Acoustic Emission Source Localization in Thin Plates through a Dispersion Removal Approach

Krzysztof GRABOWSKI *, Mateusz GAWROŃSKI *, Wiesław Jerzy STASZEWSKI *, Tadeusz UHL *, Ireneusz BARAN **, Wojciech SPYCHALSKI ***, Paweł PAĆKO *
* AGH University of Science and Technology, Kraków, Poland
** Cracow University of Technology, Kraków, Poland
*** Warsaw University of Technology, Warsaw, Poland

Abstract. The work concerns with the acoustic emission source localisation in thin plate-like structures. An accurate approach has been proposed through the dispersion removal technique. The acquired signals are inherently deformed by the dispersive character of wave interaction with structure, and depend on the structural properties, e.g. material constants, geometry, source frequency content etc. The deformation of the signals increases with the propagation distance making the results interpretation difficult. Thus, the damage localisation is cumbersome and prone to errors. Authors propose an application of dispersion removal technique to transform the AE signals from the time to the distance domain, showing explicitly the distance between the sensor and the source. A set of spectral characteristics is used to perform the mapping operation. Then, employing triangulation techniques the source is localised. The method is compared to the existing methods in terms of accuracy, showing the advantages of the proposed approach.

Introduction

Acoustic Emission (AE) source localization is crucial for damage qualification, quantification and structural health evaluation. However, it is widely known that due to source variability, different complex phenomena accompanying energy release, and unknown propagation path, accurate localisation of damage is a challenging task. A number of strategies have been developed for this purpose throughout the years [3, 6, 2]. Typically, damage localisation techniques based on AE events utilise responses from a network of sensors. Time signals or events acquired during a measurement are subsequently processed by numerous types of triangulation methods to find probable source location [1, 6]. A number of parameters involved in these analyses are adjusted based on expertise or identified by a simple tests carried out prior to actual measurement, and are therefore prone to errors. As a consequence the damage location is frequently not evaluated correctly. Other difficulties include very noisy signals obtained through typical sensors, which makes precise localization problematic. Such data requires complicated filtering often leading to slow information processing and small improvement of final result.

Numerous works have been conducted to develop AE source localization methods. Most of them introduce similar algorithms such as triangulation method, beam-forming and in most cases, variations of these two. Both of previously mentioned methods assume that wave speed in a medium is known, and estimate possible distance of a source from respective transducers in a network. An accurate estimate of wave speed is therefore crucial for damage localisation.

Acoustic emission signals excited by sudden release of strain energy in a structure are broadband. Thus, waves in certain range of frequencies are propagated from the source to receivers simultaneously. This poses no significant problems unless non-dispersive media are considered, i.e. media where wave speed is not frequency-dependent. As it is widely known this is not the case for thin plates, where the Lamb waves propagate. For such structures wave of different frequencies travel at different phase speeds, and, possibly, as a different wave modes. Precise estimation of a single wave speed required by a damage localisation technique is therefore not possible.

In this paper an approach to AE source localization in thin plates using dispersion removal algorithm is presented. It is based on a transformation of measured responses from time to the propagation distance domain. As the wave speed in materials differ from each other based on the frequency of excitation, considering the dispersion characteristics in analysis allows for more precise source localisation. User intervention and parameters tuning can be also avoided as the most important and core information about material properties are obtained from the physical setup parameters. Subsequently, distance domain signals are fed to a triangulation technique. Implementation of triangulation algorithm enhanced by a signal filtering, helps narrowing the approximation error improving the final result.

The paper is organised as follows. Brief introduction to triangulation and time-distance transformation techniques is described in the first section. Section 2 shows results of source localisation simulations. Following, in section 3, experimental results obtained by the proposed approach and other methods are described. The paper is summarised in Section 4.

1. Source localisation methods

There are several methods developed for localization of an event occurring in plate-like structures. Each has its strengths and weaknesses but in most cases, simplicity and accuracy of algorithm are the main factors, which determine practical usage of particular method. Localisation of AE source is in fact an inverse problem solution, which is well posed only under certain, strict assumptions such as isotropy of material properties, infinite propagation medium, ideal coupling conditions of the sensors etc. For plate like structures, due to dispersion effects, accurate damage localisation strongly depends on the input parameters such as wave speed. Vast majority of methods used in industrial applications are based on time-domain triangulation [1, 6]. In contrast, the method proposed in this work makes use of a triangulation approach based on distance domain signals. Preliminaries necessary for explaining the idea of the approach are given below.

1.1 Triangulation method

The most popular approach for damage localisation is triangulation [3]. When a wave excited by an AE source hits a sensor the time of such event is acquired and compared with arrival times for other sensors in the network. Time shifts between arrival times among the sensors, along with pre-set wave speed value are used to find location of an event. For this purpose a circle is drawn for each sensor. Radii of circles are increased incrementally by a small value, until a common crossing point of all circles is found. The method is simple and quick, and gives relatively good results when the signals are not distorted heavily by noise. It should be noted that sensors should not be arranged in a symmetric setup as this will lead to mirrored damage locations.

Triangulation is very sensitive to noisy signals. Wave arrival time has to be calculated very accurately, as distance calculation for circle radii changes proportionally to time. Due to geometrical spreading of elastic waves the determination of arrival time becomes increasingly difficult with increasing distance from the source. This causes unavoidable calculation errors for triangulation method, leading to event locations shifting.

1.2 TDDT

Triangulation is typically performed in time domain, or by using simple linear mapping using a pre-set wave speed value. This lead to inaccurate estimates of damage localisation for dispersive media where waves of different frequencies travel with different velocities. Due to dispersion the time signal is deformed, and changes it shape with propagation distance. The TDDT is a method of transforming a dispersive signal from the time domain (typically, amplitude as function of time) to the distance domain where dispersion relationship is a nonlinear function of wave speed and excitation frequency. A particular advantage of the TDDT method is its ability to resolve broadband signals, as those encountered in AE.

Following [7], the frequency domain response at a point due to excitation can be defined as:

$$V(\omega) = E_a(\omega)E_s(\omega)G(r_0,\omega)V_a(\omega) \tag{1}$$

where $V_a(\omega), V(\omega), E_a(\omega)$ and $E_s(\omega)$ are excitation signal, signal received by the sensor, electro-mechanical efficiency and efficiency of PZT respectively. Taking into consideration transform function from source signal to the sensor we can simplify equation to:

$$V(\omega) = E_a(\omega)E_s(\omega)V_a(\omega)A(r_0,\omega)e_0^{-iK(\omega)r} \tag{2}$$

$$= V_a(\omega)H(\omega), \tag{3}$$

where $H(\omega) = E_a(\omega)E_s(\omega)A(r_0,\omega)e_0^{-iK(\omega)r}$ is the transfer function which includes Lamb wave, it's propagation and finally reception by the sensor. Following these equations it can be noted that phase of the received signal $V_a(\omega)$ is reduced by $K(\omega)r_0$, where $K(\omega)$is dispersion curve; dependent on the frequency. Accordingly, different frequency components of the signals will have different time arrivals to the sensor. The TDDT transforms "original" signal taking into account each frequency components and its time arrival according to the dispersion curve. Finally the signal in the space domain is obtained, which can be denoted as:

$$v(r) = v_a(r) * h(r) \tag{4}$$

with $h(r)$ as distance impulse response and $v_a(r)$ as IFT result of $V_a(\omega)$.

Once the TDDT is applied to an AE signal, the time domain is converted into distance domain. Subsequently estimation of damage location can be done in a straightforward manner. More details on TDDT can be found in [7]. It should be emphasized that the procedure requires no parameters tuning, as all can be estimated prior to measurement.

2. Numerical simulations

First the method was verified using numerical simulations. For this purpose, the Graphical Processing Units (GPU) based Local Interaction Simulation Approach (LISA) has been used [5]. A 3D model of a plate has been build and excited using a model source. The time signal representing the source was obtained through an inverse analysis of experimental test [8]. Virtual sensors were placed at the plate's surface to collect time responses. Then, the TDDT was applied and damage localisation performed.

2.1 Metallic plate numerical simulation

To test effectiveness of proposed method, a virtual experiment was carried out. The setup reconstructed the actual laboratory test to be performed. Plate dimensions were 1000x500x10 mm. Steel material properties were assumed, i.e. E = 180 000 [MPa], ρ = 7750 [kg/m^3], η = 0.33 [-]. Since magnetic holders are typically used to attach the transducer to the structure, the model included cylindrically shaped objects at plate's surface. The dimensions of the cylinders were: diameter equal to 16 mm and height of 3 mm. Material properties of the magnets were E = 230 000 [MPa], ρ = 7500 [kg/m^3], η = 0.24 [-]. Responses were acquired as time signals of out-of-plane displacement component of a single grid point. Excitation was applied in several positions to verify the proposed approach. Positions were defined as: Sen.1 - x = 270 mm, y = 250 mm, Sen.2 - x = 350 mm, y = 180 mm, Sen.3 - x = 500 mm, y = 200 mm and Sen.4 - x = 800 mm, y = 300 mm. Figure 1 shows numerical model used in calculations with cylindrical magnets attached.

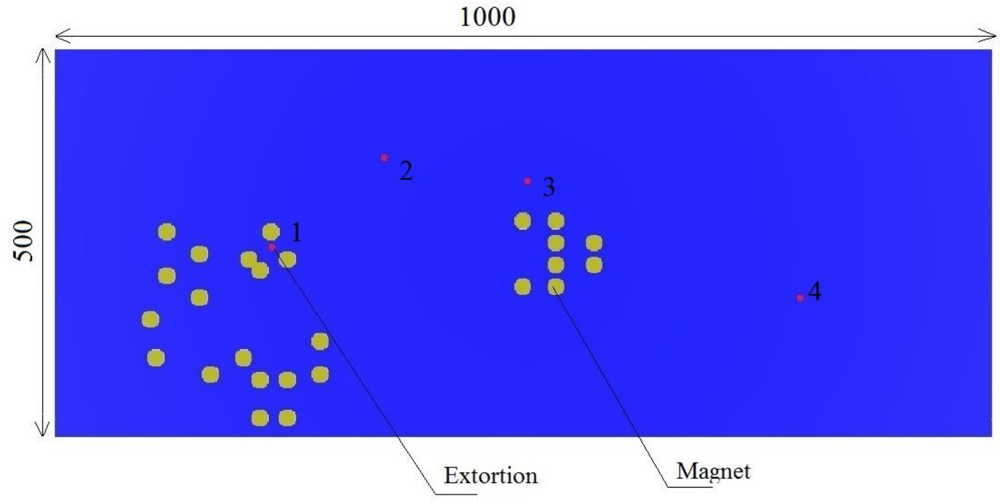

Fig. 1. Magnets and excitation positions

The plate was excited by two previously identified [8] time signals modelling a HSU-like source (see Figure 2). The responses were recorded by four sensors. The transient dynamic analysis consisted of 2000 time steps, corresponding to analysis time of 200 μs.

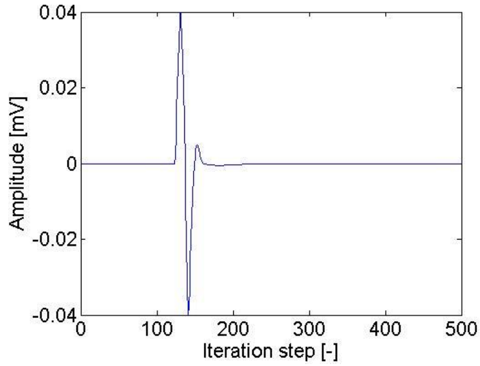

Fig. 2 An example of excitation signal modelling the HSU source.

Results obtained after importing sensor data to MATLAB and running proposed localization method are summarized below. Red stars show localization results, black circles are points, where actuators were placed. Blue circles are sensors positions.

In Figure 3 it can be seen that the accuracy of the algorithm is approximately 75% when it comes to events detection. For very close and very far excitation points, the method was not found accurate due to edge reflections and internal reflection from the magnets.

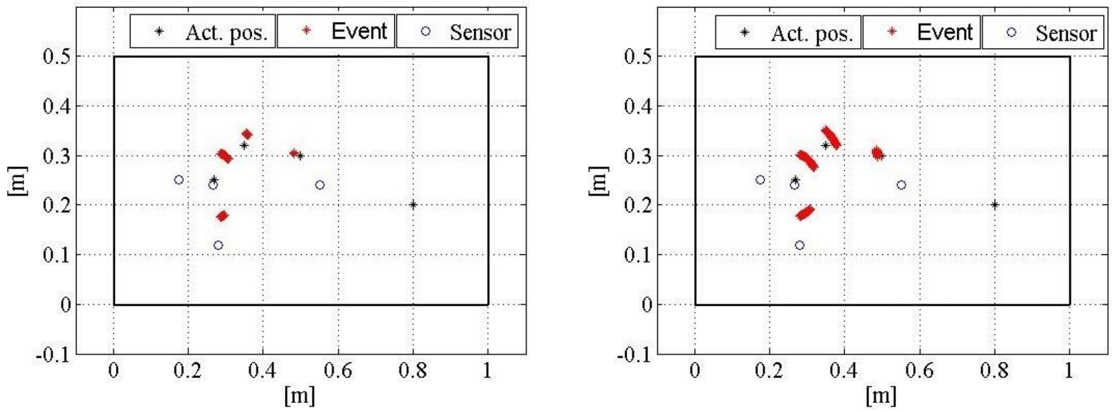

Fig. 3 Localization results for model HSU excitation signals (1) and (2) on plate

3. Experimental tests

Subsequently, a set of experiments was performed. A steel plate of dimensions 1000x500x10 [mm], was equipped with 4 sensors, as presented in Figure 4. The setup was analogous to numerical model. Measurement hardware used was Vallen GMBH unit with four channels. Four sensors of type VS150-M with preamplifiers AEP4H were used. The plate was excited by pencil throughout the plate, between sensors 1, 2, 3, as well as with pulser near the locations of sensors 1 - 4.

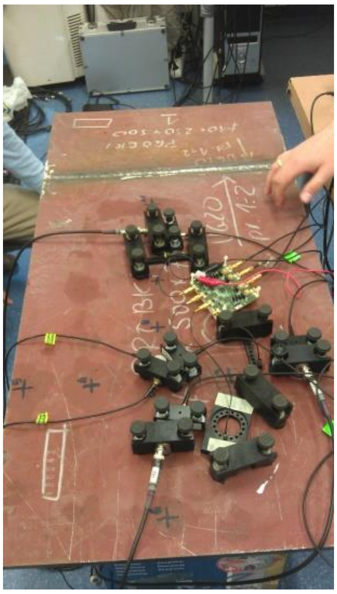

Fig. 4. Measurement setup

Figure 4 shows the experimental setup. Obtained experimental data were first processed by default localisation algorithm for planar structures. The localisation algorithm requires the wave speed to be provided by the user. The following values were used to determine source position: 5100 [m/s] and 3300 [m/s]. Results for each wave speed value are presented in Figures 5 and 6. Presence of large number of magnets has lead to wave reflections. This results in very large number of recorded artificial events, both in proposed and industrial localization methods.

The same dataset was loaded into the TDDT-based localisation framework outlined in section 2. Elastic constants, density and plate thickness used by the algorithm were E = 180 000 [MPa], ρ = 7750 [kg/m^3], η = 0.33, and were chosen as average values for steel. Localisation results obtained by the proposed framework for respective source positions are shown in Figure 7.

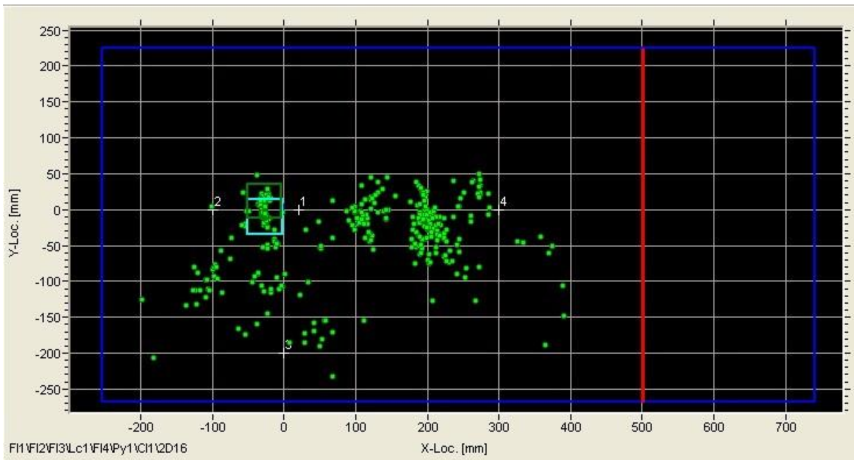

Fig. 5 Vallen software results for velocities: 3300 [m/s]

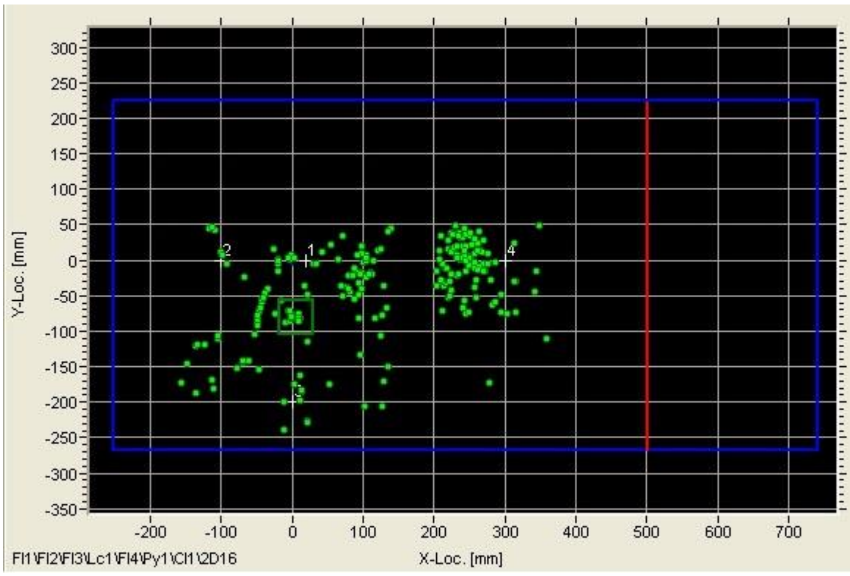

Fig. 6 Vallen software results for velocities: 5100 [m/s]

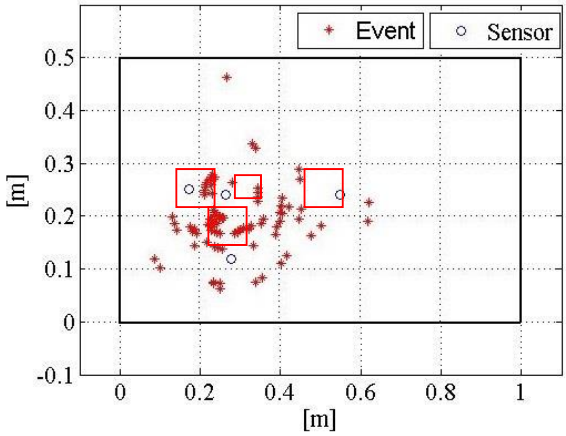

Fig. 7 Results obtained using TDDT method

Red rectangles represent areas, where excitations were conducted. Results are very similar for both methods. Vallen Systeme software gives different localization which varies, depending on set wave velocity travelling through medium. Proposed method however has its problems when it comes to events occurring in more distant areas of a plate. As there were many HSU and HSU-like extortions near sensors 1, 2 and 3, it is most likely that results received through both ways gave accurate crack positions, however using TDDT we omit the influence of the operator on the system (there is no need for assumption of wave velocity).

4. Conclusions

Proposed algorithm has shown promising results when applied to localization of artificial sources in metallic plates. As the method is still in early development stage, there is great potential for creating an efficient tool for AE source localisation. The ultimate goal of the work is to avoid providing tuneable parameters for damage localisation. Instead, only physical parameters, such as elastic constants and plate thickness are used. On-going work is focused on decreasing accuracy errors for events occurring near and very far away from sensors. Implementing solutions for dealing with dispersion phenomenon has great potential when it comes to defining event occurrence distance in regard to sensors positions. Comparison of numerical and experimental results shows, that there are discrepancies between these two environments. They occur mostly due to simplifications of input parameters such as sensors or actuator positions, material properties and object dimensions. However, similarities can be shown in every aspect of identification, thus proving the usefulness of numerical simulations.

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