Tomography Techniques for Acoustic Emission Monitoring

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Abstract. The acoustic emission (AE) technique represents a structural health monitoring approach that uses AE events caused by crack formation and growth in a structure under external load to monitor its structural integrity. Besides pure counting (AE activity), localization as well as moment tensor inversion are well known variants of AE analysis. In this paper a new imaging technique is presented that uses AE events as sources for ultrasonic travel time tomography. For that purpose the localization algorithm is iteratively combined with an appropriate tomography algorithm. In addition to visualizing the volume of the specimen in terms of source positions, the resulting new imaging technique provides a locally varying wave speed distribution. Moreover, the finally determined sources can be used to image the reflection properties by applying synthetic aperture focusing techniques (SAFT). The new imaging method was developed, tested, and validated by using extensive numerical simulations based on the elastodynamic finite integration technique (EFIT). Examples of application in the field of concrete testing and guided wave monitoring of plate-like structures are presented.

1. Principles of Acoustic Emission Tomography

The traditional localization algorithms used in acoustic emission (AE) analysis usually require a homogeneous background medium in order to determine time and location of source events. In practice however, the structures to be monitored are heterogeneous in many cases, i.e. wave speed is a function of space and time in general. This heterogeneity is caused by inhomogeneities of the microstructure (e.g. grains and pores), structural elements (e.g. tendon ducts in concrete) and dynamic material changes caused by the damage mechanism itself (e.g. micro crack growth). These inhomogeneities usually limit the accuracy of traditional localization algorithms.

In order to avoid the difficulties as described above, the localization algorithms can be combined with algorithms for travel time tomography by using the AE events as acoustic point sources. Based on the latest wave speed distribution, a relocalization of the sources, i.e. an update of the current source positions is iteratively performed after each tomographic inversion (and vice versa). This procedure is in principle known from geophysics where earthquakes are first localized and then used for tomographic imaging of the earth’s interior.

The new technique is called acoustic emission tomography and consists of two main components, the localization algorithm and the tomography algorithm. Both modules are first explained separately in sections 1.1 and 1.2, respectively. After that they are combined to the new imaging algorithm in section 1.3. In this paper, presentation of extensive mathematical formulae is abandoned. For more details the reader is referred to [1]. In chapter 2 numerical examples of application are presented in order to verify the physical soundness and consistency of the new algorithm. Finally, chapter 3 provides a survey of
ongoing work to verify the method experimentally and gives an outlook how the algorithms can be extended to anisotropic composite materials being relevant for aircraft applications.

1.1 Source Localization

The localization algorithms as used for traditional AE analysis are usually based on a homogeneous isotropic background medium with constant wave speed. If the sensor positions are known and the arrival times of the elastic waves at the different sensor positions have been determined by using appropriate picking algorithms, a nonlinear system of equations can be set up in which source coordinates and source time represent the unknowns. For that reason, in three dimensions at least four sensor signals are needed in order to solve the system of equation explicitly.

The traditional approach is based on a simple straight ray model, in which the travel time of a wave from the source to the sensor is given by their geometrical distance divided by the fixed wave speed of the matrix medium. In general, the system of equations as mentioned above cannot be solved analytically but an iterative solution, e.g. based on the method according to Geiger [2], is available. For that purpose one starts with plausible initial values for the spatial and temporal source coordinates. If the wave speed of the matrix medium is known, the theoretical arrival times of the waves at the different sensors can be calculated. From the difference between theoretical and actually measured arrival times correction values for the next iteration can be derived. This procedure is repeated until space and time coordinates of the source converge to a constant value. This usually happens after a few iterations only. The technique can be easily extended to heterogeneous and anisotropic media by associating each ray with an individual effective wave speed.

As already mentioned above, exactly four sensor signals are needed for a 3-D source localization. In this case the solution is uniquely defined. If more than four sensor signals are available the problem is over-determined and a least-squares method has to be used. In 2-D or quasi 2-D geometries like plate- or shell-like aircraft structures the minimum number of sensors for localization is reduced by one, i.e. three sensors are needed at least.

As an alternative to iterative methods, direct algebraic methods of resolution as successfully used for the Global Positioning System (GPS) can be applied [3, 4]. They turned out to be more robust especially in cases where the arrival times are flawed to a certain degree. A review about the topic is given by Kurz et al. in [5].

1.2 Acoustic Travel Time Tomography

In acoustic travel time tomography transmission measurements under different angles of incidence are performed similar to the procedure well-known from X-ray tomography. The transmission data is then passed to a tomography algorithm that constructs an image of local changes of a certain physical quantity inside the structure under test. This physical quantity can either be the wave speed (“travel time tomography”), acoustic attenuation (“attenuation tomography”), or an acoustic impedance mismatch (“reflection tomography”).

The following considerations are restricted to travel time tomography. For that purpose a specific number of actuators/sensors are arranged along the surface of the specimen to be investigated. The acoustic waves are then transmitted from each actuator to the opposite sensors (see figure 1).
Normally each one of the $N$ transducers is used as both, actuator and sensor, resulting in a maximum of $N(N-1)/2$ acoustic rays. The exact number of useable rays depends on the specific locations of the transducers. From the measured travel times along the intersecting rays an image of the spatial wave speed distribution can be reconstructed.

Mathematically, two different kinds of tomography techniques can be distinguished [6]. The transform based methods are known from X-ray tomography and medical ultrasound tomography. They are using the Fourier slice as well as the Fourier diffraction theorem for non-diffracting and diffracting sources, respectively. These methods are very robust and are characterized by high computation speeds offering the possibility for quasi-online imaging, even in 3-D. One drawback of the transform based methods is that the data must be recorded along evenly distributed \textit{straight rays}.

A second class of tomography algorithms stems from seismics and uses iterative methods to reconstruct the wave speed distribution. The best known and oldest method is the algebraic reconstruction technique (ART). Other more advanced techniques are SIRT (simultaneous iterative reconstruction technique) and SART (simultaneous algebraic reconstruction technique). These methods are less efficient than Fourier-based techniques and sometimes suffer from stability problems caused by their iterative nature. However, they also have a number of advantages. For instance, they can be used with irregular ray geometries as well as with incomplete data sets. The most important advantage, however, is the possibility to incorporate curved ray paths. This fact is of particular interest for acoustic waves since they show a refraction index unequal to one if passing from one medium to another. There exist powerful ray-tracing algorithms that take refraction and diffraction effects explicitly into account [7, 8].

The mode of operation of an iterative tomography algorithm is similar to those of the iterative localization algorithm described in section 1.1. One always starts with an initial wave speed distribution (e.g. a homogeneous medium) and - based on that - calculates the theoretical arrival times between actuators and sensors. The comparison between measured and calculated arrival times then leads to correction values that adjust the wave speed distribution step-by-step until the measured arrival times match the calculated ones.

Using ART the correction is performed on a ray-by-ray basis, i.e. after treatment of an individual ray, the wave speeds of the tomography cells intersected by this ray are updated immediately. In SIRT all available rays are evaluated first and then a mean correction value for the wave speed is applied to the tomography cells concerned. If curved...
ray paths shall be taken into account, an update of the ray profile based on the current wave speed distribution can be additionally incorporated.

1.3 Acoustic Emission Tomography

After introducing the two main components ‘localization’ on the one hand and ‘travel time tomography’ on the other hand, the new concept of acoustic emission tomography is obvious. For that purpose the AE events are used as point sources for acoustic travel time tomography (figure 2). Since in contrast to traditional tomography source location and time are not known a-priori, localization algorithm and tomography algorithm are iteratively combined.

![Figure 2: Monitoring set-up in acoustic emission tomography. The AE events are used as acoustic sources for travel time tomography. In contrast to traditional tomography only sensors but no actuators are needed.](image)

The process always starts with an initial guess of the wave speed distribution, e.g. a homogeneous isotropic medium with constant wave speed. In a first step, source localization based on the start model is performed by using one of the methods described in section 1.1. The source positions are then used to perform a travel time tomography as introduced in section 1.2. As a result, a new heterogeneous wave speed model is obtained.

In a second step, the new wave speed distribution can be used to perform a relocalization of the sources by associating each ray with an individual effective wave speed. The improved source coordinates lead to a better tomography result which in turn results in better source coordinates, etc. This iterative procedure with alternating steps of localization and tomography is repeated until the differences between calculated and measured arrival times reach a minimum or a predefined accuracy level. The process corresponds to the solution of the generalized inverse localization problem in locally isotropic media. Besides the source positions, the volume of the specimen is imaged in terms of a locally varying wave speed distribution.

While traditional ultrasonic tomography often suffers from the limited number of transducers and thus, an inadequate ray coverage, in acoustic emission tomography hundreds or thousands of AE events are typically available. Each new incoming event increases the number of rays and therefore, also the accuracy of the tomographic image. In this context a limited number of sensors can partly be compensated by picking a correspondingly larger number of AE events.
In many cases the position of the sources is restricted to a few active damage zones leading to a non-uniform ray coverage. However this is not a disadvantage in general, since in most cases the immediate vicinity of the damage zones is of particular interest and in these regions good ray coverage associated with a high tomographic resolution is reached.

Another significant advantage of acoustic emission tomography compared to traditional AE analysis is the treatment of sources of interference. For instance, in a flying aircraft the majority of AE events is caused by joints and other contact points and usually large effort is needed to separate the sources of interference from the wanted signals produced by the damage mechanisms. In acoustic emission tomography these sources of interference can also be used for imaging provided they can be described by transient or at least non-stationary point sources. While traditional AE analysis can only detect active damage zones, acoustic emission tomography is able to identify active as well as passive defects. Structural elements like tendon ducts in concrete for example are also displayed.

In principle the AE events from inside the specimen under test can be replaced by sources artificially generated on the surface of the sample. This can be realized by applying a number of statistically placed pencil lead breaks or mechanical impacts. Since each additional AE event improves the ray coverage and thus, the tomographic image, an NDE inspector could selectively and interactively produce new source events in order to improve the image in a specific region. In this process it is not necessary to exactly place the source to a specific point or to determine the exact source position (as in traditional tomography). This task is automatically handled by the iteration algorithm of acoustic emission tomography.

At the end of this chapter it should be mentioned that acoustic emission tomography represents a purely algorithmic extension of traditional AE analysis. No additional measuring expenditure is needed since exactly the same raw data is used.

2. Examples of Application

In order to prove the physical concept of acoustic emission tomography, synthetic AE data sets were produced by the elastodynamic finite integration technique (EFIT, [9]). For that purpose a 440 × 440 mm² cross section of an existing steel reinforced concrete specimen of ETH Zürich including steel re-bars in the corners and a polyethylene tendon duct in the center was chosen (see figure 3). 16 sensors were evenly distributed along the perimeter of the sample. A total of 40 isotropic point sources were generated randomly inside the model and for each event the time-domain signals of normal particle velocity as detected by the different sensors were calculated. After that the arrival times of compressional waves were determined by using an energy-based picking algorithm. The arrival times then served as input for the tomography algorithm, which is called AE-TOMO in the following. Further details about numerical simulations and arrival time picking can be found in [10].

In the following two sections, the case of uniformly and non-uniformly distributed AE events, respectively, is considered and the corresponding tomography results are presented. In both case the AE-TOMO algorithm is based on the iterative localization algorithm according to Geiger and on a tomographic ART algorithm using straight ray paths.
2.1 First Example: Uniformly Distributed Sources

In the first example the 40 AE events were randomly placed within the concrete matrix. Together with the 16 evenly distributed sensors this leads to a more or less homogeneous ray coverage according to $40 \times 16 = 640$ rays (figure 3).

Figure 3: Ray coverage of the concrete model according to 16 sensors and 40 AE events randomly placed within the concrete matrix. Thus a total of 640 rays, uniformly distributed within the cross section, can be used for acoustic emission tomography.

Figure 4 shows the results of the AE-TOMO algorithm after a different number of iterations in each case. We start with a homogeneous model with constant wave speed (iteration 0). After only 5 iterations, the first indications of the four steel re-bars in the corners and the ungrouted tendon duct in the middle become apparent. After 15-20 iterations a saturation behaviour is observed leaving the tomographic image approximately constant.

In figure 4 light colours represent wave speeds larger than the speed of the concrete matrix. These higher wave speeds occur at the positions of the steel re-bars. Dark colours in turn represent regions with effectively reduced wave speed. This is valid in the region of the ungrouted duct, since the waves have to move around the duct leading to increased travel times.

In figure 4 it is striking that the image of the re-bar in the lower left corner is worse compared to the images of the other three re-bars. This is probably due to the insufficient ray coverage in this region (compare figure 3).

The heterogeneity of the wave speed distribution as given in figure 4 directly leads to a better source localization compared to traditional algorithms based on a constant wave speed. From the numerical data, a 60% on average better temporal and spatial localization could be obtained. For more details the reader is referred to [1].

In contrast to traditional localization algorithms, each new incoming AE event leads to a better approximation to the real velocity field and thus, to a better localization of all other source events as well. Therefore, increasing the number of detected AE events leads to better and better localization results in principle, only limited by a saturation effect as observed in figure 5.
Figure 4: Results of acoustic emission tomography obtained at a concrete model with steel re-bars and ungrouted tendon duct after 0, 5, 10, 15, and 20 iterations of the AE-TOMO algorithm based on the ray coverage shown in figure 3. After about 15 iterations the wave speed model becomes more and more stable. The steel cables with locally increased wave speed (light-coloured regions) in the corners and the ungrouted tendon duct with effectively decreased wave speed (dark regions) in the center of the model are clearly visible.

A further increase of the number of rays does not necessarily lead to a better tomographic image as long as the number of tomography cells remains constant. Instead of that, the tomography cells can be further refined in this case which directly yields a higher image resolution.

In figures 4 and 5, the structural elements inside the cross section of the concrete specimen can be clearly identified. Nevertheless, the images still show a number or artifacts mainly caused by the simplified straight ray model used within the ART algorithm. Due to the large differences in acoustic impedance between the concrete matrix and the scatterers this model is not well satisfied in the present case. Consideration of diffraction and refraction effects in the framework of curved ray paths should therefore lead to significantly improved tomography results in the future.

Another reason for some of the artifacts seems to be the non-uniform ray coverage leading to strong variations in the number of rays per cell. It is expected that the usage of adaptively sized tomography cells will lead to a more balanced ray density and therefore to a better tomographic image.
Figure 5: Results of acoustic emission tomography obtained at a concrete model with steel re-bars and ungrouted tendon duct using 5, 10, 20, 30, and 40 AE events for reconstruction (after 25 iterations in each case). The wave speed model becomes better and better if the number of AE events and thus, the number of rays is increased.

2.2 Second Example: Non-Uniformly Distributed Sources

In the first example of application the AE events were evenly distributed within the concrete matrix. In practice however, the source events are generated predominantly in the immediate vicinity of local damage zones. For instance, in a pull-out test where the tendon duct is continuously pulled out of the concrete matrix, the AE events will be restricted to the vicinity of the duct’s surface. This leads to strongly non-uniform ray coverage as shown in figure 6. Once again, 40 sources and 16 sensors were used.

As can be seen from the figure, very good ray coverage is obtained near the duct, while the corners of the cross section are not covered. Consequently, the steel re-bars cannot be displayed in this case but the duct can be imaged with high resolution.

For tomographic inversion, four different duct models were used, (i) an ungrouted duct as already known from the first example, (ii) a duct grouted with mortar, (iii) a duct with a void in the mortar filling, and (iv) a duct grouted with mortar and steel strands. The corresponding results of acoustic emission tomography are shown in figure 7. It can be recognized that each model is characterized by a specific tomographic image being significantly different to the others. The cavity in the mortar grouting (model 3) as well as the steel strands in model 4 can be clearly identified.
**Figure 6:** Star-shaped ray coverage of the concrete model according to 16 sensors and 40 AE events randomly placed in the immediate vicinity of the duct’s surface. Again, a total of 640 rays can be used for acoustic emission tomography.

**Figure 7:** Results of acoustic emission tomography obtained at four different duct models, based on the ray coverage from figure 6. The void in the mortar filling (dark spot in the lower left picture) as well as individual steel strands inside the grouted duct (white spots in the lower right picture) are clearly visible.
3. Experimental Verification: An Outlook

The results from chapter 2 revealed that the physical concept of acoustic emission tomography is sustainable and has a number of advantages compared to traditional AE analysis. However, experimental verification is not yet finished and is therefore subject of ongoing research. This work is focused on two different kinds of application, namely structural health monitoring (SHM) of concrete structures on the one hand and SHM of panel-like aircraft structures on the other hand. In the following only some aspects of the latter problem are discussed.

3.1 Structural Health Monitoring of Aircraft Components

In aviation shell-like structures, consisting of isotropic aluminum or anisotropic composite materials (CFRP) are frequently used. In the latter under external load, a significant number of AE events caused by fibre cracking, matrix debonding or delaminations can be expected. Therefore, acoustic emission tomography seems to be a promising candidate for efficient monitoring of such parts.

In a first step, laboratory measurements at a 2.5 mm thick aluminium plate with a growing crack were performed (figure 8). Of course in aluminium significantly fewer AE events than in CFRP occur. However, wave propagation in aluminum is isotropic and thus, a direct application of the algorithms developed so far is possible. In the present case the AE events were generated by pencil lead breaks applied to the surface of the plate.

![Ray coverage used for traditional travel time tomography](image1)

![Ray coverage used for acoustic emission tomography (only 3 sources out of 100)](image2)

**Figure 8:** A 2.5 mm thick aluminum panel as used for the experimental investigations. It contains a growing crack starting from the center of the plate. Traditional travel time tomography was performed by the help of eight evenly distributed transducers acting as both, transmitters and receivers (picture on the left). For acoustic emission tomography, AE events simulated by pencil lead breaks on the surface of the plate were used. In this case the eight transducers served as sensors only.

For reasons of better comparison, data sets for traditional travel time tomography were also recorded. For that purpose, eight transducers (center frequency = 300 kHz) serving as transmitters and receivers, were uniformly placed on the panel surface. The corresponding ray coverage is shown in the left picture of figure 8. The result of the travel time tomography is shown in figure 9. The crack was stepwise enlarged by sawing. For each crack configuration an acoustic travel time tomography based on the symmetric Lamb mode S0 and the ray distribution shown in figure 8 was performed. Three selected images are shown in figure 9.
Due to the small number of rays a significant change in the tomographic image is obtained not until the crack, growing in south-east direction, intersects ray AB. In this case the diffraction around the crack leads to a local decrease of effective wave speed (dark spot in figure 9).

![Figure 9: Results of traditional acoustic travel time tomography obtained at the aluminum plate shown in figure 8 (courtesy of E. Schulze, Fraunhofer-IZFP, Dresden). Not until the growing crack intersects the ray AB, a local decrease of wave speed of the guided S0 mode can be observed (dark spot).](image)

In order to verify acoustic emission tomography experimentally and to compare it with traditional travel time tomography, about 100 AE events were produced by pencil lead breaks on the surface of the plate and the corresponding time-domain signals were recorded by the eight sensors. For evaluation the primary wave, i.e. the symmetrical zero-order Lamb mode S0, is evaluated. A total of $100 \times 8 = 800$ rays is obtained compared with the $(8 \times 7)/2 = 28$ rays in traditional tomography. It is therefore expected that by the help of acoustic emission tomography, a significantly better image resolution associated with a higher sensitivity to the growing crack can be reached. The data evaluation is currently under way and results will be published elsewhere.

### 3.2 Extension to Anisotropic Composite Materials

The final goal of the ongoing work is to extend acoustic emission tomography to anisotropic composite materials like CFRP and GFRP as typically used in aircraft structures and wind energy installations. For that purpose, angle-dependent group velocities...
have to be taken into account, affecting both, localisation and tomography algorithms. Figure 10 shows an instrumented CFRP panel and a directional group velocity diagram of the S0 wave measured at the panel.

Figure 10: Instrumented CFRP panel (top picture, courtesy of IMA GmbH, Dresden) and the measured angle-dependent group velocity of the S0 Lamb mode (bottom picture, courtesy of L. Schubert, Fraunhofer IZFP, Dresden).

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<tr>
<th>Angle [°]</th>
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Figure 11: Localisation results for AE events in a triaxial GFRP plate. Left picture: Source locating by using an isotropic localisation algorithm, right picture: source locating by using an anisotropic algorithm based on the corresponding group velocity diagram.

- Real AE locations, • Calculated AE locations, o Sensor Positions
For a reliable and accurate localization of AE events it is essential to take directional group velocity diagrams explicitly into account (see figure 11). Only in this case, correct ray paths for acoustic emission tomography can be constructed.

Another interesting extension of the present algorithm would be to use the finally determined sources to image the reflection properties of scatterers by applying synthetic aperture focusing techniques (SAFT). The problems to be solved in this context are subject of ongoing research in the SHM working group at IZFP-Dresden. The results obtained so far indicate that acoustic emission tomography has great potential for structural health monitoring and offers totally new perspectives for traditional AE analysis as well. In case efficient and robust imaging techniques for SHM purposes could be developed in the future, a significantly increased acceptance of monitoring techniques in general can be expected. Successful examples for such developments can be found in 3-D X-ray tomography and medical ultrasound, where in the first place the implementation of fast imaging algorithms has led to a remarkable break through.

References