A GENERIC Technique FOR ACOUSTIC EMISSION SOURCE LOCATION

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Abstract

Acoustic emission (AE) source location is an essential part of any quantitative AE test as it provides information about damage mechanisms and allows spatial separation so that signals from unwanted sources can be eliminated. In this paper, an AE source location technique described as the best-matched point search method is presented. The application of the best-matched point search method is demonstrated in two source location experiments: one on a large anisotropic carbon-fibre composite (CFC) plate and one on a thick oolitic limestone disc. In the large composite plate test, source location is achieved using the S₀ mode, which displays a complicated group velocity pattern. In the oolitic limestone experiment, three-dimensional source location is demonstrated. The best-matched point search method successfully determines the location of AE sources in both tests. Errors in source location are attributed to the extraction of delta-t times from the AE signals.

Keywords: Source location, Best-matched point search method, Carbon-fibre composite, Limestone

Introduction

Acoustic emission (AE) source location is an essential part of any quantitative AE test. In addition to confirming the spatial origin of AE signals, AE source location can be used to selectively eliminate AE signals from unwanted acoustic sources and provide useful information about the development of damage mechanisms [1]. Further, in quantitative source characterisation experiments, AE source location is used to determine the distance between the acoustic source and AE sensors, which is subsequently used to remove propagation effects from measured signals [1 - 4]. The majority of reported AE source location techniques involve two independent stages which can be considered separately: the measurement of arrival times from received waveforms and the use of these arrival times to determine the origin of the acoustic source. The work in this paper is concerned with the latter of these two stages.

An AE source location technique described as the best-matched point search method is presented. The best-matched point search method is an approach, which builds on ideas mentioned by Tobias [5]. The technique was first introduced in a recent conference paper [3] and is expanded upon in this paper to demonstrate its application to three-dimensional solids. The technique was originally developed to determine the origin of acoustic events in plates with complex angular group-velocity patterns and an example of its application to a cross-ply carbon-fibre composite (CFC) plate is given. AE source location for plates with circular or elliptical group
velocity patterns, found in composite plates with quasi-isotropic or uni-directional lay-ups respectively, can be determined analytically using algorithms proposed by Tobias [5], Paget et al. [6] and Kurokawa et al. [7]. Some composite plates, frequently used in laboratory-based source characterisation experiments, contain lay-ups, which lead to complicated angular group-velocity patterns [8, 9]. Analytical two-dimensional source location in plates with complicated group-velocity patterns is exceptionally challenging and as a result, a generic technique for determining the location of acoustic sources on plates with any angular group-velocity pattern is highly desirable. Although some success in this area has already been achieved using iterative convergence schemes [4, 10, 11], the authors are unaware of any literature, which describes source location using group-velocity patterns as complicated as the S₀ mode in cross-ply composite plates.

The best-match point search method is a generic source-location technique and as a second example, the technique is used to determine the three-dimensional source location of Hsu-Nielsen pencil-lead breaks (PLBs) in an oolitic limestone disc. The results of the AE source location testing on the oolitic limestone disc demonstrate the versatility of the technique. The practical application of the best-matched point search method and suggestions for how the technique can be applied in specimens with more complicated geometries are discussed.

The Best-Matched Point Search Method

The best-matched point search method is a simple numerical approach for determining AE source location. The method is broken down into two stages: point generation and point matching. In the point generation stage, the specimen geometry is represented by an array of points with spatial location vectors \( \mathbf{r} \). The theoretical time, \( t_i \), taken for an elastic wave to propagate from a point, \( \mathbf{r} \), to the \( i^{th} \) sensor is given by:

\[
 t_i (\mathbf{r}) = \frac{|\mathbf{r} - \mathbf{s}_i|}{v_{gr}(e)}
\]  

(1)

where \( \mathbf{s}_i \) is the spatial location vector of the \( i^{th} \) sensor and \( v_{gr} \) is the group velocity of the elastic wave, which is a function of the propagation direction between the sensor and point.

The unit vector, \( e \), which describes the propagation direction between the \( i^{th} \) sensor and a point is given by:

\[
 e = \frac{\mathbf{r} - \mathbf{s}_i}{|\mathbf{r} - \mathbf{s}_i|}
\]  

(2)

The difference in arrival time between two sensors (known as a delta-t time, \( \Delta t \)) is then calculated for each point in the array. With the exception of certain ambiguous points, discussed later in this section, each point has a unique combination of delta-t values, which corresponds to a location on the plate. The array of delta-t values only needs to be compiled once for any given specimen/sensor configuration:

\[
 \Delta t_{ij}(\mathbf{r}) = t_i(\mathbf{r}) - t_j(\mathbf{r})
\]  

(3)

where \( i \) and \( j \) denote sensor locations.

In the point matching stage, the delta-t array is searched for the best match to the experimentally measured delta-t values. The estimated position of the source, \( \mathbf{r}' \), is given by:

\[
 \mathbf{r}' = \arg\min_r \left[ \sum_{i,j} \left( \Delta t_{ij}^{\text{exp}} - \Delta t_{ij}(\mathbf{r}) \right)^2 \right]
\]  

(4)
where $\Delta t^{exp}$ are the experimentally measured delta-t values. The summation is applied for every independent combination of delta-t values, $N$, which for a number of sensors, $S$, is given by:

$$N = \frac{S^2 - S}{2}$$

(5)

It should be noted that certain combinations of delta-t times are ambiguous and in these situations, a source location is not unique [3, 5]. If two points on the specimen are separated by a large distance and have similar delta-t values, then an error in the source location can occur. Unique combinations of delta-t values can be obtained by adding sensors to the specimen and increasing the number of independent delta-t values. The topic of ambiguous delta-t values is described by Tobias [5] with visual examples of the problem presented by Scholey et al. [3].

**Application of the Best-Matched Point Search Method to Two-Dimensional Plates**

To demonstrate the source location capability of the best-matched point search method on anisotropic plates, a source location test was conducted on a large, cross-ply CFC plate. The plate was constructed from uni-directional SE84HT prepreg with a lay-up [(0, 90)$_6$]. The plate was 3.6-mm thick and had in-plane dimensions of 1166 x 924 mm. Experimental measurements of the $S_0$ group velocity were made on the plate. The measurements were made in different directions relative to the surface ply, between $0^\circ$ and $90^\circ$ at $10^\circ$ intervals. A 2-cycle Hanning-windowed toneburst with a centre frequency of 150 kHz was used to pulse a transducer at the centre of the plate. A second transducer, located 294 mm away, was placed at different angular locations and the arrival time of the $S_0$ signal used to calculate the group velocity in that direction. The delay in the equipment was measured and accounted for in the group velocity calculation. Figure 1 shows the experimental points measured. It should be noted that measurements were only taken between $0^\circ$ and $90^\circ$ and that the points between $90^\circ$ and $360^\circ$ are only shown for completeness. It can be seen that the angular group-velocity pattern of the $S_0$ mode is neither circular nor elliptical and therefore source location on this plate cannot be solved analytically using the methods reported in the literature [5 - 7].

![Figure 1: $S_0$-mode group velocity in different directions on a SE84HT [(0, 90)$_6$]s plate.](image-url)
Three AE sensors were mounted on the plate at locations (450, 350), (750, 350) and (450, 650) with units in mm. The AE sensors were manufactured from cylindrical pz-27 piezoelectric elements, with a diameter of 3 mm and a height of 3 mm. The sensors were attached to the plate using commercial superglue. A 0.5-mm Hsu-Nielsen pencil-lead break (PLB) was used as an acoustic source at 13 different locations on the plate. Due to the high attenuation of ultrasonic waves in the CFC plate at 150 kHz and the low excitability of the S0 mode, the locations of the PLB sources were chosen to ensure that each sensor could measure the S0-mode signals. The received signals were amplified using Physical Acoustic Corporation (PAC) 2/4/6 amplifiers and were received on a LeCroy 6030 Waverunner digital oscilloscope.

To obtain delta-t values, the signals were frequency-filtered with a raised cosine window centred on 150 kHz and a bandwidth of 300 kHz. The filtered signals were enveloped and the arrival time determined using a threshold amplitude just above the noise level. Delta-t values were calculated using Eq. (3). Figure 2(a) shows the estimated source location for the 13 different points, calculated using the mean group velocity of 5.35 mm·µs\(^{-1}\) (i.e., the average at all angles). With the exception of the points near the centre of the sensor array, where the propagation directions of all ray-paths from the source to the sensors is similar, the source location is quite poor. Figure 2(b) shows the estimated source location using the measured group-velocity pattern with a point array resolution of 2 mm. It can be seen that the estimated source locations are in good agreement with the actual source locations. Only one point, far from the centre of the sensor array provides any substantial error. It should be noted that the errors in the extraction of the arrival times from measured waveforms are automatically incorporated in these plots.

![Fig. 2: Source location on the SEHT84 CP CFC plate. (a) average group velocity, (b) S0 group velocity profile (Sensor locations ‘o’, true PLB locations ‘•’, estimated PLB locations ‘x’).](image)

Application of the Best-Matched Point Search Method to Three-Dimensional Solids

The best-matched point search method is a generic source location technique, which can be applied to different types of structure. The ability of the technique to locate acoustic sources in plates with complex group-velocity patterns was demonstrated in the previous section. In this section, the technique is used to determine the source location of PLBs in a thick oolitic lime-
stone disc. Oolitic limestone is a soft, homogenous rock, which is a composed of calcite. The rock, widely found in the UK, is porous and beige in color.

Elastic wave propagation in the limestone disc at ultrasonic frequencies is assumed to be dominated by bulk waves. The oolitic limestone disc is assumed to be isotropic and as a result, the propagation velocity is equal in all directions. The velocity of a longitudinal wave propagating through the oolitic limestone was determined experimentally using ASTM standard D2845-08 [12]. A cylindrical oolitic limestone specimen, diameter 47 mm and length 100 mm, was used in the velocity test. A 2-cycle Hanning-windowed tone-burst with a centre frequency of 250 kHz, generated by an Agilent 33220A Arbitrary Waveform Generator, was used to pulse a piezoelectric transducer. The transducer was manufactured from a PCM51 cylindrical element with a diameter of 3 mm and a height of 3 mm. The transducer was mounted at the centre of the face on one end of the specimen. At the opposite end of the specimen, a second PCM51 transducer was used to receive the elastic wave energy. The received signal was amplified using a PAC 2/4/6 amplifier and recorded using a LeCroy 6030 Waverunner digital oscilloscope, which also captured the output signal from the waveform generator. Due to the high attenuation of elastic wave energy in the oolitic limestone material at 250 kHz, the signal-to-noise ratio was improved by averaging the received signal 10,000 times.

The time taken for the wave to propagate along the length of the specimen was taken to be the difference in arrival times of the output signal from the waveform generator and the arrival of the signal from the propagated wave. A system delay of 1.1 $\mu$s was determined and accounted for in the calculation. The group velocity was estimated as 3.34 mm$\cdot$$\mu$s$^{-1}$. ASTM Standard D2845-08 [12] presents a crude method for measuring the velocity of elastic waves since material attenuation and energy spreading lead to changes in the waveform shape and amplitude. In the absence of a phase delay technique [13], an improvement in the propagation time estimation time was sought by enveloping the signals used in the calculation. The application of the signal envelopes gave a new propagation time and an estimated group velocity of 3.06 mm$\cdot$$\mu$s$^{-1}$. The measured velocity is in the range reported for limestone material [14].

The source location test was conducted on an oolitic limestone disc. The disc was 30-mm thick and had a diameter of 100 mm. A flat slit, width 30 mm, passed through the entire thickness of the disc. The purpose of the slit was to act as a crack initiator in an unrelated series of tests. Four AE sensors were mounted on the side of the disc on the mid-plane at regular intervals. The AE sensors were manufactured from cylindrical pz-27 piezoelectric elements, with a diameter of 3 mm and a height of 3 mm. The sensors were attached to the plate using commercial superglue. A 0.3-mm Hsu-Nielsen pencil-lead break (PLB) was used as an acoustic source at 17 different locations on the upper surface of the disc. The signals were amplified using PAC 2/4/6 amplifiers set at 40 dB gain and were captured on a PAC PCI-2 AE system. The arrival times of the signals were obtained by using a threshold crossing technique applied to the enveloped raw signals. The threshold amplitude was set a few dB about the ambient noise level. Delta-t values were then calculated using Eq. (2). A three-dimensional array of points with a resolution of 1 mm was established and was searched in the best-matched point search method. Since the experiment is symmetrical about the mid-plane of the disc, only one half of the disc is considered in the point array.

Figure 3 shows the estimated source location for the 17 different points, calculated using a bulk wave velocity of 3.06 mm$\cdot$$\mu$s$^{-1}$. At each PLB location (marked ‘•’), the estimated through-thickness location of the source is also given; the range is from 0 mm (the mid-plane of the disc)
up to 15 mm (the upper surface where the PLBs were applied). It can be seen that for all events, the lateral location of the PLB source as estimated by the best-point search method is good. In most cases, the best-point search technique also successfully identifies the through-thickness location of the source. However, there are large errors in the estimated through-thickness location of the PLB source at five locations, with errors in through-thickness location of up to 15 mm.

![Diagram of source location results for the oolitic limestone disc experiment.](image)

**Fig. 3:** Source location results for the oolitic limestone disc experiment (Sensor locations ‘o’, true PLB locations ‘•’, estimated PLB locations ‘x’, numeric subscripts describe estimated through-thickness location).

**Discussion**

The best-matched point search technique relies on delta-t values obtained from experimental AE signals. In this work, arrival times were measured from enveloped RF signals using a threshold crossing technique. Threshold crossing techniques are frequently used in AE testing to determine the arrival of signals, but errors can exist in the measured arrival times, which lead to errors in delta-t times and estimated location. A second source of error is the elastic wave velocity used to calculate the theoretical propagation times in the point array. In the absence of known material properties, the elastic wave velocity must be determined experimentally. In this work, the elastic wave velocity was determined experimentally for both specimens.

The sensitivity of the reported source location with respect to changes in delta-t value can vary and is dependent both on the position of the acoustic source and the configuration of the sensors [3]. In regions “outside” the sensor array, the location resolution decreases rapidly and as a result, a small change in a delta-t value leads to a large change in the estimated source location. The reduction in source location resolution exaggerates any errors in the assumed velocity and/or experimental delta-t values. The effects of poor location resolution are seen in both tests. In the
CFC plate test, larger errors occur away from the centre of the sensor array. In the limestone disc location test, all of the sensors were mounted on the mid-plane of the specimen and as a result, the specimen had a poor location resolution in the through-thickness direction. Consequently, the source location in the plane parallel to the mid-plane of the disc was excellent but the estimated through-thickness location of some events was poor.

The best-matched point search method is a simple, generic technique, which can be applied to many practical structures. The technique relies on the generation of a point array, which for some geometries could be difficult to generate. In this work, the point arrays used for both tests were generated in Matlab and had a regular spacing in all spatial dimensions. An example of a regularly spaced point array is shown in Fig. 4(a). More sophisticated arrays can be used. For example, Fig. 4(b) shows an array where the spacing of the points varies on the specimen. Such an array could be used in a test where the acoustic source is expected to occur in the centre of the specimen, allowing improved resolution where desired without increasing the total number of points that need to be searched. Further, the powerful meshing algorithms in finite element software could be used to generate the co-ordinates for the point arrays in more complex geometries.

![Fig. 4: Point arrays.](image)

Conclusions

The best-matched point search method has been used to determine the source location of PLBs on an anisotropic cross-ply CFC plate and in a thick oolitic limestone disc. Source location on the anisotropic plate was determined using the $S_0$-mode signals, which have a complicated group-velocity pattern. Source location on the oolitic limestone disc gave both in-plane and through-thickness source location. Errors in both tests have been attributed to errors in the capture of delta-$t$ times from the AE signals, errors in the assumed elastic wave velocity and the position of the source relative to the sensors. The applicability of non-regular point arrays has been discussed and it has been noted that the approach may be extended to more complicated geometries using the powerful meshing algorithms in finite element software.
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