wave package is a compressional wave where the material oscillates in the same direction as the wave propagates. The wave mode is referred to as symmetrical mode ($S_0$ mode). The velocity of this mode depends on the material properties...
(tensile stiffness) which can result in different propagation velocities in different direction in anisotropic materials [6]. The second, usually much slower propagating mode is a flexural wave where the material oscillates perpendicular to the wave propagation. This mode is referred to as anti-symmetrical mode ($A_0$ mode) and is mainly caused by shear stress inside the material [7]. This mode is dispersive, depends on the thickness of the structure (flexural stiffness) and is not affected by the fibre orientation [6]. The amplitude ratio between both modes can vary depending on the source orientation in the specimen and the amount of shear stress and tensile stress affecting the material [8]. Since both modes travel with different velocities the wave packages separate during propagation and the distance between the origin of the wave and the sensor can be calculated when both velocities are known. Using this method source location is not limited to the area within an array of sensors. Other authors use the modal analysis to determine the exact wave velocity depending on which mode triggered the AE system [9].

Sachs [10] patented a source location method with a small array of four sensors. This method monitors the area exterior to the array by determining the distance and direction to the source with out prior system calibration and group velocity measurements.

Another method proposed in the literature where the source location is not calculated but the arrival time of an event at different sensors is compared with an arrival time map. This map has to be generated for the area to be investigated beforehand using artificial AE [2, 5].

**Purposed Source Location Method**

The proposed source location method in this paper uses modal analysis to evaluate the origin of the AE event with respect to the centre of the sensor array. The sensor arrangement is a close triangular setup with a sensor spacing of just 45 mm. The algorithm in the method first determines the direction from which the wave travels to the array and secondly, the distance between sensor array and source using the wave mode separation.

**Experimental setup**

Artificial AE was generated using pencil lead fractures (Hsu-Neilsen source or H-N source) on a large carbon fibre reinforced epoxy composite plate (CFRP). The plate was manufactured by Carbon-Composite Technology with a carbon fibre twill weave, an approximate fibre content of 60% and a fibre alignment in 0° and 90°. The dimensions of the plate were 1300x900x2.5mm (1.17 m$^2$ area). Bubble wrap was placed between the composite plate and the table to reduce wave dispersion effects into the table. Three AE-sensors ($Micro-80S$, Physical Acoustics Corporation, 100-1200 kHz, sensor diameter: 10 mm) were installed in the centre of the plate in a triangular arrangement with a sensor to sensor distance of 45 mm (centre point to centre point) respectively. The signal was pre-amplified by a Vallen system AEP4 (40dB) and recorded by a Gage Octopus CompuScope CS-8280 data acquisition card (12 bits, 5MS/s, 100 MHz bandwidth) driven by LabView. The recording was threshold triggered, where a pre-trigger setting of the data acquisition card allowed the capturing of data prior the triggering event to ensure that the whole event was recorded. Afterwards the raw data was digitally filtered by a band pass filter of 100-1000 kHz and processed using LabView and Scilab. The plate was divided into a 15x23 grid starting 100 mm from the edge of the plate respectively to avoid signal corruption by reflections. The grid spacing was 50 mm in horizontal and vertical directions. Three pencil lead breaks were performed on every grid point (a total of 1035 events) and the arrival time of the $S_0$ mode and the $A_0$ mode was determined for all events and for all three sensor signals respectively.
Wave mode analysis
An algorithm was written in LabView to automate the arrival time measurement of both wave modes for every event. First of all the Gabor wavelet transform (WT) was calculated to generate a time–frequency representation of the signal. Fig. 2a) shows an AE signal generated by a pencil lead break. This event was located in a distance of about 540 mm from the sensor. Both wave modes are clearly visible in the Gabor WT, as shown in Fig. 2b). Since the wave velocity is dependent on material, wave mode and frequency [7], the same frequency was chosen to measure the mode arrival time for both modes respectively. For the automated wave mode detection a frequency was chosen where both modes were present, but the earlier arriving $S_0$ mode had a much smaller amplitude in comparison to the $A_0$ mode. In the here used test setup, the frequency of 100 kHz was best suited and an example of the WT coefficient of the signal is shown in Fig. 2c). A threshold was set just above the noise level to detect the beginning of the event and a peak detection tool in LabView was used to find the first peak after the first threshold crossing. The peak detection should lower the influence of the actual threshold setting. Since the $S_0$ mode is the faster propagation wave, the first peak is said to be the $S_0$ mode. A second threshold is set to 90% of the maximum amplitude of each event respectively and again a peak detection tool is used to find the first peak after the crossing. This second peak is said to be the $A_0$ mode.
Misreading of the mode arrival times were identified when one result differs significantly from the result of neighbouring grid points or from the result of the other two sensor signals of the same event. These events were then manually reassessed. 47 of the 3105 AE signals (1035 events x 3 sensors) had to be reassessed. This is an error of 1.51%. In most cases just one of the three sensor signals were corrupted.

This automated wave mode detection was used for H-N sources which are quite repeatable. However the wave mode amplitude ratio varies significantly for real AE data dependent on the source orientation and failure mechanism [8]. This will affect the accuracy of this method for “real” AE testing.

**Evaluating direction from which the wave approaches the array**

In the first step to locate an AE source the direction from which the wave travels to the sensor array has to be determined. In anisotropic materials, such as CFRP, this has to be done before calculating the distance because the $S_0$ wave velocity is dependent on the fibre orientation. The $A_0$ mode is chosen to determine the direction since its velocity is not dependent on the fibre orientation.
Figure 3 shows the arrival time differences of the $A_0$ mode ($\Delta t_{A0}$) for all three sensor pairs at every grid point. Values between grid points were interpolated. The maximum absolute difference in the arrival time of the $A_0$ mode ($\Delta T_{\text{max}}$) between two sensors would be measured when the AE source is in line with the sensor pair. This time is calculated using the distance between the sensor and the wave velocity. When the source is located perpendicular to a straight line through the sensors the wave would arrive at exactly the same time at both sensors, thus $\Delta t_{A0}$ is zero.

The angle of arrival referenced to the centre point of one sensor pair can be calculated using the Arcus-Cosines function (Figure 4). However this leads to two possible results: One angle between 0° and 180° (denoted as $\alpha$) and the other one is the angle $\alpha$ mirrored about the 0°–180° axis (360°–$\alpha$). This ambiguity can be removed by introducing the third sensor to the array. The First Hit method is used to break down the search area in three segments (Figure 5). The sensor at which the AE wave arrived first gives the indication in which segment the source is located. The angle is calculated with the smallest absolute arrival time difference of all three sensor pairs in the array. Thereby the two results of the Arcus-Cosines function are relatively far apart (First result: between 30° and 150°; second result between 210° and 330° with respect to the sensor pair). Only one result can be within the area found by the first hit method.
This result is relative to the sensors pair chosen for the calculation. Dependent on the orientation of this sensor pair, the angle needs to be rotated to coincide with the global coordinates. For example: the coordinate system for the array should be 0° pointing to the right and 90° pointing upwards, the angle $\alpha$ for sensor pair 1-2 is $\alpha - 60^\circ$, for sensor pair 1-3 $\alpha = \alpha - 120^\circ$ and sensor pair 2-3 coincide already with the global coordinate system.

### Evaluating Sensor to Source Distance

The distance between each sensor and the AE source can be calculated by the formula:

$$L = \left( b_{A0} - b_{S0} \right) / \left( \frac{1}{V_{A0}} - \frac{1}{V_{S0}} \right)$$ \[11\]

If the velocities of both modes ($V_{A0}$ and $V_{S0}$) are known and the arrival time of both modes is $b_{A0}$ and $b_{S0}$, the distance between sensor and source is $L$.

If the material is isotropic or quasi-isotropic, the waves propagate with the same velocity in all directions. However in anisotropic materials the wave velocity depends on the material properties and its orientation. In the case of CFRP, the wave speed of the compression wave mode ($S_0$) is varying dependent on the fibre orientation. This problem must be addressed for an accurate source location.

The composite plate used in this experiment had a fibre lay-up in 0° and 90°. The $S_0$ mode has a velocity of 5.80 mm/µs in fibre direction and 4.80 mm/µs in 45° direction. The $A_0$ mode had a constant velocity of 1.68 mm/µs in all directions. Hence the modes are slightly faster separating in fibre direction compared to 45° (and 135°) direction.

![Wave mode velocity dependent on angle](image)

**Fig. 6: Wave mode velocity dependent on angle**

The wave propagation pattern in the plate is illustrated in Figure 6. This pattern can be represented sufficiently by the cosines function with an offset and an amplitude dependent on the wave velocities of both modes. The actual wave velocity ($V_{S0}$) can be calculated as a function of the angle of arrival ($\alpha$) using the following formula:
\[ V_{S0} = \cos(4\alpha) \ast \frac{1}{2}(V_{S_{\text{max}}}-V_{S_{\text{min}}}) + [V_{S0} + \frac{1}{2}(V_{S_{\text{max}}}-V_{S_{\text{min}}})] \]

The maximum \( S_0 \) velocity \( (V_{S_{\text{max}}}) \) is the in \( 0^\circ \) and \( 90^\circ \), \( V_{S_{\text{min}}} \) is diagonal to the fibre orientation \( (\pm 45^\circ) \). If the propagation pattern is elliptical, the factor of \( 4\alpha \) needs to be replaced by a factor of \( 2\alpha \).

The source-sensor distance was identified for all sensors and then the average of all three results was calculated to get a result which is relative to the array centre point. This causes an error for sources inside or close to the array but decreases rapidly with distance (Error < 1.7 mm at a radius 100 mm). This error is tolerated since it is very small in comparison to the error caused by mode arrival measurements. For example sources inside of the array are too close to the sensors to detect a separation of modes and hence the calculated distance is zero. The Standard Deviation of wave mode separation measurements for H-N sources at the same location were about 4\( \mu \)s which is correspondent to an error of \( \pm 10 \) mm.

**Results**

The result of the source location of each event can either be expressed as polar coordinates (distance, angle) or as Cartesian coordinates \((x, y)\) relative to the array centre point.

Figure 7 shows the source location result of one AE event for each grid point respectively (randomly selected). "x" represents the actual source location and "\( \Delta \)" the calculated location. Each calculated location is connected to its real counterpart by a line.

Fig. 7: Source location results (\( x \) = actual location; \( \Delta \) = calculated location; \( \bullet \) = sensor)
It can be seen that this method works quite accurate on close range, but its accuracy decreases with distance. The Standard Deviation in a radius of 350 mm from the array was 13 mm, whilst for the whole plate was 33 mm.

It also can be seen that the radial distance between array and source is usually determined quite accurately but the angle is more prone to errors. This is probably due to errors when measuring the exact arrival times especially of highly attenuated signals. The Standard Deviation of the angle was 4.3° in a radius of 350 mm and 6.0° for the whole plate. The Standard Deviation of the distance was 7 mm and 11 mm respectively.

**Benefits and limitations of the here presented source location method**

The biggest challenge for this method is to get the exact mode arrival times. There are situations when one mode is very weak and hardly detectable. This source location technique only works when both modes are detected in the same event (if just one mode is detected the direction can still be determined but not the distance). Tests with real damage had shown that usually a large number of events are emitted long before the specimen finally fails and even if not all events can be used for source location, areas with high AE activity can still be located.

The range of this array is limited by the actual attenuation in the material. Theoretically the accuracy of the direction decreases with distance but the main error is thought to be associated with the uncertainty in detecting the mode arrival times.

The main benefit of a closely arranged sensor array is the possibility to install all sensors in one housing. This would simplify mounting and wiring up of the AE system. Furthermore it is suitable for wireless application where the three sensors, the power supply and the transmitter could be installed as one unit.

Since the sensors are installed very close to each other, the signal of an event should look fairly similar at all sensors. This makes it easier to identify exactly the same wave feature in all three sensor signals. In a wide spread sensor array, the signal changes quite significantly due to attenuation and dispersion. As a result wave features could alter, be hidden or completely disappear in the different sensor signals. This could lead to measuring errors.

Another advantage of this source location method is the potential for reducing the sensor number needed to monitor a large area. A propagating damage releases energy in form of motion, heat and acoustic emission. The energy of the acoustic wave is proportional to the overall energy released during the event [12]; hence is related to the damage size and propagation speed. It also depends on different other factors such as the material involved. The AE wave propagates from the source and attenuates due to wave spreading, reflections and friction in the material. The maximum distance between sensors depends on the minimum damage size to be detected and the intrinsic attenuation characteristics in the material. The circles in Figure 8 represent this minimum distance. The left figure represents a conventional Time of Arrival (TOA) source location method. Source location is only possible in the dark area in the middle where all three circles are overlapping. Acoustic Emission will also be detected in the other areas, but the exact position can not be evaluated. The here presented sensor array covers a bigger area as long as both wave modes can be detected.
Figure 8: Comparison of covered area of TOA (left) and local triangular sensor array (right) method

Conclusion

A new source location method has been introduced which uses a closely arranged sensor array. The location of AE sources is determined by a combination of time of flight and modal analysis. Its benefits and limitations have been highlighted as well.

References