ACOUSTIC EMISSION SOURCE DETECTION USING THE TIME REVERSAL PRINCIPLE ON DISPERSIVE WAVES IN BEAMS

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ABSTRACT: The common approach for the localization of acoustic emission sources in a beam requires at least two measurements at different positions on the structure. The acoustic emission event is then located by evaluating the time-difference of the arriving elastic wave at two positions. This paper introduces a new method, which allows the detection and localization of multiple acoustic emission sources with only a single, one point, unidirectional measurement. The method makes use of the time reversal principle and the dispersive propagation behavior of the first bending mode. Whereas time of arrival (TOA) methods struggle with the distortion of elastic waves due to phase dispersion, the presented method uses the dispersive behavior to locate the origin of the acoustic emission event. Therefore, the localization algorithm depends solely on the measured wave form and not on arrival time estimation. The method combines an acoustic emission experiment with a numerical simulation, in which the measured and time reversed displacement history is set as the boundary condition. It is shown, that geometrical effects such as thickness changes or geometrical discontinuities do not affect the detection of acoustic emission events.

In this paper, the method is described in detail and the feasibility is experimentally demonstrated by investigating acoustic emission events which are produced by breaking pencil leads on an aluminum beam according to ASTM E976 (Hsu-Nielsen source). The relative error in localizing the acoustic emission sources was found to be below 1%.

INTRODUCTION

Acoustic emission (AE) in the field of nondestructive testing according to ASTM E1316 - 11b Standard Terminology for Nondestructive Examinations refers to transient elastic waves that are generated by the rapid release of energy from localized sources within a material. These AE signals may arise due to growing cracks in monolithic materials or breaking fibers or fiber-matrix cracking in composite materials, see for e.g. Salinasa et al. (2010), Kundu et al. (2008) and are used as an indicator in nondestructive testing applications to monitor the integrity of critical structures.

An important aspect of AE testing is the ability to determine the location of AE sources. The standard procedure for AE source localization relies on the identification of precise arrival times and the knowledge of an appropriate propagation velocity. With these parameters, a triangulation method can be established where the source is identified as the intersection of three circles, whose centres are the sensors location, also known as Time of Arrival Methods (TOA), see for e.g. Tobias et al. (1976).

Beside TOA methods, there is a group of methods, that explicitly uses the different wave speed of different lamb wave modes for the localization of AE sources. These methods are known as Single Sensor Modal Analysis Location (SSMAL) methods, since they allow the determination of the transducer-source distance with only one sensor, see for e.g. Baxter et al. (2007), Pullin et al. (2005).

The method presented here is related to the above mentioned SSMAL methods in the sense, that it uses the relative shape of a dispersing wave to determine the location of the AE source. This approach combines the ease of using less transducers as found in SSMAL techniques and the
robust performance in structures with complex geometries. The application of a time reversal numerical simulation for guided wave testing was previously studied by Leutenegger and Dual (2002) and Ernst, Weder and Dual (2012). These studies showed promising results for the localization of notches and cracks in tubes and beams. The concept of using time reversal mirrors in wave propagation problems was first investigated by Fink et al. (2000).

METHOD

Acoustic Emissions are typically broadband and therefore can raise many propagating modes in a beam. Holford et al. (1999) found, that most of the energy is carried by the first symmetric and asymmetric lamb modes. The first asymmetric lamb mode, here referred as flexural wave, shows strong dispersive behavior at low frequency - thickness numbers. Therefore, an AE initiated flexural wave pulse distorts and diverges as it travels along the beam. The presented method for locating AE sources consists of two steps. In a first step, the lateral deflection due to the incident flexural wave is measured at the end of the structure by means of a laser vibrometer. In a second step, the measured displacement data is reversed in time and set as the boundary condition in a numerical model of the beam. In the simulation, the distorted flexural wave form recompresses and reaches maximal amplitude at the location of its origin. This allows the detection of the AE source by simply finding the local maxima in an x-t diagram, also known as Lagrange diagram.

![Figure 1. Experimental setup for AE experiments. Pencil leads were broken at location \([1.3 \text{ m}, 1.5 \text{ m}, 1.7 \text{ m}]\) for the uniform beam and at \([0.8 \text{ m}, 1.3 \text{ m}, 1.5 \text{ m}]\) for the two non-uniform beams.](image1)

![Figure 2. Geometry of the 3 beams. All beams have a square cross section with 6 mm side length and a total length of 2 m. Two beams were prepared with machined discontinuities. Beam 2 has a reduced crosssection from 6 x 6 mm to 6 x 4 mm along 100 mm. Beam 3 contains 3 notches at different sides that are 2 mm deep and 1 mm wide. Locations where AE were triggered are marked with an X.](image2)

After having converged at the location of the AE source, the different frequency components of the flexural wave will diverge again leading to a decrease in the amplitudes of the flexural wave. This allows the detection of multiple AE events with a single measurement. The method described here requires only a single, one point, unidirectional measurement, because only the dispersion of the flexural wave mode is used. A further advantage is, that multiple AE can be detected because the wave amplitudes decrease after having converged at the source position.
Multiple AE sources at an identical position are temporally separated in the Lagrange diagram. Acoustic emission parameters extracted from the simulation of several AE sources at different positions can easily be compared because dispersive effects on the shape of the waveform are inherently compensated. However, the effect of damping on the waveform is not compensated.

**Experiment and numerical simulation**

After having obtained the necessary material parameters, AE experiments were performed. In order to validate the method, we artificially created AE source by breaking pencil leads on the surface of a beam, according to ASTM E976. The experimental setup is depicted in Figure 1. We performed AE measurements on three different beams, all being 2 m long and having rectangular cross sections, see Figure 2. Beam 1 is uniform along its length and has a quadratic cross section with a side length of 6 mm. Beam 2 is a similar beam, but between x = 1.6 m and x = 1.7 m, the cross section is reduced to 4 mm x 6 mm. Beam 3, again similar to beam 1 but at x = 0.7 m, x = 1.0 m and x = 1.9 m, notches were machined into the beams, with a depth of 2 mm and a width of 1 mm. Beam 2 and beam 3 were designed to investigate the performance of the method for non-uniform structures.

Figure 3 shows an example of a measured displacement vs. time signal obtained by breaking a pencil lead on a beam. This data is then filtered and reversed in time. Figure 3c) shows the normed amplitude spectrum of both signals.

With a single point measurement at a location within the beam, the propagation direction of a recorded wave remains unknown. Therefore, the measurement is done at the end of the beam. However, at the free end of a structure, one measures not only the incident wave but also the reflected wave and local vibrations. The incident wave must be carefully extracted from the total displacement, see for example Mei & Mace (2005).

The numerical simulation is done with Abaqus Explicit 6.9, a commercial FEA program. The beam was modeled as a 2D plane stress structure, using quadratic linear quadrilateral elements of type CPS4R. The beams were modeled longer than they were in reality in order to avoid reflections. The lateral displacement at the measurement position at the end of the beam was...
prescribed by the time reversed displacement vector for the entire cross section. The rotary degree of freedom was not prescribed.

RESULTS

Table 1, 2 and 3 list the results from the AE measurements. The first column displays the position X, where the acoustic emission is triggered. An uncertainty of ± 1 mm in the triggering location is assumed. The three following columns x₁, x₂ and x₃ list the predicted positions from three individual measurements.

**Table 1.** Results from the time reversal numerical simulation for the uniform beam 1.

<table>
<thead>
<tr>
<th>X [m]</th>
<th>x₁ [m]</th>
<th>x₂ [m]</th>
<th>x₃ [m]</th>
<th>err_mean [m]</th>
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<tr>
<td>1.7</td>
<td>1.700</td>
<td>1.699</td>
<td>1.697</td>
<td>0.001</td>
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<tr>
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<td>1.499</td>
<td>1.502</td>
<td>1.503</td>
<td>0.002</td>
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<td>1.301</td>
<td>1.306</td>
<td>1.303</td>
<td>0.003</td>
</tr>
</tbody>
</table>

**Table 2.** Results from the time reversal numerical simulation for the non-uniform beam 2.

<table>
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<th>X [m]</th>
<th>x₁ [m]</th>
<th>x₂ [m]</th>
<th>x₃ [m]</th>
<th>err_mean [m]</th>
</tr>
</thead>
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<td>1.502</td>
<td>1.499</td>
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</tr>
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<td>1.304</td>
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<tr>
<td>0.8</td>
<td>0.808</td>
<td>0.805</td>
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<td>0.008</td>
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**Table 3.** Results from the time reversal numerical simulation for the non-uniform beam 3.

<table>
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<th>x₁ [m]</th>
<th>x₂ [m]</th>
<th>x₃ [m]</th>
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<td>1.297</td>
<td>1.299</td>
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<td>0.8</td>
<td>0.803</td>
<td>0.803</td>
<td>0.802</td>
<td>0.003</td>
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</table>

DISCUSSION

**General Reproducibility and accuracy of the method**

Every simulated acoustic emission was detected and localized with a maximal error of 12 mm or 6 \( \% \) with respect to the length of the beam. The average error over all measurements is 4 mm or 1.8 \( \% \) with respect to the length of the beam. The reproducibility and accuracy was good considering the uncertainty of ± 1 mm in the triggering of the AE. The method performed reliable with no missed or wrong detections. As can be seen in Figure 1, the distance a wave travels from source to detector is not X, but 2 m – X, with X being the position of the AE source. A tendency is noticeable, that the localization error increases with larger source-detector distances. This could be
explained with a not perfectly matching propagation speed in the model. However, the dataset is too small to see statistically significant effects.

Results for the non-uniform beam 2
The geometry of beam 2 is similar to beam 1 but has a symmetric reduction of the cross-section between 1.6 m and 1.7 m from 6x6 mm to 4x6 mm. Waves, that were excited by the pencil lead, pass this section before they are recorded by the laser vibrometer at the end of the beam. Despite this non-uniformity, the AE was again localized with an overall error of 6 mm with the time reverse simulation accounting for the reduced cross-section. By using a straight beam without a reduction of the cross-section as a model in the time reversal simulation, the AE was still detected but with an localization error of 23 mm. A simple hand calculation using Bernoulli theory and assuming a center frequency of 10 kHz for the measured wave makes this result plausible. The group velocity for the two beam sections are:

\[ c_{gi} = 2 \left( \frac{EI}{\rho A_i \omega^2} \right)^{1/2} \]  \hspace{1cm} (1)

where \( E \) is the Young’s modulus, \( I \) the second moment of area, \( \rho \) the density, \( A_i \) the respective cross-section and \( \omega \) the angular frequency. The localization error due to an inaccurate geometric model without the reduced cross-section is in that case 0.0225 m. For precise localization of the AE source, we need an accurate numerical model of the structure, however, if the model has some inaccuracies, the AE can still be identified and detected. As opposed to traditional TOA methods, the geometry can be rather complex without affecting the localization of the AE.

Results for the non-uniform beam 3
The non-uniform beam 3 contained several sharp notches, as illustrated in Figure 2. Waves originating from pencil lead breaks, hit these notches and are again reflected at these discontinuities, but by far the most part of the energy is transmitted without any noticeable change in the waveform. Dual et al.(1990) discussed reflection and transmission coefficients for beams with lateral notches and reported, that, although frequency dependent, the transmission coefficient is always much larger than the reflection coefficient for an incident flexural wave. Therefore, all AE were successfully localized with a mean error of 0.002 m. The localization error did not change significantly for simulations that incorporate the notches in the model and simulations without the notches. This result implies, that it is more important, that the simulation accurately captures the overall wave propagation characteristics than that it incorporates every small geometric detail to achieve good AE localization results. On the other hand, a one point measurement of only a short period, as done in these experiments, might not suffice to recover the exact waveform amplitude of the original AE because reflections and mode conversions at scatterers result in a leakage in the recording of the wave information.

CONCLUSIONS
A single one point, unidirectional measurement with a laser vibrometer and a subsequent numerical simulation, was successfully used to localize acoustic emission sources simulated by breaking pencil leads on the surface of both uniform and non-uniform aluminum beams. No time of arrival information was used. The method requires, that the structure is of one dimensional shape, the acoustic emission triggers first order flexural wave modes at a frequency range, where phase dispersion occurs and the sensor is sensitive in the respective frequency range. As a side benefit, the waveform of the acoustic emission event is recovered during the simulation and
acoustic emission features can be extracted and compared within AE sources at different locations. We note, that the breaking of a pencil leads on the surface of the beam excited very dispersive flexural waves. This was beneficial for the reported method. The performance of the described method in real AE applications is subject of further studies.

REFERENCES

Leutenegger, T., Dual, J. (2002). Detection of defects in cylindrical structures using a time reverse method and a finite-difference approach. Ultrasonics, 721-725.