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Determination of the Source Localization and the Beginning Time of the Acoustic Signal

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Abstract

For the problem of PAT, that is, determining the coordinates and the beginning time of an acoustic signal, it is necessary to carry out synchronized registration of acoustic signals of a source using a multichannel receiving system. Synchronously recorded signals are the signals with a delayed (long) front. A threshold method is proposed for determining the arrival time of noisy acoustic signals with a delayed front based on the evaluation of an adaptive threshold. An approach that allows to reduce the problem of determining the coordinates and the beginning time of an acoustic signal to solving a system of linear algebraic equations is proposed. Matrix A of the system of linear algebraic equations depends on the arrival times of synchronized registered signals (source coordinates). Therefore, when collecting data for a given geometry of the product and the location of the receivers, it is necessary to calculate areas, where matrix A is ill-conditioned. Areas of poor conditionality of matrix A should be excluded from the permissible areas of location of sources of acoustic signals. For these areas there will certainly be poor accuracy. The results of simulation and experimental testing of the developed PAT technologies are presented.

Keywords: acoustic signal, multichannel receiving system, source localization, signal processing, linear algebraic equations, coefficient of conditionality of matrix

1. Introduction

The key technologies of PAT are:

- Synchronized registration of acoustic signals of sources by multichannel receiving system

- Determination of the arrival times of the acoustic signals with the long (delayed) front to the receivers of the multichannel receiving system

- Calculation of the source localization and beginning time of the acoustic signal

- Calculation of the projection data—the propagation times of the acoustical signal (averaged slowness) along the propagation paths from the source to the receivers of the multichannel receiving system

- Tomographic reconstruction of the spatial distribution of the acoustic characteristics of the material

If necessary, iterative refinement of the source localization of acoustic signals and the spatial distribution of the acoustic characteristics of the medium is possible.

2. Synchronized recording of the acoustic signals

An important stage of the PAT is the synchronized recording of acoustic signals by a multichannel receiving system, which is necessary to determine the coordinates of the source and the beginning time of the signal.

Acoustic and electromagnetic synchronization of the recording of acoustic signals by a multichannel receiving system is used. In [1] a system for determination of localization of cracks from acoustic emission signals in which synchronization of recording is achieved by using an electromagnetic emission pulse is described.

The acoustic synchronization of the recording of acoustic signals consists in the following. When a signal arrives at the nearest detector of the multichannel receiving system, all other detectors start registering acoustic signals.

Synchronized recorded acoustic signals are the signals with delayed front. They consist of two sections. The first section is a noise segment that is associated with the time of propagation of an acoustic signal from a source to a receiver. This section is used to determine projections (travel times or slowness averaged over propagation paths). The second section is the noisy acoustic signal. This section is used for determination of the signal travel time, which is used to calculate of the source localization and beginning time of the signal.

3. The method for determination of the arrival time of an acoustic signal with a delayed front

The measured parameters by PAT are the arrival times of synchronized registered acoustic signals by a multichannel receiving system.

The techniques of determination of the signal arrival type are dependent on this signals nature, particular on the delayed front that is caused by the noise segment at its beginning.

In **Figure 1** an example of a particular time realization is shown, which is registered from one of the channels of an eight-channel acoustic signals recording system that were caused with a short blow with a scalpel on a steel plate.

To determine the arrival time of noisy signals with a delayed front, several methods have been developed [1–3].

A new method for determining the arrival time of a signal with a noisy front section was developed. The technique takes the attenuation of signals into account.

Let the implementation of the acoustic signal be a set of discrete samples:

$$s = \{s(n)|n = 1, \dots, N\}. \tag{1}$$

We choose the averaging filter window Δ and perform averaging of the signal:

$$z = \left\{ z(m) = \frac{1}{\Delta} \sum_{k=m-\frac{\Delta}{2}}^{m+\frac{\Delta}{2}} s(k) \middle| m = \frac{\Delta}{2} + 1, \ldots, N - \frac{\Delta}{2} \right\}. \tag{2}$$

Then we calculate the modulus of changes between consecutive samples of realization z:

$$d = \left\{ d(m) = |z(m+1) - z(m)| \middle| m = \frac{\Delta}{2} + 1, \ldots, N - \frac{\Delta}{2} - 1 \right\}. \tag{3}$$

After this, we choose the averaging filter window and perform averaging of the realization:

$$y = \left\{ y(m) = \frac{1}{\Delta_d} \sum_{k=m-\frac{\Delta_d}{2}}^{m+\frac{\Delta_d}{2}} d(k) \middle| m = \frac{\Delta}{2} + \frac{\Delta_d}{2} + 1, \ldots, N - \frac{\Delta}{2} - \frac{\Delta_d}{2} \right\}. \tag{4}$$

Further, we construct the line of a threshold that linearly decreases from p_m to 0 as the reading number m increases from $m_{\min} = \frac{\Delta}{2} + \frac{\Delta_d}{2} + 1$ to $m_{\max} = N - \frac{\Delta}{2} - \frac{\Delta_d}{2}$:

$$p = \left\{ p(m) = p_m \left(1 - \frac{m - \frac{\Delta}{2} - \frac{\Delta_d}{2} - 1}{N - \Delta - \Delta_d - 1} \right) \middle| m = \frac{\Delta}{2} + \frac{\Delta_d}{2} + 1, \ldots, N - \frac{\Delta}{2} - \frac{\Delta_d}{2} \right\}. \tag{5}$$

The signal arrival time is then taken to be the reading m_s for which:

$$p(m_s) = y(m_s). \tag{6}$$

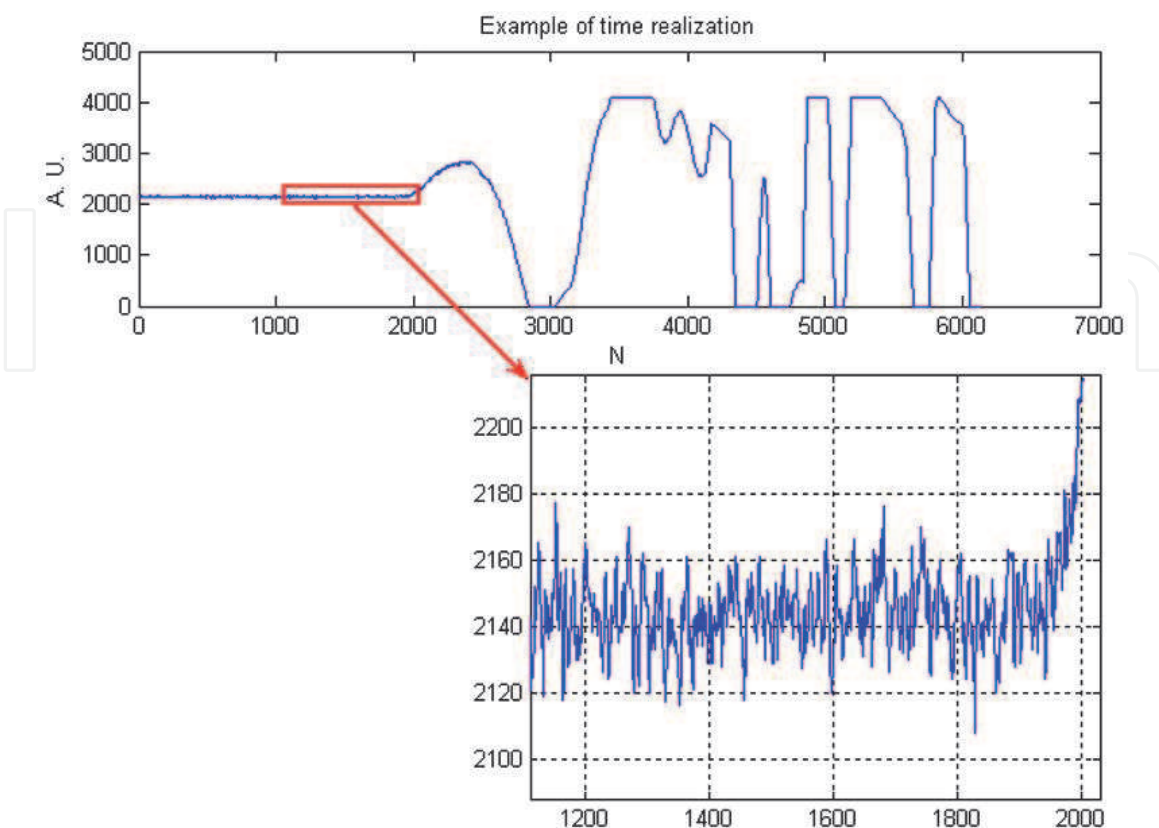The parameters Δ, Δ_d, p_m were selected based on experimental research.

Figure 1.
An example of a temporal implementation of a registered acoustic signal.

When the arrival times of acoustic signals synchronized registered by the recording system have been determined, the problem is to calculate the source localization and beginning time of the acoustic signal.

4. Determination of the source localization and beginning time of an acoustical signal

There are a number of methods of localization of acoustic sources [4–6].

Let us consider a 2D case and assume that we use a three-channel recording system to determine the source localization and beginning time of an acoustic signal.

Let (x_0, y_0) be unknown coordinates of the source of acoustic signals and $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ be the coordinates of the detectors. For the uniform distribution of the propagation velocity of acoustic signal, we have:

$$c(t_1 - t_0) = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2}$$
$$c(t_2 - t_0) = \sqrt{(x_2 - x_0)^2 + (y_2 - y_0)^2}, \qquad (7)$$
$$c(t_3 - t_0) = \sqrt{(x_3 - x_0)^2 + (y_3 - y_0)^2}$$

where t_1, t_2, t_3 are the arrival times of the synchronized detected signals at the detectors and t_0 is the beginning time of the acoustic signal.

In practical terms, we can only determine the times of delay in the signal's arrival at one detector with respect to another $t_1 - t_2, t_1 - t_3$. Based on Eq. (7), we obtain the following system of two equations with two unknown coordinates of the source of acoustic signals:

$$c(t_1 - t_2) = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} - \sqrt{(x_2 - x_0)^2 + (y_2 - y_0)^2}$$
$$c(t_1 - t_3) = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} - \sqrt{(x_3 - x_0)^2 + (y_3 - y_0)^2} \qquad (8)$$

From the geometrical viewpoint, solving Eqs. (7) or (8) reduces to finding the point of intersection of several circles or hyperbolae, respectively.

We present an approach that allows us to reduce the problem of determination of the coordinates of the source and the beginning time of an acoustic signal to solving of a system of linear algebraic equations.

The source coordinates (in 3D-case) and beginning time of acoustic signals are determined based on detecting of signal arrival times by four receivers:

$$(x_n - x_e)^2 + (y_n - y_e)^2 + (z_n - z_e)^2 = c^2(t_n - t_e)^2,$$
$$(x_k - x_e)^2 + (y_k - y_e)^2 + (z_k - z_e)^2 = c^2(t_k - t_e)^2,$$
$$(x_l - x_e)^2 + (y_l - y_e)^2 + (z_l - z_e)^2 = c^2(t_l - t_e)^2, \qquad (9)$$
$$(x_m - x_e)^2 + (y_m - y_e)^2 + (z_m - z_e)^2 = c^2(t_m - t_e)^2$$

where $(x_i, y_i, z_i; t_i)$ are the coordinates of the receivers and the recorded signal arrival time $(i = n, k, l, m)$ and $(x_e, y_e, z_e; t_e)$ are the sought-for source coordinates and beginning time of the acoustic signal. The z_i coordinate is the same for all the receivers that are situated on the surface of the test article. Let n be the ordinal

number of the receiver that was the first to register the signal. If the receivers are positioned equidistant on the sides of the article (which is taken to be a rectangle), we have $k = n + N/4$, $l = n + N/2$, and $k = n + 3/4N$, where N is the number of receivers that is a multiple of four.

After subtracting the first equation from the second equation, the first equation from the third equation, and the first equation from the fourth equation for a homogeneous medium (c = const), we arrive at the system of three linear algebraic equations:

$$As = b. \tag{10}$$

Here $A = \begin{pmatrix} 2(x_k - x_n) & 2(y_k - y_n) & 2c^2(t_n - t_k) \\ 2(x_l - x_n) & 2(y_l - y_n) & 2c^2(t_n - t_l) \\ 2(x_m - x_n) & 2(y_m - y_n) & 2c^2(t_n - t_m) \end{pmatrix}$; $s = (x_e, y_e, t_e,)^T$ is the

sought-for vector, and $b = \begin{pmatrix} (x_k^2 - x_n^2) + (y_k^2 - y_n^2) + c^2(t_n^2 - t_k^2) \\ (x_l^2 - x_n^2) + (y_l^2 - y_n^2) + c^2(t_n^2 - t_l^2) \\ (x_m^2 - x_n^2) + (y_m^2 - y_n^2) + c^2(t_n^2 - t_m^2) \end{pmatrix}$. The

coordinate z_e is determined from Eq. (9).

If the thickness of the article is considerably smaller than its length or width, we can take z_e to be half of the article thickness.

The matrix A depends on the arrival times of synchronously detected signals (the source coordinates). Therefore the allocation of the area where matrix is ill-conditioned should be determined when gathering data on the test article with the prescribed geometrical parameters and known receivers disposition (x_e, y_e, z_e).

The condition number of a matrix is given by [7]:

$$k = \frac{|\lambda_{\max}|}{|\lambda_{\min}|}, \tag{11}$$

where $|\lambda_{\max}|$ and $|\lambda_{\min}|$ are the maximal and minimal (by moduli) eigenvalues of A, respectively.
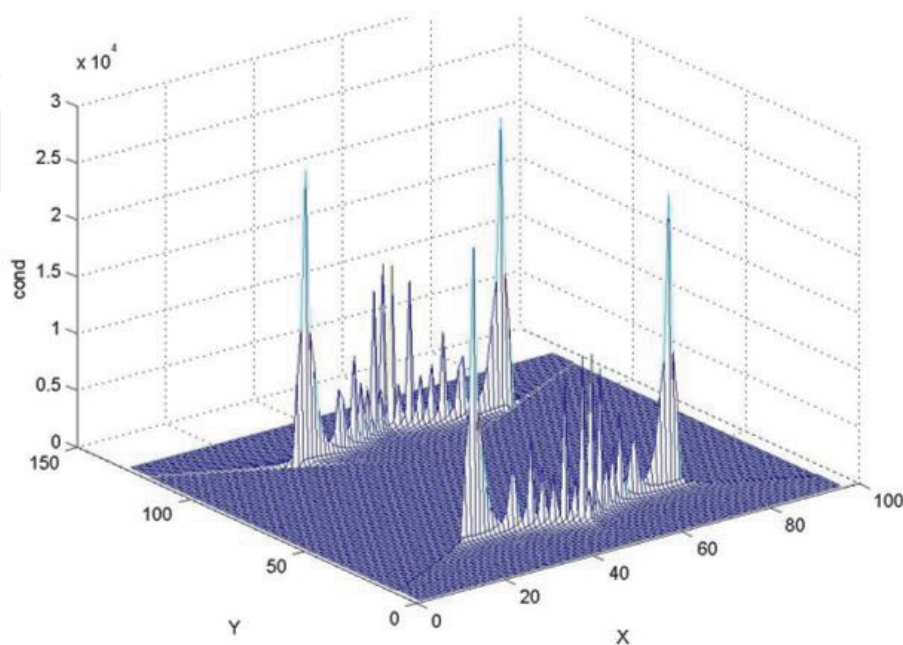

Figure 2.
Dependence of the condition number of the matrix on source coordinates.

Figure 2 provides an example of the dependence of the matrix condition number on the source coordinates (x_e, y_e) for a plane-parallel object with dimensions $96 \times 128 \times 8$ mm, with the receivers situated on the object surface at the centers of the sides. The domains where the matrix A is ill-conditioned must be excluded from admissible domains for the location of source of acoustic signals.

5. Description of the experimental setup and results of experimental testing

An experimental bench (an eight-channel acoustic emission tomograph [8]) was developed for experimental testing of the techniques of passive ultrasonic tomography. It is based on an eight-channel recording system that allows synchronized detection of acoustic signals with a 12-bit ADC with a sampling rate of 10–65 MHz. Acoustic and electromagnetic synchronizations for detection are provided in the tomograph. Experimental testing of the techniques was performed with a thick sheet St20 plate ($480 \times 640 \times 30$ mm) with a welded joint across the middle of the shorter side (at $x = 240$ mm, if the x axis is directed along the shorter side). Wideband DISM1 acoustic emission transducers [9] with a transmission bandwidth of 200–1200 kHz manufactured at the Bakul Institute of Superhard Materials of NAS of Ukraine were used for registration of acoustic signals. The transducers were attached to the butt ends of the sides at "points" with the coordinates (in mm) (160, 0); (320, 0); (480, 640/3); (480, 640 × 2/3); (320, 640); (160, 640); (0, 640/3); and (0, 640 × 2/3).
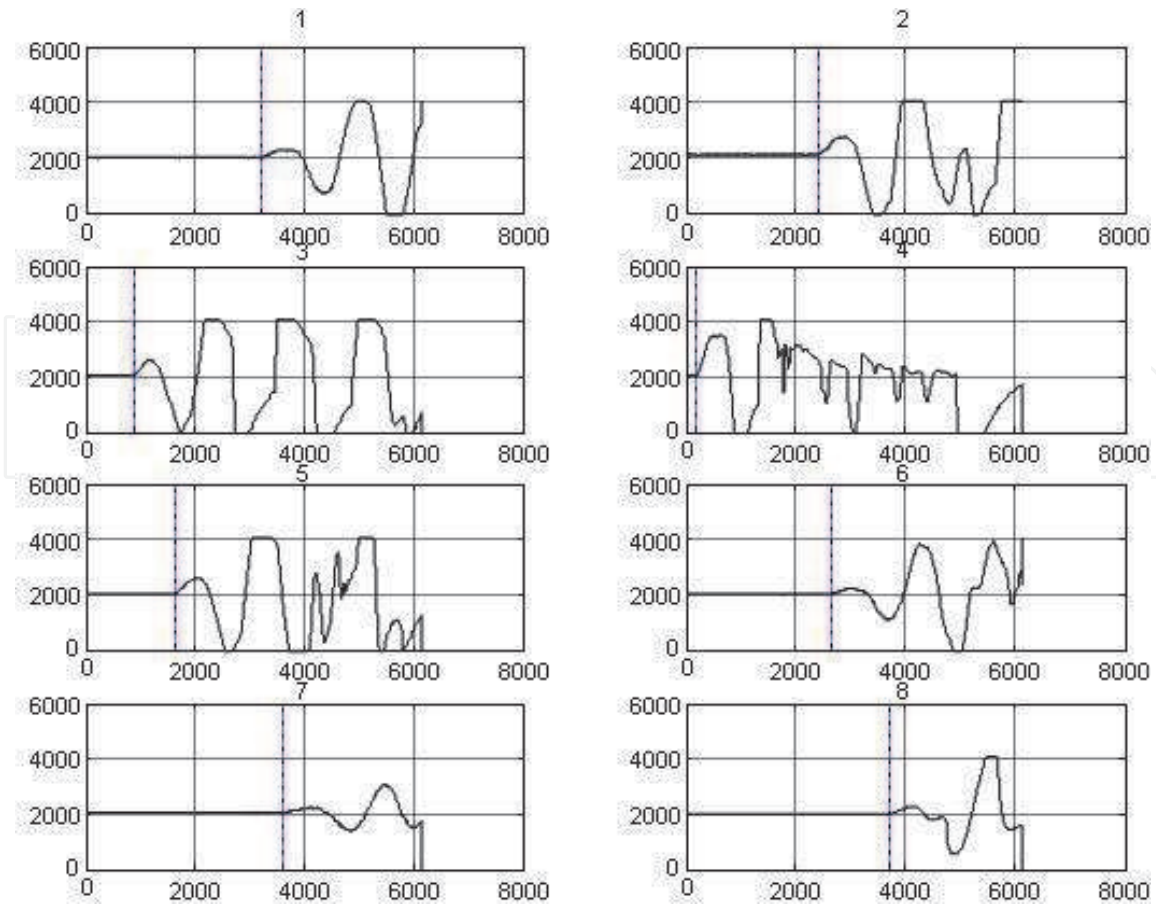

Figure 3.
An example of time realization of acoustic signals, synchronously detected by an eight-channel receiving system after a knock with a scalpel.
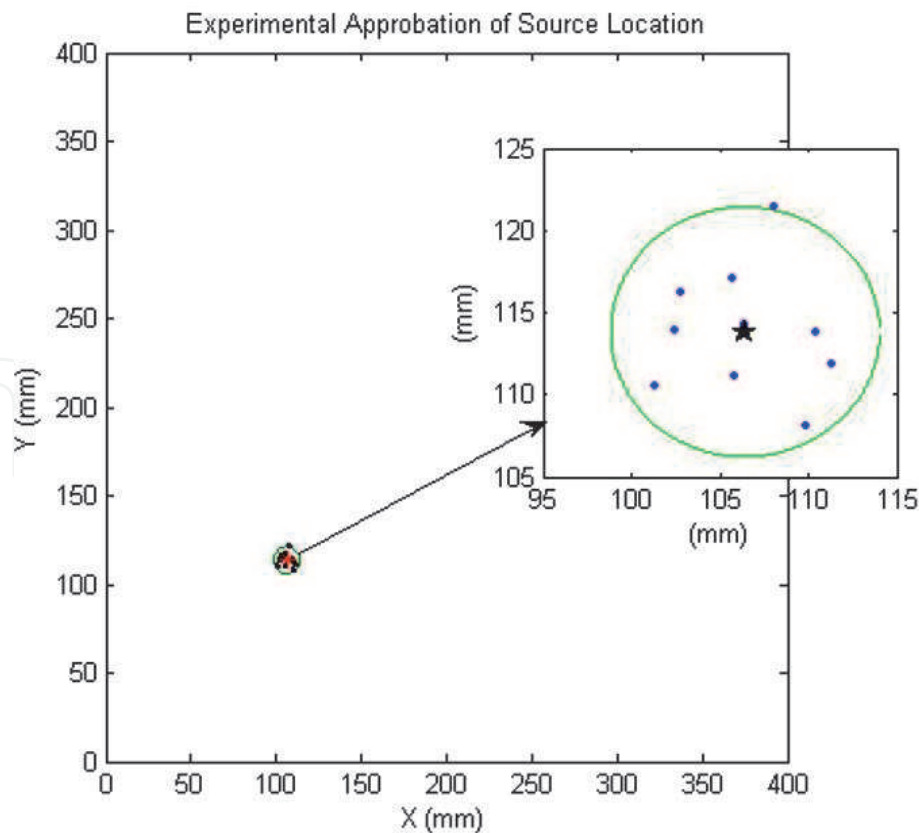
Figure 4.
The results of experimental studies of the accuracy of determining the coordinates of the source.

Figure 3 provides an example of time realizations of acoustic signals that were synchronously detected by the eight-channel recording system after fast knock on the metal plate with a scalpel. Synchronization was achieved by the electromagnetic method (i.e., the channels were triggered for recording of acoustic signals by a knock on the plate with the scalpel).

Experimental testing of the suggested method for determining the signal arrival time was performed implicitly, based on calculating the source coordinates and beginning time of acoustic signals.

A great deal of experiments were held in determining the location of signal source for different positions of the excitation point. Results of determination of source coordinates based on synchronously experimental registered realization for a knock on the plate with the scalpel near the location (110 mm, 110 mm) are presented in **Figure 4**.

6. Conclusions

The important problems of the PAT are the determination of the arrival time of the synchronously registered signals by the multichannel receiving system and calculation based on these source coordinates and the beginning time of the acoustic signal.

The method of determination arrival times of synchronously registered acoustic signals with a delayed front based on the use of an adaptive threshold is proposed. The threshold is chosen according to the linear dependence of the decreasing of threshold with the increasing of the delay.

The approach to the determination of the source coordinates and the beginning time of acoustic signal on the basis of the problem reducing to the solving of the

system of linear algebraic equations is proposed, which allows to estimate the accuracy of determination of the source coordinates and the beginning time of the acoustic signals. The matrix of the system of linear algebraic equations depends on the location geometry of the source and receivers of the multichannel system. Those sources, for which the matrix of the system of linear algebraic equations is poorly conditioned, are not taken into account when collecting projective data.

The results of simulation and experimental testing of the proposed technologies confirmed their effectiveness.

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