ACOUSTIC EMISSION TOMOGRAPHY TO IMPROVE EVENT LOCATIONS AND DIAGNOSTICS OF INHOMOGENEOUS EQUIPMENTS AND STRUCTURES

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ABSTRACT: Acoustic emission testing is an effective technique to assess the condition of several types of structures, including electric power transformers and reactors. Traditional event location algorithms assume uniform propagation speed for the acoustic signals. This may not correspond to reality in case of inhomogeneous structures or equipments, as is the case with power transformers, since they are constituted of several materials, such as copper, steel, insulating oil, paper and cardboard, each one with a different acoustic propagation speed, limiting the accuracy of event location. A travel-time tomography algorithm can be used for the event location algorithm, giving a better precision to the results, as well as giving a mapping of acoustic propagation speeds inside the equipment under test. This mapping corresponds to an imaging of the internal components, allowing a better diagnostic, since the events can be better evaluated, correlating them with the position of critical components of the equipment. Basic principles of acoustic emission tomography are presented, as well as results obtained from electric power equipment tests.

KEYWORDS
Acoustic Emission, Acoustic Emission Tomography, Travel-time tomography, Power Transformers.

ACOUSTIC EMISSION TOMOGRAPHY

In contrast with conventional ultrasound tomography, where external ultrasound sources are used to illuminating the object, acoustic emission events are used as signal sources in Acoustic Emission (AE) Tomography [1],[2]. After the signal processing, a mapping of propagation speed of the signals inside the object is obtained. Also, a better estimation of the AE event locations can be obtained since the location algorithm now relies on a better estimation of the acoustic propagation speed distribution inside the object. The image obtained can be useful to the analyst as he can associate the AE events location with particular components or structures inside the object, when no detailed knowledge about this internal structure is available to him.

In acoustic emission, the time of arrival of the signals at each sensor is a function of the source location and of the propagation speed of the acoustic waves. For inhomogeneous bodies, this speed is not constant along the ray trajectories, as different materials enter in the constitution of the whole body.

Modeling the region under interest as an array of cells, where in each one the propagation speed of the signal is constant, and assuming a straight-ray propagation model, this system can be
represented schematically as in Fig. 1, which shows a two-dimensional model for simplification reasons.

![Diagram of acoustic emission tomography](image)

Figure 1. — (Left) Model of an heterogeneous body for acoustic emission tomography. The shaded area has a different propagation speed. (Right) Detail of a tomographic cell (i,j) of size u, showing \( w_{ij}^{k} \) in Eq. (1).

The time of arrival of the signal received at each sensor can be stated as:

\[
T_{k}^{i} = T_{k}^{o} + \sum w_{ij}^{k} \cdot s_{ij}
\]  

(1)

Where:

- \( k = \{1, 2, \ldots, s\} \) refers to each ray from the acoustic event source to each sensor.
- \( i = \{1, 2, \ldots, m\} \) and \( j = \{1, 2, \ldots, n\} \) are indexes indicating the position of each tomographic cell.
- \( s_{ij} = 1/c_{ij} \) is the “slowliness” of the signal propagation along the tomographic cell, defined as the inverse of its propagation speed \( c_{ij} \).
- \( w_{ij}^{k} \) represent the distance travelled by the \( k \)-th ray inside the cell (i,j). Note that most of these elements are zero, since only a relative 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.
- \( T_{k}^{o} \) is the time of occurrence of the event that originates the ray “k”.

The solution of (1) can be obtained iteratively with a process known as Algebraic Reconstruction Technique – ART, as described below [1], [2], [3]:

1. An initial guess is defined for all \( s_{ij} \), usually starting with an homogeneous case (same constant speed for all tomographic cells)
2. The event location is calculated based on the values assigned for the propagation speed of the signals.
3. The arrival times of the signal at each sensor are calculated as
\[ t_k^A = t_k^o + \sum w_{ij}^k s_{ij} \]  

(2)

4. A correction is calculated for the \( s_{ij} \) as:

\[ \Delta s_{ij} = \left( T_{k}^A - t_k^A \right) \frac{w_{ij}^k}{\sum_{i,j} (w_{ij}^k)^2} \]  

(3)

5. The tomographic cells crossed by the ray have its “slowness” updated by

\[ s_{ij}^{\text{new}} = s_{ij}^{\text{old}} + R \Delta s_{ij}, \]  

(4)

where \( R \) is a relaxation factor of the order from 0.01 to 0.1, used to ensure the stability of the iterative process [1], [2], [3].

The process is repeated from step 2 until convergence is obtained. At the end, it will give as outputs a better estimate of the event locations, as well as a mapping of the propagation speeds \( c_{ij} \) of the signals inside the object under test.

In the modeling described above, finding adequate values for the weights \( w_{ij}^k \) is not easily achieved. In some simple implementations of the ART algorithm, the \( w_{ij}^k \) are approximated by zeros or ones, depending upon a simple criterion, such as whether or not the ray crosses the cell at a minimum distance of its center. In this case, the correction formula at the step 4 above reduces to [3]:

\[ \Delta s_{ij} = \frac{\left( T_{k}^A - t_k^A \right)}{N_k} \]  

(5)

where \( N_k \) is the number of cells crossed by the \( k \)-th ray.

In the ART algorithm described above, the cell parameters are updated on a ray-by-ray basis, therefore, as one ray is processed, it may alter the cell that was just updated in the preceding ray calculation.

In SIRT (Simultaneous Iterative Reconstruction Technique) algorithm, as the changes \( \Delta s_{ij} \) are calculated, they are not directly used to update the cells, but, instead, they are stored in a separate array and averaged as all the rays are processed. Only after all rays are processed, performing one complete iteration, the \( \Delta s_{ij} \) averaged are used to change the cell values. This process is repeated until convergence is reached. SIRT results in smoother images than in conventional ART algorithm [3], [4].

Another approach to the image reconstruction, known as SART – Simultaneous Algebraic Reconstruction Technique - is to use bilinear elements to the cells to represent the ray integrals, instead of finite sums. Also, to reduce noise in the results, in similar way as the SIRT algorithm, the correction terms \( \Delta s_{ij} \) are applied simultaneously to all rays after all they are considered in computation at the end of one iteration [3], [4].
**Benefits of Acoustic Emission Tomography**

In addition to the more evident benefits in using acoustic emission tomography, such as determination of event locations with greater precision and the possibility of obtaining an image that represents the mapping of the acoustic propagation speed inside the equipment under test, which is dependent on the distribution of materials in the body interior, some other interesting features arise from this technique as listed as follows:

- In traditional acoustic tomography, the image resolution is dependent on the number of emitters and receptors, while in acoustic emission tomography, a smaller number of sensors can be compensated by a larger number of acoustic emission events normally available as signals sources.

- “Undesirable” acoustic emission sources, such as friction, leaks, etc, that would be considered as noise in a acoustic emission test, become useful as signal sources to improve image resolution in AE tomography. Additionally, other sources, such as pencil breaks, hammer impact, or the automatic sensor test feature, available in some acoustic emission test instruments, can be used to artificially produce AE signals to the tomography algorithm.

- The image resolution becomes better in the defective region, since a greater number of events is produced in it. This is a positive feature, since these regions are required to be investigated in more detail, as the image resolution improves with the number of events.

- There is no need to develop specific hardware, since the AE tomography uses the same data available in conventional AE testing equipment.

**TEST RESULTS**

To verify the concepts described above, an acoustic emission test was performed on a series-resonant reactor, an equipment used in generating high voltages, of the order of 1000 kV, to test electric power equipments, shown in Figure 2. It consists of a cylindrical tank of about 0.8 m diameter and height 3 m. Inside, as shown in detail in Figure 3, there is an adjustable magnetic nucleus and a mechanism remotely controlled to displace this nucleus in order to put the reactor in electric resonance and produce the desired voltage. The tank is filled with insulating oil to ensure good electrical insulation of its internal parts.

A total of eleven AE sensors were distributed around the circumference of the tank, on a horizontal plane in order to treat the problem as bidimensional, at approximately the same height of the internal mechanism described above. Acoustic emission events were produced due to friction on internal components of the reactor, by operating the adjusting mechanism. As shown in Figure 4, around 70 AE events were recorded and the data obtained was input to a routine that performs the ART algorithm described above. The horizontal plane area under study was divided into a matrix with 40 by 40 tomographic cells, each one with dimensions around 2 x 2 cm. Figure 5 shows the obtained tomographic image, in a color scale representing the “slowliness” (inverse of propagation speed) of the acoustic signals at each tomographic cell.
Although the image obtained is relatively “noisy”, it is possible to note two regions where the propagation speed is higher than in its surroundings. They correspond to the movable magnetic nucleus and its adjusting motor. The darker areas represent lower propagation speed of the acoustic signals and correspond to the oil-filled space. The image quality should be improved if a greater number of acoustic events is produced and by using averaging algorithms, such as SIRT and SART to process the data.
CONCLUSION

Acoustic emission tomography can be an interesting tool to complement the analysis of data from acoustic emission tests, since it gives a mapping of the propagation speed of the acoustic signals inside the object under test. In the case of a non-homogeneous object, this mapping can reveal details of its internal structure, as the propagation speed is dependent on the materials that constitute the object. The technique is useful also with homogeneous objects, when this propagation speed varies in different parts of the object, depending on some other variable such as stress or temperature, which could also be mapped using tomography algorithms. Better estimates of the event locations can be obtained as the spatial distribution of the acoustic signals speed becomes available. 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 equipments, and on a software routine to process this data in a tomography algorithm.

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