SOME OBSERVATIONS ON RAYLEIGH WAVES AND ACOUSTIC EMISSION IN THICK STEEL PLATES

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Abstract

Rayleigh or surface waves in acoustic emission (AE) applications were examined for nominal 25-mm thick steel plates. Pencil-lead breaks (PLBs) were introduced on the top and bottom surfaces as well as on the plate edge. The plate had large transverse dimensions to minimize edge reflections arriving during the arrival of the direct waves. An AE data sensor was placed on the top surface at both 254 mm and 381 mm from the PLB point or the epicenter of the PLB point. Also a trigger sensor was placed close to the PLB point. The signals were analyzed in the time domain and the frequency/time domain with a wavelet transform. For most of the experiments, the two data sensors had a small aperture (about 3.5 mm) and a high resonant frequency (about 500 kHz). These sensors effectively emphasized a Rayleigh wave relative to Lamb modes. In addition, finite-element modeling (FEM) was used to examine the presence or absence of Rayleigh waves generated by dipole point sources buried at different depths below the plate top surface. The resulting out-of-plane displacement signals were analyzed in a fashion similar to the experimental signals for propagation distances of up to 1016 mm for out-of-plane dipole sources. Rayleigh waves were generated in the experiments for all three locations of PLBs. In the case of the bottom surface PLBs, the Rayleigh wave propagated to the plate edge, up the edge and then along the plate top surface to the sensors. Due to the time delay from the propagation up the edge to the plate surface, Rayleigh waves from edge PLBs resulted in a strong signal that interfered with a straightforward analysis of the intense frequency/time regions of the Lamb modes from these source positions. The FEM results for the out-of-plane dipoles showed that the surface out-of-plane displacement amplitude of the Rayleigh wave decayed relative to the Lamb mode amplitudes as the depth of the source below the surface “pseudo” sensors increased. A Rayleigh wave was not observed for sources deeper than about 23 % of the plate thickness. In contrast, for a case of an in-plane buried dipole, an out-of-plane Rayleigh wave was not observed in the FEM results for a source depth of only 5 % of the plate thickness.

Keywords: Pencil-lead break, Rayleigh waves, Source depth, Thick plate, Wavelet transform

Introduction

One of the key roles of acoustic emission (AE) technology in plate-like structures is to locate in two dimensions the source that generated the waves. To obtain accurate locations requires the determination of arrival times of a part of the signals that corresponds to a known velocity. In the case of thin plates, typically only the fundamental Lamb modes are present with significant

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amplitudes in the AE signals. In thick plates, additional higher-order Lamb modes significantly contribute to the signals. Previously for thin plates, a series of publications demonstrated both with finite-element modeling (FEM) results and experimental results (with an AE sensor that had relatively uniform response over its frequency range) that monopole pencil-lead breaks (PLBs) on the edge of the plate created waves that most closely resembled those from buried dipole-type sources [1, 2]. The reason for this result was that PLBs on the plate top or bottom surface created waves that exaggerated the amplitude of the $A_0$ mode relative to its amplitude from buried-dipole AE sources. Additional publications showed, for a thin plate, that accurate group velocity arrival times could be obtained by use of time/frequency analysis of the signals obtained from real AE sensors excited by waves from edge PLBs [3, 4].

The research presented here was originally meant to follow up previous publications that provided results from FEM of AE source operation and subsequent wave propagation in a steel plate of 25.4 mm thick [5, 6]. The follow-up was intended to obtain experimental group-velocity arrival times from the signals from different types of real AE sensors excited by waves from PLBs on the edge of a nominal 25-mm thick steel plate. With some of the sensor types, the initial analysis of these signals demonstrated the presence of a Rayleigh wave, whose arrival time did not correspond to the time calculated by the distance (parallel to the plate surface) from the plate edge divided by the velocity of a Rayleigh wave in steel. Instead the Rayleigh-wave arrival time (as will be demonstrated later) corresponded to the distance from the PLB position up the plate edge to the plate top surface plus the distance along the top surface from the edge to the sensor. Since the original FEM study [5, 6] showed an identifiable Rayleigh wave only when a buried out-of-plane dipole source was near the surface, on which the “pseudo” sensors (out-of-plane displacement at a point from the FEM results) were located, the potential to use PLBs on the edge of a thick plate at different distances below the plate surface to simulate real AE from buried sources presented complications. In addition, the absence of Rayleigh waves from AE sources not near the plate surface raised questions relative to the common practice in AE field tests of using surface PLBs to obtain information on expected signal frequencies and propagation velocities. With these two issues in mind, the goal of the research was revised. Thus, the research presented here is the result of a more general examination of Rayleigh waves from both surface PLBs with real AE sensors and finite element modeling of buried AE sources.

Previous literature on the subject of Rayleigh waves typically concerned the generation of Rayleigh waves by laser pulses. Some examples of these studies involved experiments and others involved both experiments and corresponding theory [7, 8, 9]. Since the source rise times in these studies were on the order of 10 ns to 15 ns, their applicability to PLBs with typical rise times on the order of 1400 ns to 2500 ns [10] is uncertain due to the large differences in the range of wavelengths that would be present in the Rayleigh waves. Further, the frequencies observed in the signals from real AE sources indicate that their source rise times are in the same ranges at those for PLBs. Thus, an extended study relative to Rayleigh waves generated by PLBs seemed to be in order, and in addition a study that examined in detail the effects of the depth of an AE source on the potential generation of a surface Rayleigh wave.

Experiments with PLBs on the Bottom and Top Surface of a Thick Steel Plate

A thick steel plate with dimensions of 1320 mm x 780 mm x 24.4 mm (the physical plate had to be resurfaced so its thickness was 1 mm less than the previously completed FEM results) was instrumented on its top surface with resonant sensors (resonant at about 500 kHz) of small aperture (about 3.5 mm). These sensors were chosen due to their small aperture and their high
resonance frequency, which would emphasize the amplitude of Rayleigh waves versus their response to Lamb modes. The sensors were placed on the top surface with their centers at 356 mm and 483 mm from the long edge of the plate. They were coupled with vacuum grease and were connected to preamplifiers of 40 dB gain without filtering. After passing through a custom built decoupling circuit (to remove the dc voltage to the preamplifiers), the signals were high-pass filtered at 50 kHz by passive four-pole Butterworth filters. The resulting signals were digitized at an interval of 0.1 µs/point with 12-bit vertical resolution. PLBs (at least three at each position to assure that a representative result was used for the subsequent analysis) were carried out as illustrated in Fig. 1 with 0.3 mm nominal diameter lead (2H, about 3 mm long) on both the top and bottom surfaces at a location 102 mm from the long edge of the plate. In addition, a third sensor was coupled on the plate top surface close to the PLB points to provide a first-arrival trigger signal that would correspond to wave transmission at the bulk longitudinal velocity from the PLB position to this sensor. The signal from this sensor was digitized (with pre-trigger data) simultaneously with those from the other two sensors.

a) Analysis of Top Surface PLBs

By use of a bulk longitudinal wave velocity for steel of 5940 m/s [11] along with the distance of the direct path from the PLB point to the center of the trigger sensor, the propagation time from the PLB position to the trigger sensor was calculated. By use of this time increment along with the first arrival time in the trigger sensor signal, the zero times of the small aperture sensor signals were adjusted to correspond to the time of the PLB. In addition, wavelet transform (WT) results were calculated for these signals. Appropriate Lamb-mode group velocity curves [5] were superimposed on the WT results by use of the propagation distance parallel to the plate surface from the PLB point to the centers of these sensors. The parameters used in the WT [12] for all the results in this paper were a frequency resolution of 3 kHz (frequency band) and a wavelet size of 600 samples.

Figures 2 and 3, respectively, show the time domain signals and the WT results of the signals from the two small-aperture sensors. In the WTs of Fig. 3, the arrival times at the peak magnitude for the high frequency (really the frequency band) intense portion of the signals are shown (using the most intense frequency at the furthest propagation distance) for both distances. It is important to point out that for frequencies above about 320 kHz (for the current plate thickness) the group velocities of the S₀ and A₀ modes are asymptotic to the Rayleigh velocity. Propagation

Fig. 1. Steel plate (24.4 mm thick) showing locations of top-surface mounted sensors and PLB points. All dimensions are in millimeters.
Fig. 2. Signals from small aperture sensors for PLB on top surface of steel plate. Propagation distances from the PLB point to the sensors were (a) 254 mm and (b) 381 mm.

velocities were calculated for the direct path along the top surface by use of the indicated arrival times (see Fig. 3) at the intense (high amplitude of WT coefficients) frequency of 498 kHz. In addition, the velocity of this signal portion between the two sensors was calculated. The results are shown in Table 1 along with a published velocity for Rayleigh waves in steel [11]. The table also shows the percentage differences of the experimental results as compared to the published values. These results demonstrate that the calculated experimental velocities correspond to the Rayleigh velocity. In addition, the WT figures show that the arrival times correspond to the parts of the group velocity curves that are asymptotic to the Rayleigh velocity. Finally, as will be pointed out later in the analysis of the bottom surface PLBs, sensors on the surface opposite the PLB did not exhibit a high frequency signal of significant amplitude that was asymptotic to the A₀ and S₀ Lamb modes. Hence, because the Lamb modes did not contribute significantly to the signal amplitude, the appropriate wave regions in Figs. 2 and 3 are labeled as Rayleigh waves and indentified with arrows. As a final observation, Figs. 2 and 3 show reflections from the edge nearest the PLB point. These reflections arrived (based on the WT results) at about 156 µs and 198 µs, respectively, for the sensors at 356 mm and 483 mm. Using the distance from the PLB point to the near plate edge and then from the edge back to the sensors, one can verify that these arrivals correspond to waves propagating at the Rayleigh velocity.

**Table 1** Experimental and published [11] Rayleigh velocity for top surface PLB.

<table>
<thead>
<tr>
<th>Distance description</th>
<th>Velocity [mm/µs]</th>
<th>Published velocity [mm/µs]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB to 1ˢᵗ sensor</td>
<td>2.92</td>
<td></td>
<td>2</td>
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<tr>
<td>PLB to 2ⁿᵈ sensor</td>
<td>2.94</td>
<td>2.98</td>
<td>1.3</td>
</tr>
<tr>
<td>First to second sensor</td>
<td>2.98</td>
<td></td>
<td>0</td>
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</table>
Fig. 3. Wavelet transforms of the signals shown in Fig. 2. Parts (a) and (b) correspond to those parts in Fig. 2. Initial portion of the time scale not shown to focus on the arrival of the Rayleigh wave at the most intense portion of the signals.

b) Analysis of Bottom Surface PLBs

By use of a procedure similar to that applied to the top surface PLB data, the zero times of the signals from the small aperture sensors were adjusted to correspond to the PLB time. Figures 4 and 5, respectively, show the time-domain signals and the WT results of the signals. As before, group-velocity curves for the Lamb modes were superimposed on the WT results by use of the distances from the epicenter of the PLB point (on the bottom surface at 102 mm from the edge) to the two sensors. This propagation distance was used, because the guided Lamb modes are created by the various reflections from the top and bottom surfaces of the plate. In both the time domains and WT figures, a portion of the signal with high-frequency intensity (beyond the high-frequency portion of the group velocity curves in Fig. 5) is identified with arrows. This portion of the signals is well beyond the slowest high-frequency region of the group velocity curves that have significant amplitude. The arrival times (at the WT peak magnitude in the region of the arrows) shown on the WT results in Fig. 5 at a frequency of 510 kHz (from the most intense
Fig. 4. Signals from small aperture sensors for PLB on bottom surface of steel plate. Propagation distances from the epicenter of the PLB point to the sensors were (a) 254 mm and (b) 381 mm.

Fig. 5. Wavelet transforms of the signals shown in Fig. 4. Parts (a) and (b) correspond to those parts in Fig. 4. Initial portion of the time scale not shown to focus on the arrival of the Rayleigh wave at the most intense portion of the signals. Multiple modes are shown to establish where they appear in time.
frequency in that region at the further propagation distance for both distances) were used to calculate velocity. The velocities were calculated by dividing the indicated arrival times into a propagation distance, computed from the distance from the PLB to the near long plate edge plus the thickness of the plate (up the edge) plus the distance from the edge to the appropriate sensors. These velocities are shown in Table 2. The table also includes a published [11] velocity for Rayleigh waves in steel and the percentage difference of the experimental velocities compared to the published value. Based on the closeness of the experimental velocity to the published one and the observed frequency range, it was concluded that this portion of the signals was indeed a Rayleigh wave that traveled around two 90° corners to reach the sensors. This result is not surprising since the fact that Rayleigh waves can travel around corners has been observed in the past with laser-generated signals [7]. It is also apparent in the WT results that there is not a high frequency signal of significant intensity present in the high-frequency region where the A₀ Lamb mode is asymptotic to the Rayleigh wave velocity. Thus a Rayleigh wave (in Fig. 5) corresponding to the distance from the epicenter of the PLB to the sensors was not present, as was the case for the top-surface PLB, as shown in Fig. 3. As an interesting aside, one can see in Figs. 4b and 5b the arrival at about 165 µs (using the WT result) of a high frequency signal portion that corresponds with the “reversal” in time of the A₃ mode.

Table 2 Experimental and published [11] Rayleigh velocity for bottom surface PLB.

<table>
<thead>
<tr>
<th>Distance description</th>
<th>Velocity [mm/µs]</th>
<th>Published velocity [mm/µs]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLB to 1st sensor; two 90° bends</td>
<td>2.96</td>
<td>2.98</td>
<td>0.7</td>
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<tr>
<td>PLB to 2nd sensor; two 90° bends</td>
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<tr>
<td>First to second sensor</td>
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**Rayleigh Wave Amplitude Versus Depth of Source – Out-of-plane Source**

Previously published FEM results for thick steel plates [5, 6] showed that a recognizable Rayleigh wave was not present for buried out-of-plane dipole sources that were not near the surface where the “pseudo” AE sensor was located. Thus, the use of signals from the above described out-of-plane PLBs to guide the setup of AE monitoring and/or analysis parameters may not be fully appropriate relative to real AE from sources at different depths. Hence, a more detailed FEM study was conducted of the Rayleigh wave out-of-plane displacement amplitude as a function of out-of-plane sources with more closely spaced source depths (below the surface). The examination of depth-of-source effects on the presence of significant Rayleigh waves is relevant, because the AE technique is sensitive to sources throughout the thickness of a plate, and in particular, to sources on the bottom surface, which in field testing may not be accessible to placement of sensors. Further, previous FEM results have shown that similar Lamb modes in plates are excited by both in-plane and out-of-plane sources as a function of source depth [2].

The modeling was performed by use of a previously validated finite-element approach [13, 14] with an axisymmetric code for out-of-plane buried dipoles located at various depths below a surface. The out-of-plane displacement was obtained at various distances from the epicenter of the sources. In addition, to enhance the analysis of the modeling results, the out-of-plane displacement on the bottom surface was obtained at the same distances. The axisymmetric code was able to provide results for a thick plate with large propagation distances for sources of short rise time by use of a domain large enough to prevent reflections from the domain edge arriving.
during the duration of the direct waves. The axisymmetric code could accomplish these modeling conditions without excessive computer run times. The steel plate domain had a thickness of 25.4 mm. In addition, a source rise time of 1.5 $\mu$s was used with a maximum wave propagation distance of 1016 mm from the source epicenter to the “pseudo” sensor. The input properties for the FEM calculation were based on the bulk velocities and density for steel (longitudinal velocity = 5940 m/s, shear velocity = 3220 m/s and density = 7.8 kg/m$^3$) [11]. The 1016 mm propagation distance resulted in a large amount of dispersion for the Lamb waves, while the Rayleigh wave was not subject to dispersion. Hence, at this distance the amplitude of a Rayleigh wave would potentially not be reinforced to the same degree by the presence of Lamb waves with similar velocities as compared to the situation when only short propagations distances were present. The short rise time was used since previous work [14] had shown that shorter rise times were needed to generate a reasonable Rayleigh wave. The FEM was carried out with a domain of 2540 mm, a cell size of 0.125 mm and a time step of 18.9 ns. The out-of-plane dipole source was composed of a single cell (without a body force) along with a one-cell monopole above and below each with a body force equivalent to 1 N. The resulting displacement results were resampled to 0.1 $\mu$s/point to correspond to typical waveform recording of AE signals.

![Fig. 6. Out-of-plane displacement versus time after a propagation distance of 1016 mm for dipole sources at two depths below the top surface of a steel plate 25.4 mm thick. Parts (a) and (b) are for a source at a depth of 1.93 mm in contrast to (c) and (d) at a source depth of 7.78 mm.](image)

A typical set of out-of-plane displacement versus time results is shown in Fig. 6 for sources centered at 1.93 mm (parts (a) and (b)) and 7.78 mm (parts (c) and (d)) below the top surface of the plate. Note that the femtometer scale for the displacement does not imply that AE sensors can detect such signals. The results in this section and the later section dealing with FEM signals are not dependent on this scale. Figure 6 shows both the top and bottom surface displacements at a propagation distance of 1016 mm. In the top surface result (part (a)), an arrow points out the
Rayleigh wave (verified by the analysis below). Figure 7 shows, for the source at a depth of 1.93 mm, the WT results of the displacement signals corresponding to Fig. 6 parts (a) and (b), respectively, along with superimposed group-velocity curves. In addition from the result in Fig. 7 (a), the arrival time at the maximum WT magnitude of the most intense portion of the WT results was found to be 341.8 µs at a frequency of 510 kHz. When the velocity of this portion of the wave was calculated by use of the propagation distance of 1016 mm (parallel to the top surface of the plate), a value of 2.97 mm/µs was obtained, which is within 0.3 % of a published value [11] of 2.98 mm/µs. This result, along with the associated high-frequency region, indicates that this portion of the signal is a Rayleigh wave that traveled at the Rayleigh wave velocity. In the bottom-surface time domain (Fig. 6(b)) and corresponding WT result (Fig. 7(b)), there is no evidence of a relevant portion of a Rayleigh wave. To more clearly show this fact, Fig. 8 shows a time-expanded view of the out-of-plane displacement versus time for both surfaces. Clearly, there is no distinct Rayleigh wave present in the bottom surface signal that corresponds to that present on the top surface. Because in the far field, the top and bottom surface displacement of Lamb waves are essentially the same except for a phase reversal (for one set of modes), the absence of this arrival on the bottom surface further demonstrates that the top surface arrival at the Rayleigh velocity is in fact a Rayleigh wave and not a part of the Lamb modes. Figures 6(c) and (d) for the source at a depth of 7.78 mm show no evidence in the time domain of a Rayleigh wave, and the WTs (not shown) showed no evidence of a Rayleigh wave.
In order to examine an approach to provide a best estimate of the amplitude of the Rayleigh wave versus source depth, the bottom surface out-of-plane displacements at a propagation distance of 1016 mm were subtracted from the top surface displacements at the same distance for an out-of-plane source at a depth of 5.79 mm. The “subtraction” signal and corresponding WT result with superimposed symmetric group-velocity curves are shown in Fig. 9. For comparison, Fig. 10 shows the “sum” of the top and bottom surface signals and the corresponding WT result with superimposed antisymmetric group-velocity curves. When the WT results in these two figures are compared, it is clear from Figs. 9 and 10 that the “subtraction” of the signals removes the antisymmetric modes, and the “sum” removes the symmetric modes. It is also clear that the $A_0$ anti-symmetric mode could contribute to the amplitude of the Rayleigh wave in the time domain if the “sum” were used (see arrow in the WT result in Fig. 10). This potential contribution could arise from the portion of the $A_0$ mode that has a velocity only a small amount greater than that of the Rayleigh wave. In contrast, Fig. 9 illustrates that most of the signal intensity in the higher frequency portion of the $S_0$ mode has a velocity slower than that of the Rayleigh wave. Hence, the “subtraction” of the signals was used to obtain a best estimate of the peak amplitude of the Rayleigh wave. This choice seems to provide a best estimate of the Rayleigh wave amplitude, because the “sum” peak amplitudes were all larger. This fact indicated there was more reinforcement (as described above) of the Rayleigh wave amplitude by the $A_0$ mode in the case of the “sum.” Hence, the “subtraction” approach was applied to the time-domain signals obtained from the FEM results for the different source depths.

The Rayleigh wave peak amplitudes (absolute values) and their arrival times determined from the “subtraction” time domain signals are shown in Table 3 as a function of the source depth for a propagation distance of 1016 mm. This table also shows the WT-determined frequency of the most intense high-frequency portion of the Rayleigh wave and the peak signal amplitudes (absolute values) of the original top and bottom surface out-of-plane displacement signals. It must be pointed out that the “Rayleigh amplitude” value in this table for the depth of 7.78 mm was taken from the peak signal amplitude in the same time region of the Rayleigh peak.
Fig. 9. Displacement signal resulting from the bottom surface signal subtracted from the top surface signal to eliminate the anti-symmetric modes. Source at 5.79 mm below the top surface and propagation distance 1016 mm. Inset of same WT result to remove the “blocking” effect of group velocity curves.

Table 3 Amplitudes of Rayleigh wave and top and bottom surface peak amplitudes versus depth of source.

<table>
<thead>
<tr>
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<td>62</td>
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</tr>
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<td>----</td>
<td>-----</td>
<td>71*</td>
<td>67</td>
<td>58</td>
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</table>

* No Rayleigh wave; amplitude at the typical arrival time of Rayleigh wave.
observed for the sources that were not as deep. This approach was used because no distinct Rayleigh wave was observed in the signals at this source depth or at greater depths. As can be observed in Table 3, the Rayleigh wave amplitude decreased for sources very near the surface. This decrease may be associated with the reduction in the constraint of the top monopole when the dipole is very close to the surface. The results for all three displacement amplitudes in Table 3 are plotted in Fig. 11 as a function of the source depth. Clearly the top-surface peak amplitude was dominated by the Rayleigh wave amplitude when the buried source was close to the surface. Since the top-surface peak amplitude includes the net effect of the Rayleigh wave’s interaction with the Lamb modes, it is not clear how to explain why these amplitudes are a little less than the best estimate of the Rayleigh wave amplitudes. Also, as the depth of the source increased, all three amplitudes approach each other. Finally, the frequency of the peak intensity of the Rayleigh wave was above the approximate value of 320 kHz, where the $S_0$ and $A_0$ modes are asymptotic to the Rayleigh velocity. An equation has been suggested [9] to provide an approximate frequency, $f$, below which for a given plate thickness, $t$, Rayleigh waves cannot propagate. Using this equation $[f = 8 c_T/(t\pi)]$ (where $c_T$ is the bulk shear velocity), $f$ was calculated to be 323 kHz. We note that all the frequencies at the Rayleigh wave peak are above this value. Also in Table 3, except for the source nearest the surface, the WT-determined frequency (at the WT determined
peak intensity) at the Rayleigh wave decreased as the depth of the source increased. This behavior of the high-frequency components (of the Rayleigh wave) exhibiting greater prominence for sources nearer the surface was previously observed in an analytical treatment of buried monopole pulses [15]. From the results in this table, an average arrival time was calculated to be 342.5 µs. This arrival time translates to a velocity of 2.97 mm/µs for the 1016 mm propagation distance. This velocity is almost identical to the Rayleigh wave velocity already used in this paper.

**Rayleigh Wave Amplitude and Depth of Source – In-plane Buried Source**

An additional question relative to the presence of a detectable out-of-plane Rayleigh wave concerns the case of an in-plane buried dipole AE source. To model this case with FEM, it was necessary to use a three-dimensional code. Due to the huge increase required for the computing resources, a smaller domain was used and only one source depth was run. Thus, the maximum propagation distance was limited to 381 mm so as to eliminate significant edge reflections from the smaller domain. Also a larger rise time of 2.3 µs was used for the 25.4-mm thick steel plate. Hence, the cell size was 0.5 mm and the time step was 75.5 ns. Since the rise time was slower (compared to the out-of-plane results above), to provide a meaningful comparison, both in-plane and out-of-plane dipole results were calculated with the 3-D code. As before, these dipoles were composed of single cells with body forces on either side (or above and below for the out-of-plane source) of a cell without a body force. The FEM results for the out-of-plane displacement versus time were first digitally high-pass filtered at 40 kHz with a four-pole Butterworth filter and then re-sampled to 0.1 µs/point. The top surface displacement results for the two different dipoles centered at 1.25 mm below the top surface are shown in Fig. 12 for the 381-mm propagation distance. These displacements are for the waves propagated in the direction of the forces of the in-plane dipole. It is worthwhile to note that for the in-plane dipole, the FEM results showed that the amplitude of the waves decreases in other in-plane directions to a minimum of nearly two orders of magnitude less in peak amplitude in the direction 90º from the dipole direction (a result
Fig. 12. Top surface out-of-plane displacement signals after propagation of 381 mm. Obtained using 3D code for out-of-plane dipole (a) and in-plane dipole (b). The sources were each centered at 1.25 mm below the top surface of a 25.4 mm thick steel plate.

of the source radiation pattern [16]). In Fig. 13 the corresponding WT results are shown with the fundamental Lamb modes superimposed. Examination of the WT results for the out-of-plane dipole in Fig. 13 part (a) shows a high-frequency intense region with an arrival where the fundamental group velocities are asymptotic to the Rayleigh velocity. The arrival time as shown in this figure at the peak magnitude of the frequency of greatest intensity of 411 kHz was at 130.2 µs. The corresponding velocity for the 381-mm propagation distance is 2.93 mm/µs, which is only 1.8 % less than the Rayleigh velocity. Hence, this part of the signal was determined to represent a Rayleigh wave, and the corresponding high-frequency peak at this arrival time was designated as a Rayleigh wave in the time domain of part (a) of Fig. 12.

In contrast, the WT results for the in-plane dipole shown in part (b) of Fig. 13 show no intense high-frequency region corresponding to the arrival of a Rayleigh wave. In fact the most intense WT region at the 411 kHz frequency is at about 160 µs. We note in Fig. 13(b) that the most intense arrivals from 335 kHz to at least 600 kHz are all at about this same time. These arrivals correspond to a region of higher intensity from higher Lamb modes (not shown) that also appears in the out-of-plane WT result (Fig. 13(a)). Likewise the high-frequency Rayleigh-wave arrival is missing in the time domain of part (b) of Fig. 12. These Rayleigh-wave conclusions were reinforced by the absence of high-frequency Rayleigh wave intensity on the bottom surface out-of-plane displacement results (not shown) that showed only the Lamb waves. Thus, for a buried in-plane dipole source at a depth (below the surface with the sensors) of only about 5 % of the total plate thickness, there was no evidence of the presence of a Rayleigh wave. In contrast, an out-of-plane dipole at the same depth does create a Rayleigh wave on the adjacent surface, as was shown earlier. Because the radiation pattern from an in-plane dipole generates very little
Fig. 13. Wavelet transform results for the corresponding signals in Fig. 12.

displacement in the out-of-plane direction [16], it might be expected that the in-plane dipole excited no significant Rayleigh wave. In addition, because the relative amplitude of the out-of-plane wave displacement is greater than that of the in-plane displacement for a Rayleigh wave [11], the lack of a Rayleigh wave for the in-plane dipole source may not be too surprising.

Rayleigh Waves from Edge PLBs

The original intended goal of this research was to examine whether key information on the effect of the depth of buried AE sources on the signals monitored with real AE sensors could be obtained by use of PLBs on the edge of a thick plate at various distances below the plate top surface (where the sensors were mounted). As was pointed out earlier, this approach was suggested by the positive results with such a strategy for thin plates [3, 4]. But as demonstrated in the previous sections of this paper, the intended goal was complicated by the presence of a Rayleigh wave with relatively large amplitude that moves up the plate edge (from the PLB point) and then across the plate surface to the sensors.

The complication is best illustrated by the results from a PLB on the plate edge well below the top surface. For this experiment the small-aperture sensors shown in Fig. 1 were moved so that they were at 254 mm and 381 mm from the plate edge. In addition, the trigger sensor was moved for these experiments to a similar position relative to the PLB position. Then, the PLB was done on the edge at a distance of 22 mm down from the top surface of the plate. For the two
Fig. 14. Signals from small aperture sensors on the plate top surface. PLB on plate edge at 22.2 mm below the plate top surface. Propagation distances of (a) 254 mm and (b) 381 mm.

Fig. 15. WTs of the respective signals (a) and (b) in Fig. 14 showing the delayed arrival of the Rayleigh wave (at Max 1 in both (a) and (b)) compared to the position in time of the $A_0$ and $S_0$ modes at frequencies above about 320 kHz.
propagation distances, Figs. 14 and 15, respectively, show the time domains and their WTs at the two propagation distances. The Lamb-mode group-velocity curves were superimposed in the WT results based on the top surface distance from the edge to the sensors (for the same reason as already indicated for the bottom-surface PLBs). The signals for these figures were zeroed to the PLB time in the same fashion as explained earlier in this paper. Propagation velocities were calculated by use of the distance up the edge (22 mm) plus the distance along the top surface from the edge along with the arrival times at the high frequencies shown in Fig. 15. The values of 2.90 mm/µs at the closest sensor and 2.95 mm/µs at the farther sensor were close to the Rayleigh velocity (less than 3% below). This result, along with the fact that the frequencies present in this portion of the signals were sufficiently high to be associated with Rayleigh waves, led to the conclusion that this portion of the signals was indeed a Rayleigh wave. This Rayleigh wave (indicated by arrows in Fig. 14 and by “Max 1” in Fig. 15) is a dominant feature of the signals obtained from the sensors, but, as shown in the WT results with superimposed group velocity curves, it does not arrive at the time expected within the Lamb-mode group velocities. Hence, the presence of this Rayleigh wave complicates the determination of the intense mode/frequency combinations in the Lamb modes. Similar difficulties were present for PLBs on the edge at other distances below the plate top surface.

Upper Frequency Range of Rayleigh Waves from PLBs

The data from an experiment with an edge PLB at the depth of 3 mm below the top surface with a wideband (nearly flat with frequency [17, 18]) conical-type sensor (called FHWA with appropriate preamplifier and 50 kHz high-pass passive filter) demonstrated the high frequency content present in the PLB-generated Rayleigh wave. Note that at the Rayleigh wave velocity, the 3-mm distance is equivalent to a propagation time of about 1 µs. Figure 16 shows this interesting result. In this case, a series of time-domain waveforms (not adjusted in time such that zero time corresponded to the time of the PLB) for a 381-mm propagation distance are shown for high-pass filtered signals (six-pole digital Butterworth) ranging from 50 kHz to 2 MHz. Clearly, even though the Rayleigh wave amplitudes diminished as the high-pass frequency increased, the Rayleigh wave signal extended to relatively high frequencies of up to 2 MHz. This result indicates that, depending on their frequency response, some AE sensors might be expected to be insensitive to a Rayleigh wave. The results of an experiment to test this hypothesis are presented in the next paragraph.

Detection of Rayleigh Waves by Different Sensor Types

Using the same edge PLB source at a depth of 3 mm and a propagation distance of 381 mm with a high-pass passive filter at 50 kHz (after the preamplifiers), a total of six differently designed AE sensors (with appropriate preamplifiers; internally with either no filter or a 5-kHz high-pass filter) were used to obtain results. Table 4 illustrates some of the characteristics of these sensors. Figure 17 shows the time-domain waveforms (again not adjusted to the PLB time) of the signals along with a classification of the sensors and a qualitative measure of the ability to distinguish by eye (in Fig. 17) the presence of a Rayleigh wave (ordered from the least to maximum ability to observe the presence of a Rayleigh wave; the rankings were called “not present”, “present” and “distinct”). The ability to see the potential Rayleigh wave was facilitated by the fact that a common trigger sensor was used and some of the sensor signals exhibited very distinct Rayleigh waves. To attempt to enhance the potential for detection of a Rayleigh wave in the time domain, the signals were digitally filtered (four-pole Butterworth) with a high-pass frequency of 500 kHz. The resulting signals (not shown) did not materially enhance the ability to pick out a
Fig. 16. Filtered signal showing high frequency content in Rayleigh wave at a propagation distance of 381 mm with signal from FHWA sensor. Right column shows the WTs of the left column signals along with the arrival times of the most intense signal peak corresponding to the Rayleigh wave.

Rayleigh wave in the cases where it could not be seen in Fig. 17. The best approach to determine whether a Rayleigh wave was present in the signals from the different sensors was by use of the WT. The results from the WT applied to the 50 kHz high-pass data are shown in Fig. 18. In this figure arrows point to the evidence of the presence of a Rayleigh wave. Close examination of Figs. 17 and 18 shows that the Res #3 sensor (a 150 kHz resonant frequency) signal exhibited no evidence of a Rayleigh wave. Res #1 also lacked a very clear response to the Rayleigh wave. It
is worthwhile to note that even though a resonant sensor that did not respond to a Rayleigh wave would remove the problem caused by the Rayleigh wave that propagates up the edge of the plate, it would not be very useful. The reason is that such sensors do not fully characterize the effect of the distance below the surface on the waves generated by edge PLBs over the range of frequencies in the Lamb modes.

Table 4 Sensor characteristics

<table>
<thead>
<tr>
<th>Sensor names</th>
<th>Expected response character</th>
<th>Freq. of peak response [kHz]</th>
<th>Approximate aperture [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHWA</td>
<td>Wideband</td>
<td>Not applicable</td>
<td>1.6</td>
</tr>
<tr>
<td>WB #1</td>
<td>Wideband</td>
<td>Not applicable</td>
<td>Proprietary</td>
</tr>
<tr>
<td>WB #2</td>
<td>Wideband</td>
<td>Not applicable</td>
<td>6</td>
</tr>
<tr>
<td>Res #1</td>
<td>Resonant</td>
<td>125</td>
<td>15</td>
</tr>
<tr>
<td>Res #2*</td>
<td>Resonant</td>
<td>500</td>
<td>3.5</td>
</tr>
<tr>
<td>Res #3</td>
<td>Resonant</td>
<td>150</td>
<td>15</td>
</tr>
</tbody>
</table>

* The small aperture sensor used in the first part of this research.

Fig. 17. Waveforms from different sensors showing the existence (at different levels of distinctiveness) or non-existence of evidence of Rayleigh wave from PLB at a propagation distance of 381 mm, 50 kHz high-pass data.
Fig. 18. WTs of the first 200 µs of the time domains in Fig. 17 demonstrating the presence of a Rayleigh wave and its relative intensity.

Discussion of Detection of Rayleigh Waves in AE Monitoring

There are two primary questions that are relevant to the potential detection of Rayleigh waves in AE monitoring of plates. First, is a surface Rayleigh wave present on the surface where a sensor is mounted? Second, will the particular type of sensor respond to a Rayleigh wave? With regard to the first question, the preceding parts of this paper have considered two situations: (a) either a source on the surface (includes surface edges or bottom surface, if a surface-to-surface path to the sensor mounting surface is present); or (b) a buried out-of-plane dipole source that is located not far below the sensor mounting surface. An additional case (not addressed in this research), involves a part-through crack that is open to the plate surface on which the sensors are mounted. In this situation a Rayleigh wave can be generated on the crack faces by crack growth or pop-in, as shown in experimental work [19]. This Rayleigh wave can propagate on the crack faces to the plate surface. In this situation as well as for the edge source location, the
Fig. 19. Approximate frequency below which a Rayleigh wave cannot propagate versus thickness of steel plate. Governing equation taken from reference number [9]. Wavelength values shown corresponding to frequency and Rayleigh velocity.

possibility for a part of the Rayleigh wave to continue to propagate on the plate surface will depend on whether the plate is thick enough to support a Rayleigh wave according to the equation previously introduced. A plot of this equation demonstrating frequency versus plate thickness is shown in Fig. 19 along with a second vertical axis that provides the wavelengths of Rayleigh waves corresponding to the frequency scale. This figure illustrates the approximate frequency for a steel plate, below which a Rayleigh wave cannot propagate as a function of the plate thickness. In addition, the figure points out the conditions (frequency and wavelength) for a nominal 25 mm thick steel plate. In addition, it should be noted that when a PLB is done on a plate edge, the “thickness” relative to that in Fig. 19 is typically very large. Hence, a Rayleigh wave will often be generated, but when the wave reaches the plate surface then its ability to continue to propagate will depend on the plate “thickness.” Finally, in all the cases that could lead to a Rayleigh wave, the rise time of the source must be short enough to excite frequencies above those indicated in Fig. 19. Based on FEM results [20], an estimate of the approximate high frequency from a source can be calculated from the reciprocal of the source rise time.

With regard to the second question, the sensor must have sufficient frequency response to the frequencies present in the Rayleigh wave. A key aspect of the required high-frequency response is a sensor with an aperture small enough that the Rayleigh wave (which travels on the plate surface under the sensor) wavelengths are greater than the sensor aperture size. The last column in Table 4 indicates a potential reason why signals from the sensors designated Res #1 and Res #3 exhibited no Rayleigh wave (or had almost no sensitivity to a Rayleigh wave) as discussed in the section dealing with the different sensors. For these sensors, the signal at the lowest Rayleigh-wave wavelengths would “average out” over the sensor face. It is worth noting that Fig. 19 clearly shows that the sensor aperture size must be quite small for thin plates.
Summary

There are three summary observations for thick plates (on the order of 25 mm in thickness) that can be made based on the results presented here. First, plate-surface sensor signals from PLBs on a plate edge at various distances below the top surface of a thick plate are difficult to interpret (relative to the Lamb-wave frequency/mode combinations that are excited), because a strong Rayleigh wave is generated that arrives at the sensors within the range of arrivals of the Lamb modes. Thus, the effects of the depth of buried dipole sources on the determination of intense Lamb mode/frequency combinations cannot be easily determined by use of such PLBs. This conclusion is contrary to that determined for the waves generated by PLBs on the edge of a thin aluminum plate (4.7 mm thickness).

Second, some resonant sensors have poor or no evident response to a Rayleigh wave. These sensors do not present the Rayleigh wave interpretation problem, but because of their limited bandwidth of sensitivity they are not useful to characterize the full response of the Lamb modes in the waves generated by edge PLBs at various edge depths.

Third, if PLBs on thick plates are done on the surface where the sensors are mounted to provide indications of the potential character of real AE, the signals may be dominated by Rayleigh waves unless the sensor does not respond to Rayleigh waves. Thus, the extraction of information from such PLB generated signals must be treated with care relative to the potential influence of a Rayleigh wave. This result is particularly true when subsequent experiments will generate real AE from buried in-plane sources, where Rayleigh waves are not generated even for sources just a small distance below the adjacent surface. It is also true for out-of-plane buried sources unless they are within about 23 % of the 25-mm plate thickness from the adjacent surface where the sensors are mounted.

References