Research on Source Location from Acoustic Emission Tomography

Yu Jiang¹, FeiYun Xu²

¹Fault Diagnosis Laboratory, Southeast University; Nanjing, China, jiangyupop@163.com
²Fault Diagnosis Laboratory, Southeast University; Nanjing, China, fyxu@seu.edu.cn

Abstract
Acoustic Emission source location provides a powerful tool for the engineer. In traditional methods, time of arrival (TOA) location algorithm is based on assumption of a homogeneous background medium with constant wave speed. In fact certain source mechanisms are only associated with particular geometric features, and those assumptions are rarely consistent with the actual situation. as is the case with crane, the equipment contains many inhomogeneities such as welds and thickness changes. These irregularities disrupt the path of wave propagation. wave speed is a function of space and time in general. “acoustic emission tomography” is put forward from a new perspectives for the purpose of AE source location in complicated geometric structures. This method uses AE events as sources for travel time tomography combined with TOA location algorithm to create locally varying wave speed images of the internal structure of the object without physically opening it. The result obtained from the Crane sample (Q235 steel) simulation experiment is practicable.

Keywords: Source location, acoustic emission tomography, travel time tomography wave speed image, Q235 sample simulation test

1. Introduction

Acoustic emission (AE) is used widely in non-destructive testing/structural health monitoring to detect the presence of dangerous flaws and to locate the positions of such flaws in structures of various kinds. One of the most important and useful attributes of AE is its ability to locate source of energy releasing from within a structure as AE events occur [2,23]. This process is irreversible and therefore cannot be repeated [1].Traditional methods of source location are based on simplistic assumptions that the acoustic signals are transmitted with constant wave speed in the background of homogeneous medium. However, the structures to be monitored are heterogeneous in many cases. i.e. Wave speed is a function of space and time in general. The heterogeneity limits the accuracy of AE event location.

Tomography is the technique of creating images of the internal structure of an object without physically opening it [3].AE tomography uses the AE events as signal sources for travel time tomography which can be used for improving the AE event location and giving a better precision to the results. Especially, after the signal processing, a mapping of acoustic propagation speeds inside the structures is obtained. The mapping obtained corresponds to events position of the internal critical components. AE tomography consists of two main components, the localization algorithm and the tomography algorithm. More details are described in this paper.

2. Acoustic emission tomography

2.1 Source location algorithm

2.1.1 Geiger Location Theorem
Let us suppose we have \( i = 1, 2, ..., N \) sensors and the P-wave arrival times of a single acoustic emission event have been determined by using an appropriate algorithm. In the first approximation the arrival time at sensor \( i \) is given by
Figure 2.1 Arbitrary Sensor array model

\[
\left[(x_i^s - x) + (y_i^s - y) + (z_i^s - z)^2\right]^{1/2} = v_p (t_i - t) \quad \text{......................... (1)}
\]

or

\[
t_i^A = \frac{|r^s - r|}{c_i} + t = \frac{\sqrt{(x_i^s - x)^2 + (y_i^s - y)^2 + (z_i^s - z)^2}}{c_i} + t \quad \text{......................... (2)}
\]

Where,

\( r_i^s = (x_i^s, y_i^s, z_i^s) \) is the known position of sensor \( i \) and \( r = (x, y, z) \) is the unknown location of the AE event to be determined by the location algorithm. \( t \), represents the source time of the AE event and is usually measured relative to a trigger level. \( v_p \) is the velocity of \( p \) wave. \( t_i \), describes the arrival time at sensor \( i \).

Eq. (2) is based on a simple straight ray model regarding the source-sensor travel path. In this context, \( c_i \) is the mean effective wave speed along ray \( i \). \( t_i \), is equals to \( t \). In most cases, AE location is done under the assumption of a homogeneous background medium and thus, \( c_i = c = \text{constant} \) for all rays, \( i = 1, ..., N \). On the other hand, in a heterogeneous medium the effective wave speed can be different from one ray to another, i.e., \( c_i \neq c_j \) for \( i \neq j \), in general[5].

In Eq.(2) it has four unknowns, namely, the three source coordinates \( x, y, z \) and the source time \( t \). Thus, at least four different sensors arrival times are required to solve the fundamental equations of system. Since Eq. (2) represents a nonlinear system of equations, a closed analytical solution is not available in general and thus, it has to be solved by an iterative method [4,6].

For that purpose we start with some initial values \( x_0, y_0, z_0, t_0 \) and suppose that the effective wave speeds \( c_i \) are all known. By using the same straight ray model as explained above we can now calculate the theoretical arrival times \( t_{i,0}^A \) using Eq.(2). Commonly, these theoretical times will be different from the measured arrival times, \( T_i^A \) which form the time differences \( \Delta t_i^A = T_i^A - t_{i,0}^A \), namely, the correction values for the next iteration can be obtained. Since the measured arrival times can be written as a function of \( x, y, z \) and \( t \).
\[ T_i^A = f_i(x, y, z, t) = t_{i,0}^A + \Delta t_i^A = t_{i,0}^A + \frac{\partial f_i}{\partial x} \Delta x + \frac{\partial f_i}{\partial y} \Delta y + \frac{\partial f_i}{\partial z} \Delta z + \frac{\partial f_i}{\partial t} \Delta t \] \quad (3)\]

The arrival time difference \( \Delta t_i^A \) is expressed as total differential of \( f_i \). In matrix form we have

\[
\begin{pmatrix}
\Delta t_i^A \\
\vdots \\
\Delta t_N^A
\end{pmatrix} =
\begin{pmatrix}
\frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} & \frac{\partial f_1}{\partial t} \\
\vdots & \vdots & \vdots & \vdots \\
\frac{\partial f_N}{\partial x} & \frac{\partial f_N}{\partial y} & \frac{\partial f_N}{\partial z} & \frac{\partial f_N}{\partial t}
\end{pmatrix}
\begin{pmatrix}
\Delta x \\
\Delta y \\
\Delta z \\
\Delta t
\end{pmatrix}
\]

or shortly

\[
\Delta t^A = F \Delta s \quad \text{.......................... (5)}
\]

Where,

\( \Delta t^A \) and \( F \) are known while \( \Delta s \) is unknown. If the number of sensors is \( N = 4 \), the solution of Eq.(14) is well-defined, namely

\[
\Delta s = F^{-1} \cdot \Delta t^A \quad \text{.......................... (6)}
\]

If \( N > 4 \), the Eq.(14) is over-determined. In the case a least-square approximation with regard to arrival time differences is given by the normal equation,

\[
\Delta s = (TF^{T})^{-1}TF^{T} \Delta t \quad \text{.......................... (7)}
\]

Using the result of Eq.(6), the update of source coordinates and source time from iteration \( k \) to \( k+1 \) can now be expressed as

\[
\begin{align*}
x^{(k+1)} &= x^{(k)} + R_x \Delta x \\
y^{(k+1)} &= y^{(k)} + R_y \Delta y \\
z^{(k+1)} &= z^{(k)} + R_z \Delta z \\
t^{(k+1)} &= t^{(k)} + R_t \Delta t
\end{align*}
\]

Where, The \( R_j \) with \( 0 \leq R_j \leq 1 \) and \( j = x, y, z, t \) are relaxation factor. \( R_j \), is used to assure the stability of the iterative process [6][7].

2.1.2 Time of arrival location (TOA)

The TOA method relies mainly on the arrival times of the signal at each pair of the sensors. In order to provide sufficient information to locate the event explicitly, an array with a minimum of three sensors is needed to pinpoint the source position in two-dimensional location. The concept of two-dimensional source location is shown in Figure 2.2.
In Figure 2.2, $x_i$ and $y_i$ are the location of the source, $x^i_s$ and $y^i_s$ are the location of sensor $i$, $R$ is the distance between the source and sensor 1, $D_2$ and $D_3$ are the distance between sensor 1,2 and sensor 1,3. Simple equations can be formed based on the arrival time at each sensor:

$$\Delta t_1 V = r_1 - R \hspace{1cm} \text{(9)}$$

$$\Delta t_2 V = r_2 - R \hspace{1cm} \text{(10)}$$

$$R = \frac{1}{2} \frac{D_1^2 - \Delta t_1^2 V^2}{\Delta t_1 V + D_1 \cos(\theta - \theta_1)} \hspace{1cm} \text{(11)}$$

And

$$R = \frac{1}{2} \frac{D_2^2 - \Delta t_2^2 V^2}{\Delta t_2 V + D_2 \cos(\theta_2 - \theta)} \hspace{1cm} \text{(12)}$$

The location of a source in two dimensions can be obtained by solving Equations (11) and (12) simultaneously for $R$ and $\theta$.

2.2 Acoustic travel time tomography

In acoustic travel time tomography, data collected from sending acoustic waves through an object at many different angles are used to compute an image of changes of a physical quantity within the object under investigation. This physical quantity can be the wave speed (Travel Time tomography), or acoustic attenuation (Attenuation Tomography), or an acoustic impedance mismatch (Reflection Tomography). This paper is restricted to Travel Time Tomography [9]. Mathematically, convolution methods and iterative methods are the two different kinds of tomography algorithms [1]. The former that based on Fourier slice and diffraction theorem needs to scan object field from all views and takes a long time to collect
projection data, so it is unpractical. The latter stems from seismics and uses iterative methods to reconstruct an image, the most widely-used of iterative methods are called algebraic reconstruction technique (ART), Simultaneous iterative reconstruction technique (SIRT) and Simultaneous algebraic reconstruction technique (SART). These ways are less efficient than Fourier-based techniques and sometimes suffer from stability problems caused by their iterative nature [9,10]. However, they also have a number of advantages. They can be used with irregular ray geometries as well as with incomplete data sets and incorporate curved ray paths. The mode of operation of an iterative tomography algorithm is similar to Geiger location theorem [6]. One always starts with an initial wave speed distribution, calculates the time difference between the measured arrival time and the theoretical one, and then leads to correction values that adjust the wave speed distribution step by step until the measured arrival times match the calculated ones.

In the present paper, ART algorithm represents the best method for the problem described. It adjusts the estimated slowness values, \( s_{ij} = \frac{1}{c_{ij}} \), of the discrete tomography cells \((i,j)\) in the systematic fashion until the computed arrival times \( t_{ij}^A \) for ray \( k \) match the measured arrival times, \( T_{ij}^A \). For the purpose, the path lengths, \( w_{ij}^k \), of each ray \( k \) in tomography cell \((i,j)\) and the computed arrival times for iteration \( K \) are used to obtain a new estimate of the slowness for iteration \( K+1 \):

\[
\begin{align*}
\Delta s_{ij} &= (T_{ij}^A - t_{ij}^A) \frac{w_{ij}^k}{\sum_{i,j} (w_{ij}^k)^2} \quad \text{………… (14)} \\
t_{ij}^{A(K+1)} &= s_{ij}^{(K)} + \lambda \Delta s_{ij} \quad \text{……… (13)} \\
\end{align*}
\]

The summation in Eqs. (13) and (14) is performed over all tomography cells \((i,j)\) passed by ray \( k \). \( \lambda \) is the relaxation parameter used to improve stability and convergence of the method [13, 16, 18, 19].

### 2.3 Acoustic Emission Tomography algorithm

Acoustic emission tomography uses AE events as point sources for acoustic travel time tomography. After the signal processing, AE tomography leads to a new imaging technique where, in addition to the source positions, the volume of the specimen is visualized in terms of a locally varying wave speed distribution. The mapping obtained corresponds to AE events position of the internal critical components.

#### 2.3.1 Model

Modeling the region of interest as an array of cells, where in each one the propagation speed of signal is constant, and assuming a straight-ray propagation model. Fig 3.1 shows a bidimensional model for simplification reasons.
The time of arrival of the signal received at each sensor can be stated as:

\[ T_k^A = T_k^0 + \sum \omega_{ij}^k s_j \]  \hspace{1cm} (16)

Where,

- \( k \) refers to each ray from the acoustic event source to each sensor, \( k = 1,2 \ldots s \);
- \( i, j \) are indexes indicating the position of each tomographic cell, \( i = 1,2 \ldots m; j = 1,2 \ldots n \);
- \( s_j = 1/c_{ij} \) is the "slowness" of the signal propagation along the tomographic cell, defined as the inverse of its propagation speed \( c_{ij} \);
- \( w_{ij}^k \) represents the distance travelled by the \( k \)th ray inside the cell \((i, j)\). Note that most of these elements are zero, since only a relatively small number of cells are crossed by each ray;
- \( T_k^A \) is the time of arrival of the signal from ray \( k \) at the corresponding sensor;
- \( T_k^0 \) is the time of occurrence of the event that originates the \( k \) ray;

For the solution of (16) can be obtained iteratively with a process known as ART mentioned above. Iterative formula is as described Eq. (19) [10, 21, 22]

\[ x_j^{(K+1)} = x_j^{(K)} + \lambda \frac{\omega_{ij}^K (T_k^A - t_k^A)}{\sum_{j=1}^N (\omega_{ij}^K)^2} \]  \hspace{1cm} (17)

2.3.2 Algorithm description

Detail process described above is as followings:

Step 1. An initial guess is defined for all \( s_j \), usually starting with an homogeneous case (the same constant speed for all tomographic cells);
Step 2. The event location is calculated based on the values assigned for propagation speed of the signals;

Step 3. The arrival times of the signal at each sensor are calculated as

$$t_k^A = t_k^0 + \sum \omega_{ij}^k s$$  (18)

Step 4. A correction is calculated for the $s_{ij}$ as

$$\Delta s_{ij} = \frac{(T_k^A - t_k^A)\omega_{ij}^k}{\sum_{i,j} (\omega_{ij}^k)^2}$$  (19)

The tomographic cells crossed by the rays have its slowness updated by

$$s_{ij}^{new} = s_{ij}^{old} + \lambda \Delta s$$  (20)

Step 5. The given error convergence range is $\xi$.

$$|x_j^{(k)} - x_j^{(k-1)}| < \xi, (j = 1, 2, 3N)$$  (21)

Where,

$\lambda$ is a relaxation parameter. In order to ensure convergence of the iterative method, values of $\lambda \in (0, 2)$ are typically used, $\xi$ is a given error $\xi \in (0, 10^{-7})$.

The process is repeated until convergence range is obtained. Finally, it will give as outputs a better estimate of the events location, as well as a mapping of the propagation speeds ($c_{ij}$) of the signals inside the object [3,9,10].

3. AE tomography experimentation

3.1 Experiment system

In order to verify the physical soundness described above, an acoustic emission pencil lead breaks test was implemented on a crane material sample Q235B Steel plate. The area of the cross-section of the Q235B Steel plate was 400*400mm$^2$, and there were two holes with the diameters of 12mm and 6mm respectively. Steel plate thickness is 5 mm. The AE experimentation apparatus adopted in this work was the SAEU2S with 30 channels system of Beijing Soundwel Technology Co., Ltd. The system included preamplifier with 40dB and transducer SR150. The parameters settings were as followings: wave and parameters threshold level were 40 dB, the gain of the preamplifier being 40dB with the main gain being 20 dB, sample rate was 2.5MHz, sample accuracy was 16 bit, data length was 2048, HDT was 2000us, HLT was 2000us, lock out time was 1000us, acoustic couplant was Vaseline. After
adjusting the sensor distribution on software and determining the source location area, 11 AE sensors were set up around the sample surface. By operating pencil lead breaks sources, a total of 15, 30, 60, 120 more AE events were recorded. The data of measurement time and difference of time of arrival at each sensor with an array were acquired.

Table 1. Acoustic emission set parameters

<table>
<thead>
<tr>
<th>Threshold level (dB)</th>
<th>Sampling frequency (Hz)</th>
<th>Number of samples (Hz)</th>
<th>Hit Delineation time (HDT)</th>
<th>Hit Lock time (HTL)</th>
<th>Lock Out time (Software use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>2500</td>
<td>2048</td>
<td>2000</td>
<td>2000</td>
<td>1000</td>
</tr>
</tbody>
</table>
Table 2. Q235B Chemical composition and mechanical properties

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>$\sigma_s$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q235B</td>
<td>0.16</td>
<td>0.19</td>
<td>0.54</td>
<td>0.021</td>
<td>0.030</td>
<td>335</td>
<td>475</td>
<td>34.0</td>
</tr>
</tbody>
</table>

3.2 Results analysis of acoustic emission tomography

According to Fig.2.5, the steel plate area under test was divided into a matrix with 40 by 40 tomographic cells, each one with dimensions about $2 \times 2 (cm)$[3]. The initial estimation of propagation speed of the steel plate was 5 km/s. $\lambda$ was 0.05. $\xi$, was 0.0100001. Data obtained mentioned above were input to a routine that performs the ART algorithm on Matlab7.8 platform. A mapping of acoustic emission tomography was constructed. Some interesting features as listed as followings:

![AE acoustic emission tomography](image)
Firstly, The obtained image was able to observe two regions where the propagation speed was higher than in its surroundings as Fig 2.7. They correspond to the steel plate areas with hole (12mm) and hole (6mm) under test specimen as Fig 2.5. At the same time, As the number of AE events were increasing, the acoustic emission tomographic image quality became better in the defective regions.

Secondly, Structural elements and acoustically “passive” defects can also be visualized. “Undesirable” acoustic emission sources, such as the friction that would be considered as noise in acoustic emission test, can also become useful as signal sources to improve image resolution in AE tomographic . for example, due to friction during the test, The 11th sensor, 4th sensor and 1th generated a lot of interference events, and then wave speed became higher.

Thirdly, The AE tomography used the same data available in conventional AE testing equipment, So there was no need to develop specific hardware.

4. Conclusions

A key advantage of AE technique is the ability to locate the source of an event .Acoustic emission tomography is the technique of creating images of the internal structure of an object without physically opening it and using AE events as acoustic point sources. It will be an interesting tool to complement the analysis of data from acoustic emission tests. Moreover, an attractive feature is that acoustic emission tomography does not need any additional hardware to be added or modified, since it relies only on the conventional data obtained with traditional AE test instruments, and on a software routine to process the data in a tomography algorithm. Finally, AE tomography requires a large number of sensors, accurate sensor location and the wave path duration for the iterative arguments used to develop the wave speed maps. These requirements are deemed very suitable for the engineering application and have certain practical values.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (No.650200039), the National High Technology Research and Development Program of China(863 Program) (No.2007AA04Z421). The author wishes to thank Mr. Oswaldo G dos Santos Filho, Brazil, for his support and encouragement.

References