Frequencies and Amplitudes of AE Signals in a Plate as a Function of Source Rise Time

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Keywords: AE source rise times, frequency spectrum, peak amplitude, thin plate

Abstract

Based on some preliminary studies that showed a potentially strong dependence of AE signal peak amplitudes on the source rise time, a detailed study was undertaken. The study used a validated finite element code to model the source operation and subsequent wave propagation up to a distance of 480 mm in a 4.7 mm thick aluminum plate with large transverse dimensions. To obtain the large propagation distances with sufficient transverse dimensions so that plate edge reflections did not arrive during the direct AE signal, an axi-symmetric code was used. The buried dipole AE sources were located at three different depths below the top surface of the plate, where the pseudo AE sensors were located. These sensors provided the out-of-plane displacement as a function of time. The rise times for the different finite element runs varied from 0.5 µs to 15 µs. The resulting data was high-pass filtered at 40 kHz and resampled with a time step of 0.1 µs. The peak amplitude dependence was determined as a function of the source rise time for the three different source depths. Also, the attenuation of the signal peak amplitude (due to geometric spreading and dispersion) as a function of distance was determined as well. In addition, the Fast Fourier Transform was calculated for the signals. An exponential increase in peak amplitude was found as the source rise time decreased from 3 µs to 0.5 µs. As expected, the higher frequencies were not present in the AE signals as the source rise time increased. There were also relatively large losses in peak signal amplitude over the propagation from 60 mm to 480 mm.

Introduction

In the analysis of burst-type acoustic emission (AE) signals, the peak amplitude and the frequency content of the signals are two features that are often determined. In published AE works (to numerous to cite), these features either by themselves or combined with additional features have been examined for the purpose of AE source identification. Certain experimental realities can complicate the use of these features for source identification. For example, the original frequency content of AE burst signals can be altered by the sensor’s frequency response sensitivity (based on sensor resonances and the sensor aperture), by the modes of guided wave propagation (different parts of the modes that have different levels of intensity), by the depth of a buried AE source in a plate [1] and by the electronic frequency bandpass. Other experimental aspects specifically affecting the peak amplitude of AE bursts include the realities of geometric spreading, material attenuation, signal dispersion and signal reflections (from test sample boundaries alter the peak amplitudes).

From a mechanical perspective, a real AE source releases energy during a finite time period, this time period is called the source rise time. Some years ago the rise times of potential simulated AE sources were measured by an exact inversion technique [2]. The source rise times varied from 0.1 µs to 9.5 µs. Based on this information along with some unpublished results obtained by the author, a study on the dependence of AE signal features on the rise time of a buried, self-equilibrating AE source in a plate was initiated. One previous paper examined the effect of source rise time on the epicenter response for a half-space [3]. The purpose of this paper is to report for a plate sample the dependence of the peak amplitude and frequency content on the
source rise time for the far-field signals (i.e. from Lamb waves). A future paper will examine the modal content of the signals with different rise times. Finite element modeling (FEM) was used for the study due to multiple advantages. The key advantages were the ability: i) to generate AE signals from buried self-equilibrated sources at different depths (below the surface) in a plate, ii) to generate AE signals with specific rise times; iii) to obtain the exact out-of-plane displacement versus time of a pseudo sensor (a wideband, point-contact sensor with no resonances); iv) to obtain the sensor results at different known propagation distances from the source and v) to use a specimen that did not result in reflections from the specimen edges arriving at the sensors during the major portion of the direct arrival of the AE displacement waves from the source.

Relevant Details on the Specimen Domain and Finite Element Modeling

An aluminium plate 4.7 mm thick with a radius of nearly 1000 mm served as the sample domain. The large in-plane dimension allowed propagation distances of up to 480 mm such that the direct arrival of the significant portion of the AE waves was not altered by reflections from the plate edge. A total of nine selected rise times varied from 0.5 µs to 15 µs. Since the 0.5 µs rise time generated frequencies well above the sensitivity range of even special AE sensors, shorter rise times were not examined. The sources in the continuous mesh domain were dipoles (self-equilibrating forces of two oppositely directed single-cell monopoles with one cell between them) using the “equivalent body force” concept for displacement discontinuities [4]. The forces (each monopole of the dipole had a force of 1 N) were applied with a “cosine bell” temporal time dependence $T(t)$ given by

$$T(t) = \begin{cases} 
0 & \text{for } t < 0, \\
(0.5 – 0.5 \cos \left[ \frac{\pi t}{\tau} \right]) & \text{for } 0 \leq t \leq \tau, \\
1 & \text{for } t > \tau,
\end{cases}$$

where $\tau$ was the source rise time. The same very small cell size and time step was used for each FEM run. Specifically these respective values were 54 µm and 7.7 ns. These values were chosen to meet the requirements of the validated finite element code [5] for the shortest rise time. An axisymmetric version of the code was used to carry out the modelling in the large domain with the very small cells and time steps using reasonable computing resources. The FEM code was run for a small amount of time beyond 300 µs from the start of the operation of the source. The dipole sources were out-of-plane with the centre of the dipole located at one of three different depths below the top surface of the plate where the sensors were located. The depths were 2.35 mm (mid-plane), 1.32 mm (mid-depth) and 0.243 mm (near the plate top surface). The entire FEM signals were numerically processed with a 40 kHz (eight-pole Butterworth) high-pass filter followed by resampling from the original time step to 0.1 µs per point (similar to the digitization rates often used in AE measurement systems). The material properties used for the FEM calculations were bulk longitudinal and shear velocities respectively of 6320 m/s and 3100 m/s and a density of 2.7 kg/m$^3$.

Peak Amplitude Dependence on Source Rise Time

Figures 1, 2 and 3 show the out-of-plane displacement time domains at a propagation distance of 480 mm from the epicentre of the source to the pseudo sensor for a selection of different rise times from 0.5 µs to 15 µs. These figures are respectively for the mid-plane, mid-depth and near the plate top surface source locations. Clearly the amplitude scales show the large drop in peak amplitude from the shortest to longest rise times. It should be noted that typically a small reflection (except for the 5 µs and 15 µs cases in figure 1) from the edge of the domain can be observed to arrive near the end of the signals in figures 1, 2 and 3. Figure 4 illustrates in a more
quantitative way the loss in peak amplitude in the direct arrival as the rise time increases. In this figure, the absolute values of the peak amplitudes were normalized by the peak amplitude of the 0.5 µs results. Examination of figure 4 demonstrates that the sharpest fall off in peak amplitude occurs as the rise time increases from 0.5 µs to about 3 µs. The data also illustrates that as the depth of the source moves closer to the surface the fall off is not as extreme. A similar figure (not shown) for a propagation distance of 60 mm had a similar fall off as a function of increasing source rise time. The total fall off was a little larger for the longer propagation distance. This result was likely due to signal dispersion. The changes in the peak amplitude at the 480 mm propagation distance from the shortest to longest rise time were 43 dB, 24 dB and 15 dB respectively for the mid-plane, mid-depth and near surface source locations.

Fig. 1. Out-of-plane displacement vs. time at 480 mm propagation distance for mid-plane source for different rise times.

Fig. 2. Out-of-plane displacement vs. time at 480 mm propagation distance for mid-depth source for different rise times.

Fig. 3. Out-of-plane displacement vs. time at 480 mm propagation distance for near top surface source for different rise times.

Fig. 4. Peak amplitude versus rise time at a propagation distance of 480 mm for all three source depths.

Figures 1 through 3 also show some other qualitative changes as a function of the source rise time. For the shorter rise times, the traditional AE features of threshold crossing counts and signal
energy would be much larger compared to those from the longer rise times. Further the shape in
time of the AE signals change significantly with rise time changes as well as with source depth.
This shape change leads to the observation that the time within the signal of the arrival of the
peak amplitude changes significantly over the range of rise times. One feature that does not
change significantly with rise time or source depth is the signal duration. In an experimental case,
the measured duration could change substantially depending on the threshold used to measure it.

Since real AE sensors do not have unlimited high frequency response, the previously filtered
displacement data was additionally filtered with an 800 kHz eight-pole, Butterworth, low-pass
filter. Figure 5 shows the absolute peak amplitude for the 40 kHz to 800 kHz data as compared to
the 40 kHz high-pass results at the 480 mm propagation distance for the relevant range of rise
times. These results demonstrate that the peak amplitudes at rise times less than about one
microsecond were partially the result of the contributions of the higher frequency parts of the
signals. Between the two frequency ranges the biggest differences in peak amplitude with rise
times of one microsecond or less were observed for the mid-depth source. The changes in the
peak amplitude for the 40 kHz to 800 kHz data at the 480 mm propagation distance from the
shortest to longest rise time (0.5 µs to 15 µs) were 42 dB, 17 dB and 14 dB respectively for the
mid-plane, mid-depth and near surface source locations.

The peak amplitude results in this section indicate some potential to use peak amplitudes to
distinguish two different AE source types if one source has a relatively short rise time, say in the
range of 0.5 µs to 1.5 µs versus a source with a rise time in the 5 µs to 15 µs range. Such an
approach would likely require that the AE sensor(s) be located at approximately the same
distance (due to attenuation, which is considered in the next section) from each of the two AE
source types. It should be pointed out that this potential is largely based on the much higher rate
of change of the peak amplitude over the range of shorter rise times. This type of dependence
should be contrasted with the fact of the linear dependence of the peak amplitude on the dipole
strength (monopole force times the spacing between the monopoles). With the linear dependence,
very large strength differences would be required to accurately distinguish different rise time
source types by peak amplitude analysis, since it is to be expected that there would be some
distribution of strengths for each source type. The next section examines the attenuation of the
AE signals with propagation distance relative to the question of the potential of identification of
sources with distinctly different rise times by the peak amplitudes of the signals.

![Fig. 5. Peak amplitude versus rise time with two frequency ranges: (a) mid-plane source, (b) mid-depth source and (c) near top surface source.](image-url)
Amplitude Attenuation versus Distance, Rise Time and Source Depth

Figure 6 shows the normalized peak amplitude (normalized by the peak amplitudes at a propagation distance of 60 mm from the source epicentre) versus the propagation distance for the three different source depths and a rise time of 0.5 µs. This figure also shows the theoretical geometric attenuation. Since 60 mm is more than 12 times the plate thickness, the data in this figure primarily represents the case of fully developed Lamb modes in the plate. This figure shows significant attenuation with propagation distance, but all three source depths have similar attenuation values. As expected the attenuation of the AE signal is almost always more (due to dispersion) than the theoretical value for geometric spreading. For example, the added attenuation due to dispersion at a propagation distance of 480 mm varies from about 3 dB to 5 dB. Figure 7 illustrates the attenuation with distance for the near top surface source for rise times of 0.5 µs, 2.3 µs and 15 µs. Except for relatively minor differences the data for the different rise times show a similar rate of attenuation. The results (not shown) for the other source depths for the different rise times were similar. Hence, in analyzing how different distances of propagation can affect the ability to distinguish different rise time sources, one can ignore the aspects of source depth and source rise time.

In all the cases, as shown in figures 6 and 7, the largest rate of fall off of peak amplitude with propagation distance for the developed Lamb waves occurs from 60 mm to about 240 mm. As figure 6 shows this is primarily due to geometric attenuation. If the values of attenuation with propagation distance are compared to the changes in peak amplitude with rise time, it is possible to consider if different source types might be distinguished. For example, if one could locate the AE sensor(s) so that they were between 240 mm to 480 mm from the sources, then the attenuation (based on figure 6 results) would be about 5 dB between these two distances. On the other hand, the change in peak amplitude for the previously chosen ranges of rise time (0.5 µs to 1.5 µs versus 5 µs to 15 µs) would be on the order of about 19 dB, 6.4 dB and 6.3 dB, using the differences between the peak amplitudes (data from either frequency range is almost identical) for rise times of 1.5 µs and 5 µs respectively for the mid-plane, mid-depth and near top source depths. Thus, only the sources located at the mid-plane could be distinguished. Admittedly, this example is constructed with “perfect” data, but it does show how one might go about developing an approach to source identification based on peak amplitude. In the case of the use of resonant sensors with a lower resonant frequency (for example 150 kHz), the use of peak amplitudes to distinguish sources with different rise times would be more difficult. The reason for this
conclusion is that the higher frequency contributions to the peak amplitude for shorter rise times would not be present.

Fig. 8. Spectra versus rise time, mid-plane, at 480 mm.

Fig. 9. Spectra versus rise time, mid-depth, at 480 mm.

Fig. 10. Spectra versus rise time, near surface, at 480 mm.

Fig. 11. Spectra versus additional rise times, mid-depth, at 480 mm.

Frequency Content versus Source Rise Time

The spectra of the AE signals were calculated with a Fast Fourier Transform (FFT) after termination of the signals near the end of the direct arrival. The termination was done at a zero in each case. This procedure resulted in a signal length of slightly less than 300 µs for the longest propagation distance of 480 mm. For the shorter propagation distances, where the edge reflection at the very end of the direct arrival signal was not present, the signals were terminated at a zero nearest the time equivalent to a group velocity of about 1.5 mm/µs. The FFTs were calculated with a rectangular window after extending each terminated signal with zeros to obtain a total of 4096 points. This procedure resulted in a frequency interval of 2.44 kHz in the resulting spectra.

Figures 8, 9 and 10 show the frequency spectra at a propagation distance of 480 mm respectively for the source depths of mid-plane, mid-depth and near top surface for the same rise times of time domains in figures 1 through 3. Even though typical AE sensors do not have sensitivity at higher frequencies, the results shown here extend to 2 MHz so that the effects of short rise times on the generation of higher frequencies can be fully observed. Clearly, the figures show, as expected that as the rise time decreased the higher frequencies show an increase in their magnitude. Since at the 0.5 µs rise time, the mid-depth source (figure 9) shows the more high
frequency content than the other two depths, a more detailed examination of the effects of rise time for this source depth is shown in figure 11. The gradual decrease in higher frequency content is apparent as the source rise time increases from 0.5 µs to 2.3 µs. This figure also illustrates that once the source rise time increases to 2.3 µs, the frequency range with significant magnitude is less than about 550 kHz. This frequency range is well within the sensor sensitivity range of some commercial AE sensors.

Figure 10 is interesting because for the source located near the top surface the spectra for all the rise times are dominated by a low frequency region with a peak magnitude at about 50 kHz. Due to the fact that the FEM results were filtered with the high-pass filter at 40 kHz, this peak frequency in the raw data could be lower. But, for the 40 kHz high-pass data, for a wide range of rise times from 0.5 µs to 15 µs, the rise time changes were not easily distinguished by their dominant frequency regions when the source was located near the plate surface.

Figures 8, 9 and 10 clearly demonstrate that the different source depths result in significant differences in the resulting spectra for the same rise time source for nearly all the rise time cases. Only for the mid-depth and near the top surface source locations for the 5 µs and 15 µs rise times are the spectra somewhat similar. In addition, these figures also illustrate that for the 0.5 µs, 1.5 µs and 2.3 µs rise times, the mid-depth spectrum can be roughly viewed as a superposition of the peak frequency regions from the mid-plane and near top spectral results at the same rise times.

![Fig. 12. Spectra versus rise time, mid-plane source, at 480 mm propagation distance.](image)

Other than the higher frequency content disappearing with increasing rise time the mid-plane source depth resulted in the most differences in the spectrums at the longer rise times. Figure 12 illustrates this further. The large changes in the dominant frequencies are due to the changes in the portions of the group velocity curves that are significantly excited as the rise time changes [6]. This aspect will be documented in a future modal-content paper.

Since (see figures 8, 9 and 10) the mid-depth source with a 0.5 µs rise time has the broadest frequency range with significant amplitude (both the symmetric and anti-symmetric modes are excited), this case was used to examine the potential changes in the spectra as a function of the propagation distance. For this case figure 13 shows three primary effects of propagation distance.

![Fig. 13. Spectra versus propagation distance, mid-depth source, for 0.5 µs rise time.](image)

First, there are two dominant frequency regions within the frequency sensitivity range of commercial AE sensors. Irrespective of propagation distance these are a low frequency region with a peak at about 60 kHz and another region with a peak at about 550 kHz. Second, as the propagation distance increases, the ratio of the magnitude of the low frequency peak to the higher frequency peak increases. Third, as the propagation distance increases, the fine detail in the
spectra increases. This aspect correlates with the increase in the separation in time (dispersion effect) of the modal regions. A similar examination of the effect of propagation distance for the other two source depths with the shortest rise time showed that the propagation distance has less effect as expected (only one dominate mode for each of these), and the primary observation was the same as the third observation for the mid-depth source.

In summary, there are some possibilities for the use of spectra to identify sources with large differences in rise time. Such approaches will need to consider the results presented with this modelled data as well as experimental realities. For example, the modelled results indicate that if the sources with the different rise times are always located near the surface, then the use of spectra is highly unlikely to be successful in distinguishing those sources even with very large differences in rise time shown for the 40 kHz high-pass data. In all cases, where one is attempting to distinguish sources with different rise times, the selection of a sensor with wideband significant response sensitivity as characterized by ASTM E 1106 (Test Method for Primary Calibration of Acoustic Emission Sensors) is an important aspect.

Conclusions

- For rise times decreasing from about 3 μs to 0.5 μs the peak amplitude increases rapidly.
- With decreasing rise time, the near top source shows the least increase and the mid-plane source shows the most increase in peak amplitude.
- Over a propagation distance of 60 mm to 480 mm, the peak amplitude decreases substantially. Most of the decrease is due to geometric spreading.
- Attenuation with propagation distance is largely independent of the source rise time and the source depth.
- The spectra for the near top surface show little change over the whole range of rise times examined with the 40 kHz high-pass data.
- For several of the rise times, the spectra for the mid-depth source can be approximated as a summation of the intense frequency ranges for the mid-plane and mid-depth sources with the same rise times.
- Due to the attenuation with propagation distance, the wide variation in peak amplitude from sources with large differences in rise time will typically not be reliable to distinguish these sources. If all the sources are the same distance from the sensors then peak amplitude may possibly be used to distinguish source types with a wide variation in rise time in some cases.

Acknowledgement

The finite element calculations by Dr. John Gary (retired NIST, Boulder, CO, USA) are gratefully acknowledged.

References