ACOUSTIC EMISSION SOURCE ORIENTATION BASED ON TIME SCALE

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Abstract

This paper presents the identification of the acoustic emission (AE) source orientation using the time reversal or the phase shift. The methodology requires a data acquisition system that does not modify the phase information directly detected from the AE transducers; however, it is applicable to any kinds of sensor, resonant or broadband. Using finite element simulations, the relative time reversal and scaling values of the AE transducers are evaluated to develop a correlation between the relative data and the source orientation. The numerical results are evaluated using an experimental scheme and pencil-lead break simulations at different angles. Understanding the source orientation provides the directions of the acoustic wave patterns, which can be used to improve the source location accuracy with proper wave velocity selection and the source characterization.

Keywords: Source orientation, time scale, phase shift

Introduction

The AE method has various successful applications for detecting and locating the damage in many field testing of civil structures (e.g. Nair and Cai, 2010). However, the method’s ability to identify the source orientation with available techniques requires diligently recorded AE signals without influenced by the sensor’s transfer function, electronics and reflections as well as noise. Ohtsu and Ono (1986) used the generalized theory to identify the source representations of AE at different angles and modes. The theory requires the deconvolution of waveform signature and Green’s function of the medium to find out the source representation. The authors showed the effect of crack orientation on the amplitude of the first wave arrival. This approach requires precise AE signature detection directly from the source. Ohtsu and Ono (1988) demonstrated the dependence of the amplitude of the incident P-wave to the crack orientation. However, the P wave amplitude may be influenced by other factors such as source intensity. Gorman and Prosser (1991) demonstrated that the source orientation can be extracted from the in-plane and out-of-plane displacement components of waves in plate-like structures. However, separating the amplitudes of two wave motions requires sufficiently long source-sensor distance, and the waveform should not be affected by extraneous noise and reflections.

The identification of source orientation with respect to the sensor coordinate can be critical for the accurate source localization and the source characterization. For example, depending on the crack growth direction and the sensor location, the acoustic radiation patterns control the amplitudes of longitudinal and shear wave amplitudes as angle and source dependent such as normal tear, transverse shear or longitudinal shear (Lysak 1996). The approach in this study to understand the AE source orientation is based on the time scales (i.e., phase differences) of the first arrival waveforms recorded at various sensor positions. As the source orientation depends on the first wavefront, the approach is not affected by reflections or resonating behavior of conventional AE transducers. The approach has been demonstrated with numerical models and experimental
studies. Current AE instruments require electronics at the pre-amplification level that modify the phase of the waveform. Therefore, in this study, the data was recorded using an oscilloscope without any pre-amplification.

**Basis of the Correlation**

The discrete time signals $x$ can be represented as $x[\alpha t + \beta]$ where $\alpha$ represents time scaling and reversal, and $\beta$ represents time shift. If $\alpha$ is less than 0, the signal is reversed in time. If $\beta$ is nonzero, the signal is shifted in time (Oppenheim and Willsky 1997). The time scaling and shift for a signal to match with the reference signal $y_2$ is calculated using the following correlation:

$$x[\alpha t + \beta] \rightarrow y[t]$$

where $x$ represents the original output of an AE sensor, and $y$ represents the modified form of $x$ to match with $y_2$. If two signals, $y$ and $y_2$, match, their cross correlation coefficient should be equal to 1 with 0 time delay using the following formulation:

$$R_{yy_1}(\tau) = \sum_{t=1}^{N} y(t)y_1(t + \tau)$$

where $R_{yy_1}(\tau)$ is the cross correlation coefficient of two signals, $y$ and $y_1$, as a function of a time delay $\tau$, $N$ is the length of signals. The time scale of two AE sensor responses is dependent on the AE source orientation. This is related to the radiation pattern of elastic waves released at different angles with respect to the sensors. As the complete AE waveforms are influenced by many factors such as the sensor response, source-sensor distance and path, only the first wave arrivals of two AE sensor responses placed relative to the AE source are analyzed in order to demonstrate the correlation of the time scale and the source orientation.

**Numerical Simulations**

Finite element simulations are conducted using the structural module of COMSOL 4.2 Software. The structural geometry is made of aluminum with 5-mm thickness. The finite element model is approximated as 2D plane stress model. The source simulation function is applied at the right side of the hole placed at the center as shown in Fig. 1a (distance given in m). The source angle is varied from 90° (relative to the horizontal axis) to -90° with 15° increments. The source simulation function is defined by equation 1 and plotted in Fig. 1b for 100 kHz excitation signal.

$$F(t) = \sin(2\pi f_o t)(1 - e^{-t/t_{rise}})e^{-t/t_{decay}}$$

where $t_{rise}$ is rise time, $t_{decay}$ is decay time and $f_o$ is frequency. The time step $\Delta t$ and element size $l$ for finite element calculations of propagating elastic waves for a stable and accurate solution without any numerical pollution (Hill et al. 2004) are

$$\Delta t = \frac{1}{20 f_{max}} \quad l = \frac{\lambda_{min}}{20}$$

where $f_{max}$ is the maximum frequency of interest and $\lambda_{min}$ is the minimum wavelength involved. Three frequencies are studied in order to demonstrate the frequency independence of the time scale-source orientation relationship: 50 kHz, 100 kHz and 200 kHz. The mesh size and the time step for each frequency are given in Table 1.
Table 1. Time step and mesh sizes for three AE source frequencies.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Time step (sec)</th>
<th>Mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1E-6</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>0.5E-6</td>
<td>2.5</td>
</tr>
<tr>
<td>200</td>
<td>2.5E-7</td>
<td>1</td>
</tr>
</tbody>
</table>

The oscillatory nature of the wave equation requires fine meshing, which increases the computational time significantly when the target frequency increases as shown in Table 1. Therefore, the geometry in this study is divided into two regions: near field for the observation points pt1 to pt4 as shown in Fig. 1a and far field outside the observation points. For the near field region (inside the small square shown in Fig. 1a with solid lines), the mesh size for the target frequency is selected using equation 2, given in Table 1. The far field region (between two squares shown in Fig. 1a) is included into the model in order to prevent any reflections from boundaries to the observation points during the simulation duration. However, the second region is coarsely meshed as shown Fig. 2 as the numerical accuracy is not intended.

A total of 39 finite element simulations are studied (13 different angles and 3 different source frequencies). Figure 3 shows the simulation results of three angles (i.e. 90°, 60° and 30°) for each AE source frequency. The solid line shows the strain history in –z direction (perpendicular to the planar view) for the observation point pt2 as shown in Fig. 1a; the dashed gray line shows the strain history in –z direction for the observation point pt4. For the 50 kHz AE source simulation signal, the first wave arrival is at 1.1 µs which is equivalent to 6120 m/s wave velocity as the distance between the excitation location and the observation points is 0.067 m. The second wave arrival occurs about 48 µs, which is equivalent to 1400 m/s wave velocity. For the 100 kHz excitation signal, the first wave arrival is at 1.1 µs, while the second wave arrival is at 41 µs. For the 200 kHz excitation signal, the first wave arrival is at 1.1 µs, while the second wave arrival is at 32.5 µs. The reason for the variation of the second wave arrival with the excitation frequency is the dispersion characteristic of the flexural mode. The first wave arrival is the same for all three frequencies as the extensional mode is non-dispersive here. As the source excitation in
planar direction, the extensional wave mode has higher amplitude than the flexural wave mode. When the excitation frequency is increased from 50 kHz to 200 kHz, the arrival times of two wave modes are separated further due to smaller cycle duration of higher frequency excitation. The separation of two wave modes for low frequency source is more difficult than high frequency sources.

![Fig. 2. Meshed geometry with two different mesh sizes. Distances in m.](image)

There is a clear time scale difference of the waveforms at pt2 and pt4 depending on the source orientation or the angle with respect to each sensor. For 90° simulation, the angle between the source and the observation pt2 is 42°; the angle between the source and the observation pt4 is 138°. For 60° simulation, the angle between the source and the observation pt2 is 12°, the angle between the source and the observation pt4 is 108°. For 30° simulation, the angle between the source and the observation pt2 is 18°, the angle between the source and the observation pt4 is 78°. If the angle is less than 90°, the waveform has positive slope at the first wave arrival, while it has negative slope if the angle is greater than 90°.

The time scale value of two sensor responses under the given simulation angle is calculated by finding the linear curve fit of the first wave arrival. Figure 4 shows an example of two sensor waveforms (solid line for pt2, dashed line for pt4) together with the curve fit to the first wave arrival. The ratio of the slopes provides the time scale $\alpha$ of two sensors.

$$\alpha = \frac{\left(\frac{df_2}{dt}\right)_{t=t_0}}{\left(\frac{df_1}{dt}\right)_{t=t_0}}$$  \hspace{1cm} (3)

where $f_1$ indicates the reference waveform that has the highest positive slope, $f_2$ indicates the second AE sensor response. Time scale is represented by the derivatives of waveforms at the first wave arrival at $t_o$. 

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Fig. 3. The simulation results of 90°, 60° and 30° source angles for (a) 50 kHz excitation, (b) 100 kHz excitation, (c) 200 kHz excitation.

Fig. 4. The linear curve fits to the first wave arrivals.
Table 2 shows the slopes of the waveforms recorded at pt2 and pt4 locations under 13 different simulation angles and three different simulation frequencies. As discussed above, if the angle between the source and the sensor is less than 90°, the slope has positive value (e.g., 90° to –30° for the location pt2). If the angle between the source and the sensor is greater than 90°, the slope has negative value. This is the reason for the sign changes of the waveforms at pt2 at –45° and the waveforms at pt4 at 45°. The slopes for each simulation angle under three simulation frequencies are different; however, their ratios (i.e., time scales) are the same. Figure 5 shows the time scales with respect to the simulation angles for three frequencies. The figure indicates that the time scale to identify the source orientation is independent of the frequency. For unknown source orientation, the graph in Fig. 5 can be used together with the time scale of two AE sensors in order to identify the source orientation.

Table 2. The slopes of the first wave arrivals and their time scales for 3 excitation frequencies.

<table>
<thead>
<tr>
<th>Ext. Angle</th>
<th>50 kHz source</th>
<th>100 kHz source</th>
<th>200 kHz source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pt2</td>
<td>pt4</td>
<td>Time scale</td>
</tr>
<tr>
<td>90</td>
<td>4.07E-09</td>
<td>-4.40E-09</td>
<td>-1.08</td>
</tr>
<tr>
<td>75</td>
<td>5.00E-09</td>
<td>-3.00E-09</td>
<td>-0.60</td>
</tr>
<tr>
<td>60</td>
<td>5.77E-09</td>
<td>-1.85E-09</td>
<td>-0.32</td>
</tr>
<tr>
<td>45</td>
<td>5.11E-09</td>
<td>-5.32E-10</td>
<td>-0.10</td>
</tr>
<tr>
<td>30</td>
<td>5.93E-09</td>
<td>1.42E-09</td>
<td>0.24</td>
</tr>
<tr>
<td>15</td>
<td>5.23E-09</td>
<td>2.84E-09</td>
<td>0.54</td>
</tr>
<tr>
<td>0</td>
<td>4.46E-09</td>
<td>4.46E-09</td>
<td>1.00</td>
</tr>
<tr>
<td>-15</td>
<td>2.60E-09</td>
<td>5.24E-09</td>
<td>0.50</td>
</tr>
<tr>
<td>-30</td>
<td>1.32E-09</td>
<td>5.35E-09</td>
<td>0.25</td>
</tr>
<tr>
<td>-45</td>
<td>-4.96E-10</td>
<td>5.88E-09</td>
<td>-0.08</td>
</tr>
<tr>
<td>-60</td>
<td>-1.63E-09</td>
<td>5.77E-09</td>
<td>-0.28</td>
</tr>
<tr>
<td>-75</td>
<td>-3.00E-09</td>
<td>4.88E-09</td>
<td>-0.61</td>
</tr>
<tr>
<td>-90</td>
<td>-4.40E-09</td>
<td>4.40E-09</td>
<td>-1.00</td>
</tr>
</tbody>
</table>

Experimental Simulation

The numerical results are validated with the experimental simulation. A thin aluminum plate with dimensions of 610 x 432 x 1 mm was utilized for the experimental study. The plate was instrumented on its top surface with two nano AE sensors, which were mounted on the plate using high vacuum grease. The sensors were placed with their centers at 156 mm from the long edge and 406 mm from the short edge of the plate. They were connected directly to a digital oscilloscope (MSO2014 oscilloscope with 100 MHz bandwidth and 1 GS/s sample rate) for data collection without any pre-amplifier. As the oscilloscope has high input impedance of 1 MΩ, it does not require any impedance matching electronics between the data acquisition unit and the AE sensors. The AE simulations were conducted using 0.7-mm pencil-lead breaks at a location of 216 mm from the long edge and 165 mm from the short edge on the top of the plate (Fig. 6). The source-sensor distance in the experimental simulations is the same as the numerical simulations.
The angle of the pencil with respect to the surface was about 30°. Ten lead breaks were generated at five different angles (two repetitive simulations at each angle). Another set of experiments were conducted for longer sensor-source spacing in order to understand whether the distance affects the measurement. Similar test results were obtained, which is due to non-dispersive characteristics of extensional wave mode (the first wave arrival).

![Graph showing time scale change with respect to the source angle for three source frequencies.]

**Fig. 5.** Time scale change with respect to the source angle for three source frequencies.

![Diagram of experimental setup.]

**Fig. 6.** Experimental setup.

Figure 7 shows the waveforms of two AE sensors, windowed to the first wave arrival, under the AE source simulation at 90°. The ratio of the slopes to the first wave arrival of sensor 1 and sensor 2 is –1, which agrees with the numerical time scale. The frequency of the first wave arrival is identified as 293 kHz using the windowed frequency spectrum analysis. While the numerical simulations are conducted up to 200 kHz, the experimental result for 293 kHz frequency agrees with the numerical simulations. This reconfirms the independence of the approach from the frequency. The waveform signatures of two AE sensors are not identical while their distances to the simulation point are the same and the AE sensors are the same type. This may be because
of small variations of sensor responses or the coupling thickness. Therefore, the approach in this study is to find the correct time scale value to match the first wave cycles of two AE sensors, instead of matching two complete waveform histories.

![Graph showing linear curve fits to the first wave arrival.](image)

Fig. 7. The linear curve fits to the first wave arrival.

Table 3. The slopes of the first wave arrivals and their time scales for two sets of experimental result.

<table>
<thead>
<tr>
<th>Source Angle</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensor 1</td>
<td>Sensor 2</td>
</tr>
<tr>
<td>90</td>
<td>2704</td>
<td>-2599</td>
</tr>
<tr>
<td>45</td>
<td>4838</td>
<td>-189.6</td>
</tr>
<tr>
<td>0</td>
<td>2634</td>
<td>2516</td>
</tr>
<tr>
<td>-45</td>
<td>-601</td>
<td>5189</td>
</tr>
<tr>
<td>-90</td>
<td>-3326</td>
<td>3607</td>
</tr>
</tbody>
</table>

Figure 8 shows the waveforms of the AE sensors as the positions of sensor 1 and sensor 2, which are recorded by the digital oscilloscope and re-plotted in Matlab with time shifts in order to match the arrivals of the first wave fronts. There are slight differences in the arrivals of two sensors. The time shift values $\beta$ for each source angle simulation are reported in the plots. There are no distinct arrival differences of extensional and flexural wave modes due to the proximity of the source to the sensors. However, the extensional wave mode amplitude is less than the flexural wave mode amplitude as the simulations are conducted on the surface of the plate with 30° angle and the sensors are more sensitive to the out-of-plane direction.

As an example of the analysis of the time scale as related to the source angle, Fig. 8c shows the simulation for 0° (the source oriented at the same angle to the sensor 1 and the sensor 2). After the first wave arrivals are matched with the time shift, the slopes of the first wave of two sensors are identical, which indicates that the time scale value is 1. For each angle the experiment conducted twice in order to minimize the error. Also for each of five source angles, time shift
and scale factor are calculated and shown in Fig. 8 and Table 3. The time scale factors for each source simulation angle agree with the numerical results.

Fig. 8. The experimental results of various source angles and time shift: a) 90°, $\beta = 2 \times 10^{-7}$, b) 45°, $\beta = 2 \times 10^{-7}$, c) 0°, $\beta = 4 \times 10^{-7}$, d) -45°, $\beta = 1 \times 10^{-6}$.
Conclusions

This paper demonstrates the identification of the AE source orientation based on the time scale of two AE sensors located relative to the AE source. The methodology requires no phase deformation due to the components of the data acquisition system, such as pre-amplifier and AE hardware. The source angle identification is demonstrated numerically for various frequencies in order to show that the time scale factor due to the source orientation is independent from the frequency. The experimental results validate the methodology, which can be used to increase the accuracy of source location with correct velocity selection and the source characterization. Both numerical and experimental simulations are conducted on thin plates. The approach needs to be validated for thick plates.

References