A Waveform-Based Study of AE Wave Propagation by Use of Eight Wide-band Sensors on a Composite Pressure Vessel

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Abstract

An extensive analysis of wave propagation characteristics as related to the determination of acoustic emission (AE) source locations in a composite pressure vessel was carried out. The analysis was based on signals generated by a mechanical pencil lead break (PLB) on the hoop portion of a cylindrical carbon fiber/polymer pressure vessel. The analysis was enhanced by five key factors: i) the location of the PLB was known; ii) the eight sensors were placed in a known grid on the cylindrical portion of the pressure vessel; iii) the waveforms of the signals were digitized at 5 MHz with a 12 bit system; iv) different angles of propagation relative to the hoop wraps direction were present and v) the sensors had wideband non-resonant response that resulted in relatively straightforward identification of the fundamental Lamb modes. The group velocities of the first arrivals of the extensional and flexural modes were determined for different propagation directions from the PLB. The peak intense frequencies based on the Choi Williams Distribution (CWD) were examined in the signals from each sensor for each fundamental modal region. In addition, group velocities from signal arrival times based on the CWD intense average frequency regions were determined for both the extensional and flexural regions of the waveforms. Considering both modes, the potential impacts on determination of source location due to alternate propagation paths to the sensors were also investigated. Based on the analysis results, some options for accurate source location determination are discussed and illustrated.

Keywords: Pencil lead break, wave propagation, composite pressure vessels, group velocities, source location

Introduction

Obtaining accurate locations of acoustic emission (AE) sources in an aerospace type composite pressure vessel (COPV) is challenging due to several reasons: (i) the propagation velocities can vary in different propagation directions; (ii) the vessel manufacturers typically consider the winding pattern to be proprietary and the fabrication methods as well as the fiber layup are not as uniform as those for flat composite plates; (iii) multiple source types (fiber fracture, delamination, matrix cracking, etc.) with different source orientations and source depths can complicate even the use of wideband sensors along with analysis based on Lamb modes; (iv) the polymer matrix, geometric spreading and dispersion result in high signal attenuation and (v) the amplitudes of the sources can vary over wide ranges. Thus, both simple approaches using a fixed threshold for arrival times with a single propagation velocity, as well as more sophisticated non-threshold approaches may be problematic. Thus, AE applications for COPVs have often used multiple sensors with data analysis based on first-hit sensors to locate a region of the source rather than a specific location for each AE event. Since composites are expected to fail by a weakest link process [1], more accurate locations of sources could be expected to enhance the application of AE techniques for nondestructive testing applications for COPVs.

The purpose of this research was to closely examine AE signal waveforms obtained primarily from a pencil lead break (PLB) applied to the outer composite surface of a carbon fiber/polymer cylindrical pressure vessel of the aerospace type. The decision to use PLB data was based on the fact that both fundamental modes were present in the signals, and the PLB does not introduce a non-uniform in-plane directional source of acoustic energy. In addition, this source does not complicate the signals due to different source depths. The emphasis of this study was to obtain signal and wave propagation insights relative to analysis to determine accurate source locations of real AE signals obtained during proof testing of such COPVs.
The data set used for this study was relatively unique due to five reasons: (i) a total of eight sensors were located by precise fixturing at known locations on the cylindrical portion of the COPV; (ii) the spacing of the sensor grid was such that the maximum distance of the nearest AE sensor to a source located in the cylindrical region was at most 117 mm, when the source was at the transition from the cylindrical section to the end domes, and if the source was interior to the sensor grid, the maximum distance was 84 mm (the vessels were designed to fail in the cylindrical region); (iii) the sensors were of a non-resonant type, typically characterized as wideband; (iv) simultaneous waveforms for each event were obtained from the signals from each sensor; and (v) the PLB was applied by a mechanically operated fixture at a known location on the cylindrical section.

**Relevant Details on the COPV and Experimental Conditions**

A commercially-produced filament-wound cylindrical pressure vessel (end domes) with a thin aluminum alloy liner (non load sharing) was used in this study. The carbon fiber/polymer matrix COPV had the following nominal dimensions in its cylindrical section: composite thickness = 3 mm, liner thickness = 1.3 mm, length = 290 mm and outer diameter = 125 mm. It is worth noting that such small size COPVs are often used in research due to cost factors. The filament-winding pattern in the cylindrical region had interspersed hoop and longitudinal wraps. For the PLB, the vessel was pressurized with water to 0.69 MPa (PLB signals stabilized at this pressure and above). Prior to this research, the manufacturer had applied a hydraulic proof/autofrettage cycle to 63% of eventual burst pressure of this COPV.

![Figure 1 Photograph showing the sensor support rings and sensor fixturing.](image1.jpg)

![Figure 2 Close-up photograph of the mechanical pencil in its fixture.](image2.jpg)

The test fixturing, shown in figures 1 and 2, limited contacts with the vessel cylindrical section to the spring-loaded sensors and small rubber covered contacts holding the four sensor-support rings in place. Figure 2 shows a close view of the fixture holding the pencil used to mechanically apply PLBs with 0.3 mm diameter lead of 2H hardness. Figure 3 is an unwrapped view of the vessel showing the eight sensor locations as well as the PLB location. In this figure, the cylindrical section is extended on each side so that other than the shortest propagation paths from the PLB to the sensors can be visualized. The wideband non-resonant sensors (Digital Wave, model B1025T) were coupled with vacuum grease and held in contact
by springs inside polymer fixturing so that they were perpendicular to a tangent plane at the outer surface of the vessel.

Figure 3 Unwrapped view of the COPV showing the coordinates of the sensor locations and the PLB location. Grid spacing 25.4 mm (1 inch)

The AE system simultaneously digitized the signals from each sensor when the threshold of ± 17 mV was exceeded at any sensor signal. A total of 2048 points, including a pretrigger of 250 points, were digitized at 5 MHz with the 12-bit system, which saturated at ± 500 mV. A bandpass of 0.020 MHz to 1 MHz was used, but an unexpected system fault superimposed a sinusoidal-shaped noise signal of about ± 3.9 mV on the digitized waveforms. This signal was removed by a six-pole, 20 kHz, high-pass, Butterworth filter prior to analysis of the waveforms. After this filtering, the electronic noise on the waveforms was about ± 1.3 mV. Note that all reported voltages are the values after a total gain of 32 dB (20 dB by the preamplifier and 12 dB by the AE system).

**Group Velocities of Initial Arrivals of Fundamental Modes versus Propagation Direction**

For a PLB (near sensor # 3), figure 4 shows the waveforms ordered from top to bottom by the apparent arrival of the flexural mode. The initial arrivals of both fundamental modes were extracted from the waveforms by eye. For the extensional mode, the arrival time was determined from the time at the peak of the first positive half cycle of the signal above the background electronic noise. If this peak was questionable, then the arrival time was taken at one-half the time between the questionable first positive peak and the subsequent first negative peak. A similar approach was used for the flexural mode, except its arrival time was determined by the peak of the first half cycle of either polarity that had an amplitude above the extensional mode signals. Again, if there was some question, the time was taken at one-half the time to the subsequent half-cycle peak of opposite polarity.

Since the waveform from sensor # 3 (see figure 4) indicates that both fundamental modes were developed (the propagation distance from the PLB to sensor # 3 was 8.8 times the total
an approach was implemented based on the time differences from the initial arrivals of the two modes at the other sensors relative to those arrivals at sensor # 3. Thus, the group velocities for the propagation (in the different directions) to the other sensors were determined from the difference in the PLB wave propagation distance along the shell (sensor # x minus sensor # 3) divided by the difference in the initial mode arrival time (sensor # x minus sensor # 3). These velocity results for each sensor (except # 3) are shown in table 1 for the shortest propagation path from the PLB location to the sensors. Since the velocities were observed to be relatively similar except for the propagation to sensor # 4, an average velocity (see table 1) was calculated for each mode excluding the results for # 4. Table 1 also shows the signed difference of each velocity relative to the average. It is worth noting, that the group velocities were determined between two distances where the fundamental modes had already been established. Since there were a wide variety of propagation angles for the shortest path from the PLB to the sensors, some questions arose relative to the much higher velocity results for the path to sensor # 4 as compared to the velocities to the other sensors.

In table 1, in the first column, the approximate angles (without a sign) of propagation relative to the hoop direction (0 degrees) are given. Several observations can be made relative to the velocity results for the propagation direction to sensor # 4: (i) the propagation direction from the PLB to sensor # 4 is nearly in the hoop direction (off by about 10 degrees); (ii) due to the stresses in the hoop direction being typically twice those in the axial direction for a cylindrical pressure vessel, the COPV had about twice as many fibers aligned in that direction (the hoop wraps and the portion of the longitudinal wraps that project to that direction); (iii) hence, as an approximation, the in-plane stiffness of the composite is about twice as stiff in that direction compared to the axial (longitudinal) direction; (iv) thus, it is to be expected that the velocity of the fundamental longitudinal mode will be considerably higher in that direction than in other directions and (v) since the flexural mode significantly depends on the flexural modulus, which is influenced by the low modulus of the polymer matrix, it is to be ex-

Figure 4 Recorded signals from a PLB located near sensor # 3. Sensor numbers indicated.

Figure 5 Recorded waveforms for the sequence of sensors #’s 5, 4 and 7 with increasing propagation distance. Expanded time scale.
pected that the increase in the flexural mode velocity in directions near the hoop direction will not be large compared to that in alternate directions not near the hoop direction. Based on these observations, an alternate analysis of the apparent initial arrival of the flexural mode for sensor # 4 was undertaken.

Table 1 First arrival group velocities of fundamental modes

<table>
<thead>
<tr>
<th>Sensor number; angle of propagation relative to the hoop direction</th>
<th>Ext. velocity, mm/µs</th>
<th>Ext. % difference vs. avg. w/o # 4</th>
<th>Flex. velocity, mm/µs</th>
<th>Flex. % difference vs. avg. w/o # 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>3; 50</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>2; 33</td>
<td>5.04</td>
<td>−5.4</td>
<td>1.69</td>
<td>+4.0</td>
</tr>
<tr>
<td>1; 24</td>
<td>5.58</td>
<td>+4.7</td>
<td>1.66</td>
<td>+2.0</td>
</tr>
<tr>
<td>4; 10</td>
<td>8.36</td>
<td>+57</td>
<td>2.41</td>
<td>+48</td>
</tr>
<tr>
<td>6; 57</td>
<td>5.43</td>
<td>+1.9</td>
<td>1.54</td>
<td>-5.5</td>
</tr>
<tr>
<td>5; 47</td>
<td>5.54</td>
<td>+4.0</td>
<td>1.69</td>
<td>+3.6</td>
</tr>
<tr>
<td>7; 85</td>
<td>5.08</td>
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<td>1.46</td>
<td>-10</td>
</tr>
<tr>
<td>8; 49</td>
<td>5.29</td>
<td>-0.6</td>
<td>1.73</td>
<td>+6.4</td>
</tr>
<tr>
<td>Avg. w/o # 4</td>
<td>5.33</td>
<td>−</td>
<td>1.63</td>
<td>−</td>
</tr>
</tbody>
</table>

Figure 5 shows the waveforms from the sensor # 4, as well as those from the sensors with propagation distances on either side of the distance to sensor # 4. In this figure, there are distinct differences in the region of the apparent flexural mode arrival time for the signal from # 4 compared to the flexural mode arrival for the other two signals. First, there is a sharp pulse of higher frequency indicated by the solid arrow for # 4 (the arrival time used in the velocity calculation made for the results in table 1) without the following decreasing frequency as observed in the other two signals, after the solid arrows that indicate their flexural mode initial arrivals. Second, later in signal # 4, after the arrival at the dashed arrow, the # 4 signal shows a character (frequency and amplitude sequence) much more similar to that from the other two sensor signals at the flexural mode arrival. These observations indicated potentially a later initial flexural mode arrival at sensor # 4, rather than the original choice. Hence, using the arrival time at the dashed arrow (see figure 5), the velocity of propagation to sensor # 4 was recalculated. The resulting velocity was determined to be 1.77 mm/µs, which is only about 9% faster than the average velocity for all the other PLB to sensor paths as shown in table 1. This result provided a strong indication that the originally assumed flexural arrival at # 4 was due to some other aspect.

Due to the positions of the sensors, sensor # 4 is one-half way around the vessel from sensor # 3 on the same circumferential circle. This observation led to the consideration of an alternate signal propagation path from the PLB through the fluid water (used to pressurize the vessel) to reach sensor # 4. The velocity through the fluid was about 1.48 mm/µs [2], and the distance of this path (PLB point to # 4) was determined from the geometry to be about 127 mm (just above the nominal diameter 125 mm of the vessel) with about 6 mm of this distance through the composite (both walls) and 2.6 mm of the distance through the aluminum (both walls). These values resulted in a “water path” (water and the vessel walls) transit time of about 82 µs (using bulk velocities of 6.3 mm/µs for the aluminum and 2.5 mm/µs [3] for the composite) from the PLB to sensor # 4. To estimate where this transit time appeared in the signal from sensor # 4, the average velocity for the initial arrival of the extensional waves determined in table 1 was used for the extensional wave traveling to sensor # 3 to calculate an approximate propagation time for the wave to travel from the PLB location to sensor # 3 (path at about 50 degrees relative to the hoop direction). The approximate time for this distance (37.6 mm) was 7.1 µs. As shown in figure 6, placing the time of the PLB at approximately 7.1 µs before the extensional wave initial arrival at # 3 (48.1 – 7.1 = 41 µs; on the
time scale of the waveform) provided a way to examine the “water path” timing. By use of the experimental arrival time (125.8 µs) of the sharp pulse (# 4 signal) as shown in figure 6, an experimental time difference from the PLB time to a “water path” arrival at sensor # 4 was found to be 84.8 µs (125.8 – 41 = 84.8 µs). Since the calculated propagation time for the “water path” of the vessel was about 82 µs, it was concluded that the “water path” accounts for the early arrival originally mistaken for the flexural wave arrival at sensor # 4.

![Figure 6 Signals from sensors # 3 and # 4 showing the approximate PLB time and the arrival at sensor # 4 from the “water path.”](image)

Figure 6 Signals from sensors # 3 and # 4 showing the approximate PLB time and the arrival at sensor # 4 from the “water path.”

The existence of the “water path” was further verified by the results in figure 7, which show the Choi Williams Distribution (CWD) results for the three sensor signals shown in figure 5. The parameters used to obtain this CWD result [4] (and all subsequent CWD results) were a frequency band of 2.44 kHz, 112 terms in the damping summation and an exponential damping parameter of 20. The CWD result for sensor # 4 signal shows higher frequencies in the “water path” region of the signal, where the arrival of a CWD peak magnitude at a frequency of 250 kHz is at 128.5 µs versus an arrival of 125.8 µs in the waveform. In this regard, the “water path” is expected to better preserve higher frequencies since there is no dispersion and only the bulk longitudinal velocity through the water. As an aside with respect to figure 7, note the “broken” nature in the CWD of the lower frequency (peak intensity at 105 kHz) arrival at # 4. This is in contrast to the CWD peak intensity region for the signals from sensors # 5 and # 7. As will be discussed later, the second shortest composite path to sensor # 4 results in a flexural mode initial arrival only about 16 µs (by use of the newly determined velocity of 1.77 mm/µs) after the shortest path initial arrival of this mode. Thus, the similar arrival times of the flexural mode for the two paths can be expected to create some distortion in the CWD as compared to the other two cases in figure 7, where as will be shown later, the second path flexural arrival is much later. In addition, it will be shown later that the “water path” related portion of the signal also contributes to this “broken” nature. As a final note, it is clear that the determination of arrival times by a fixed threshold would likely lead to an arrival time related to the “water path” for the signal from sensor # 4, since it arrives before the flexural mode with significant amplitude above that of the extensional mode. If this fact

![Figure 7 CWD results for the waveforms of the three sensor signals shown in figure 5.](image)
were not realized, this “water path” arrival time would lead to an error in a location calculation based on shell path distances for all the hits.

Due to the much larger velocity of the extensional wave first arrival for the path to sensor # 4, the assumption (used to calculate the velocities in table 1) of the wave front being a uniform circle (in the unwrapped view; centered at the PLB point) when it reached sensor # 3 was not correct for the propagation angle to # 4. Hence, an iterative procedure was used to recalculate an estimate of the initial-arrival extensional velocity for the path from the PLB location to sensor # 4. Using the previously calculated time interval estimate (7.1 µs) for the extensional wave to propagate from the PLB to # 3, the distance that the wave on the path from the PLB point to sensor # 4 would travel using the initially determined extensional velocity to # 4 was calculated. This distance was found to be 59.4 mm (7.1 µs times 8.36 mm/µs = 59.4 mm), rather than the originally used value of 37.9 mm (from the PLB to # 3). This distance was subtracted from the total distance from the PLB to reach # 4 (186.4 – 59.4 = 127 mm), and that distance and time difference from the extensional mode initial arrivals at # 4 minus # 3 was used to calculate a new velocity for the path to # 4. This process was repeated until the result converged at 7.52 mm/µs (approximately 10 % less than the original value). A similar iteration for the velocity of the initial arrival of the flexural mode at # 4 converged at 1.73 mm/µs, which is about 2 % less than the revised value of 1.77 mm/µs.

Since the group velocities in table 1 did not include a velocity for the signal from the PLB to travel to sensor # 3, plots were made for the PLB to sensors propagation distances versus the initial arrival times of both modes to study the fit when sensor # 3 data was included. These results are shown in figures 8 and 9 respectively for the extensional and flexural mode initial arrivals. In figure 8, the data for sensor # 4 is excluded for the extensional mode, since the extensional velocity to # 4 was already determined to be much larger for that propagation direction. For the extensional mode first arrivals, the slope velocity from this plot is 5.23 mm/µs ($R^2 = 0.997$), which is 2 % lower than the previously determined average velocity of 5.33 mm/µs. For the flexural mode first arrivals, the slope velocity from this plot is 1.63 mm/µs ($R^2 = 0.978$), which is the same as the previously determined average velocity of 1.63 mm/µs. Thus, it was concluded that the initial arrivals at sensor # 3 for both fundamental modes were characterized by the originally calculated average velocities.
Figure 10 (a) Waveforms from sensors #’s 3, 2, 1 and 6 from the PLB showing the approximate second shortest path initial arrivals for both fundamental modes (E2 and F2 respectively for the second arrivals of the extensional and flexural modes).

Figure 10 (b) Waveforms from sensors #’s 5, 4, 7 and 8 from the PLB showing the approximate second shortest path initial arrivals for both fundamental modes (E1 and F1 and E2 and F2 respectively for the 1st and 2nd arrivals of the extensional and flexural modes).

**Initial Arrivals of Second Shortest Path of Fundamental Modes**

Using the fundamental mode first arrival group velocities and the composite propagation distances for the second shortest path from the PLB to each of the sensors, the initial arrivals of the second path for each fundamental mode were approximately determined relative to those for the shortest path arrivals in the waveform signals. The propagation direction relative to the hoop direction was also determined for the second path. In all the cases the second path was closer to the hoop direction. Hence, for the calculations of some of the second path arri-
val times the higher extensional velocity (# 4 in table 1; revised to 7.52 mm/µs) was used for the paths that were nearest the hoop direction (sensor #’s 1, 2, 3, 4 and 6).

Figures 10 (a) and 10 (b) demonstrate by arrows these approximate second path initial arrivals with the notations of E2 and F2 to label by arrows respectively the extensional and flexural second path initial arrivals (and in some cases E1 and F1; the first arrivals). The waveforms in figure 10 are ordered from top to bottom by the increasing distance for the shortest path from the PLB to the sensors. Clearly, the second path flexural mode arrivals have a stronger influence on the shortest path flexural mode signals for the two sensors (# 4 and 8) that are further away from the PLB position. In addition, the amplitudes within the signals can be affected by subsequent path arrivals and/or reflections. In the next section, it will be shown that alternate path arrivals can influence the determination of arrival times by the CWD for some of the sensors.

![Figure 11 Plot of the “peak frequencies” of the peak CWD magnitudes versus the shortest propagation distance for all eight sensors for both fundamental modes.](image)

**Non-Threshold Dependent Arrival Times and their Group Velocities**

To this point the arrival times of the modes were all made using a visual determination based on the first arrival of the mode. As a next step, a method possibly suited to threshold-independent automatic-determination of shortest path arrival times was investigated by use of the CWD. First, the frequencies of the peak intensity (the peak magnitude versus time and frequency) for each fundamental mode were determined from CWD results. It was necessary to use truncated signal lengths for the extensional mode case so as to view only the lower amplitude extensional mode in the CWD diagram. For the flexural mode, for sensor # 7 a truncated signal length was also necessary to determine the frequency with peak intensity near the initial arrival of that mode. These results for the frequencies, “peak frequencies,” of the peak CWD intensity for each mode region versus the propagation distance for each sensor are shown in figure 11. This figure does not show a systematic variation with distance for the “peak frequency” for the extensional mode, and it possibly shows a small amount of increase with distance for the flexural mode. The “peak frequencies” were also examined as a function of the propagation angle of the shortest path relative to the hoop direction. In this case (not shown), no correlation was observed as well. The “average frequency” of the peak intensity was determined for each mode to be 337 kHz and 92 kHz respectively for the extensional and flexural modes using the data for all the sensors. At the “average frequency” for each fundamental mode region, the arrivals times of the CWD peak magnitude were determined (again
the signals were truncated as needed for the same reasons). This process of determination of arrival times was not done for the “peak frequencies”, since the group velocities would be expected to show some variation with frequency, particularly for the extensional mode.

Figures 12 (a) and (b) respectively for the extensional and flexural modes show plots of the shortest propagation distance from the PLB to the sensors versus the arrival times determined from the CWD peak magnitude at the “average frequencies.” As before, the data for the signal from sensor # 4 was excluded for the extensional mode case due to the significantly higher velocity for the propagation direction being near the hoop direction, and it was excluded for the flexural mode due to potential interference of the “water path” and a similar arrival in time of the of the second path. For information, the CWD arrival time for the # 4 signal is included in figure 12 (b) as a single point that was not considered in the straight-line correlation. The straight-line fits that provide group velocities as well the $R^2$ values are shown in the figures. For the extensional mode, the velocity result and $R^2$ value were respectively 4.04 mm/µs and 0.951. The corresponding values for the first arrival of this mode as determined earlier (see figure 8) were 5.23 mm/µs and 0.997. For the flexural mode the velocity result and $R^2$ value were respectively 1.47 mm/µs and 0.997. The corresponding values for the first arrival of this mode as determined earlier (see figure 9) were 1.63 mm/µs and 0.978, where sensor # 4 was included. It is worth noting that the arrival times were taken for the flexural mode at the absolute maximum of the CWD at 92 kHz for the whole signal length except for sensor # 7 where a truncated signal was used. Comparing the fits of the two approaches, in the case of the extensional mode, the fit was slightly better using the first arrival data, and for the flexural mode the CWD determined result had a better fit.

Discussion Relative to Determination of Arrival Times that Result in Accurate Source Locations – Based on PLB Study

This discussion specifically considers automatic approaches that are required due to the large number of AE events. Regardless of the fact that two approaches applied to obtain arrival times from the extensional mode (initial arrival time and arrival time of the CWD peak magnitude at the “average frequency” for all the sensors, both without # 4) resulted in good
straight-line correlations with propagation distance (providing group velocities), it does not seem to make sense to rely on these arrival times for source location calculations. For the approach using the initial arrival time, the reason is that this portion of the waveforms does not have a high signal-to-noise ratio (SNR). Hence, the initial arrival of the extensional mode may be near or dip below the electronic noise level as the propagation distance increases or when the AE source is smaller in amplitude. In addition, the poor SNR may make it difficult to automatically and accurately detect the actual first arrival. Further, considering the high attenuation with propagation in a composite, the poor SNR of this arrival may mean that there are not enough hits with amplitude above the electronic noise level to calculate a location. For the approach using the CWD peak magnitude arrival time at the “average frequency,” the SNR is still an issue, and the need to truncate the signals (to ignore the flexural mode region) in an automatic fashion may not be easy to implement when different propagation distances are present.

If the flexural mode is considered to determine arrival times, it is not clear how to automatically determine the initial arrival time of the mode. Further, as can be seen in figure 4, the SNR is not as high in that portion of the mode compared to later in the flexural mode region. On the other hand, an automatic approach of the CWD peak arrival time at the “average frequency” applied to the flexural mode provided an excellent straight line correlation for the arrival times versus propagation distance. Further, these CWD-based arrival times are determined from a region of the waveforms that had a much better SNR. But, note that these results were obtained without including the signal from sensor # 4 due to the close arrivals of the flexural mode for the two shortest propagation paths, and as will be shown shortly, the “water path” part of the signal.

As a demonstration (suitable to automation) of the use of arrival times obtained at the CWD peak magnitude of the flexural mode at the “average frequency,” the location of the PLB was calculated by use of these arrival times for the first four signals from sensors #’s 3, 2, 1 and 6. This calculation was made using planar location software for a flat plate [5] along with the group velocity (1.47 mm/µs) shown in figure 12 (b). The calculated result for the PLB location was x = - 17.1 mm and y = 208.8 mm as compared to the actual location of x = - 20.0 mm and y = 208.0 mm. The radius (relative to the actual location of the PLB) of the location error was 3.8 mm. The same calculation was also made using data from the signals from sensor #’s 2, 1, 7 (truncated signal) and 8. The results for the PLB location were x = - 18.7 mm and y = 211.6 mm with a radius error of 3.1 mm. Thus, even using arrival times with two of the sensors (#’s 7 and 8) further from the PLB provided good results as well. These location results are not completely unexpected, since the velocity was determined from the same data, but the location results do demonstrate that the excellent fit used to determine the group velocity was an important result. A poor fit would not yield such excellent location results.

There are some potential weaknesses of an automatic approach by use of the arrival times at the CWD peak magnitude at the “average frequency” for the flexural mode. First, if a less dense array of sensors is in place, then the longer propagation distances may result in the peak magnitude arrival time being due to multiple paths unless the signal is truncated to eliminate this effect, as was the case with sensor # 7. Since an automatic approach to signal truncation may not be straightforward, alternatively, it may be possible to automatically examine the values of the CWD magnitude peaks versus time at the “average frequency” to pick the first relatively large peak. Figure 13 shows with the increasing propagation distance (top to bottom) the CWD intensity at 92 kHz versus time for all the sensor signals (from the PLB) for the full recorded signal length. In this figure, when multiple peaks are present, the arrows show the peak for the arrival times that were used in figure 12 (b). In the case of the five sensors closest to the source, there is a clear and very large increase in the peak magnitude of the
CWD value that identifies proper the arrival time. Thus, an arrival time could easily be automatically determined by the first significant increase in the peak magnitude or the absolute maximum peak. For the three further sensors the situation is different. For sensor #4, there are several initial CWD peaks, and it is not clear which to choose. For sensor #7, there is a clear first peak as determined by a relatively large step up in magnitude that could be automatically determined by a procedure of continuously examining the CWD peak magnitudes as the time increases. For sensor #8, it is again not clear which of the initial large peaks to select. Thus at two (#’s 4 and 8) of the farthest propagation distances, a large step up of the CWD magnitude to identify a flexural arrival time is not as straightforward as for the first five sensors.

![Figure 13 CWD magnitude of 92 kHz frequency band for each sensor signal versus time. Arrows indicate the arrival times used for the results in figure 12 (b) when multiple peaks were observed.](image1)

To examine these three cases in more detail, figure 14 shows the signals from these three sensors and directly below, in each case, the CWD magnitude versus time at the “average frequency” of 92 kHz. This figure helps to clarify the issues that are present in determination of peak CWD-magnitude arrival times at the farther sensors. In the case of sensor #4, it is clear that there are two effects that resulted in multiple initial peaks. The first effect is the arrival of the “water path” portion of the signal, and the second effect is the close arrival in time of the second path flexural mode (see figure 10 (b)). It is not clear how to resolve these issues, other than to ignore badly “broken” CWD results. In the case of sensor #7, the arrival of the flexural mode second path in the latter part of the signal (see figure 10 (b)) leads to the absolute maximum late in the CWD magnitude plot. It seems to be clear, as mentioned above, in cases like #7, that a technique that determines when a significant step up in the CWD peak magnitude occurs could lead to an automatic determination of the arrival time that in this work was found with a truncated signal. In the case of sensor #8, the close arrival in time of the second path flexural mode (see figure 10 (b)) results in the absolute maximum peak and thus a step up in magnitude could not be used. Possibly in such a case the arrival time could be selected at the average time of these two early peaks that are 14.8 µs apart. In any event,
the adoption of these types of modifications to an automatic approach needs to be based on an extensive examination of real AE signals.

Figure 15 (a) A real composite AE event (# 314) with waveforms similar to those from the PLB and (b) the magnitude of the CWD at the average frequency of 85 kHz. Order from top to bottom by flexural mode arrival.

Some Observations Relative to Source Location with Real AE Signals from such a COPV

Figure 15 (a) illustrates a set of real composite AE signals from an event in this COPV (at 62 % of the eventual burst) which has waveforms similar to the PLB waveforms (dominance of the flexural mode). In this case the “average frequency” of the CWD for the flexural mode was determined to be 85 kHz (using only the CWD results [not shown] that did not have a “broken” nature, which excluded # 4 and # 8), which is less than the 92 kHz determined for the PLB. Figure 15 (b) shows the CWD magnitude at 85 kHz for the same top to bottom sequence. Using this “average frequency,” the arrival times at the peak magnitude of the first significant step up in magnitude (or the absolute maximum) were determined for the sensors that did not have a “broken” nature in their CWD results (the “broken” nature was assumed to be due to similar second path arrivals and possibly “water path” related waves).

Using the arrival times for sensor #’s 3, 6, 5, 2 and 1, the location was calculated. Since the “average frequency” was lower than that determined for the PLB case, the group velocity was iterated to minimize the “uncertainty” of the location calculation. At a velocity of 1.37 mm/µs (minimum uncertainty in the location calculation), the source location was determined to be x = - 4.0 mm and y = 130.56 mm. Alternatively, adding sensor # 7 to the five sensors selected, the location was calculated as x = - 4.3 mm and y = 135.2 mm with an iterated velocity of 1.38 mm/µs. Upon examining this location (see figure 3), it can be concluded that the first and second paths to sensor # 8 have a similar distance resulting in a “broken” CWD result. In addition, the initial step up in magnitude of CWD result at 85 kHz for sensor # 4 again is likely influenced by a “water path” as well as a similar time of arrival of the flexural mode second path arrival, both of which would lead to the “broken” nature of the CWD. This “water path” conclusion was verified in a similar fashion to the process used to determine the
“water path” from the PLB to sensor # 4. In the current case, the source was assumed to be in the composite in the inner higher stress region near the aluminum liner. The propagation time was calculated to be about 85.7 µs. This value compared to an experimental value of 86.0 µs.

Conclusions

Based on analysis of waveforms from a PLB source, conclusions were made relative to AE wave propagation in the current cylindrical carbon fiber/polymer pressure vessel.

- Due to the continuous nature of the COPV, multiple paths of propagation from a source to the sensors potentially complicate the AE signal. This result is particularly the case for the sensors farthest from the source.
- If a propagation path only about 10 degrees off from the hoop direction is ignored, then the group velocities for the initial arrivals of the extensional mode were within 10 % or less than the average velocity for a variety of propagation distances and angles between about 24 to 84 degrees relative to the hoop direction. For the initial arrivals of the flexural mode, this statement was true for all the directions examined from 10 to 84 degrees.
- The initial arrival times of both fundamental modes provided excellent fits (without # 4 for the extensional mode) for the determination of their group velocities, but these arrival times were obtained from regions of the signals with relatively poor SNR, which would make it difficult to automatically determine the arrival times.
- A sharp pulse in the signal from a sensor nearly opposite the PLB source position was identified as being from a “water path” that transmits a non-dispersive wave at a water longitudinal velocity. This pulse arrived prior to the flexural mode at this sensor, and with a threshold-based determination of an AE arrival time, this pulse could be mistaken as the time of the flexural mode arrival.
- Using CWD-based peak magnitude arrival times at the “average frequency” for the flexural mode signal region, the slope of the propagation distance versus the arrival times plot provided a close fit for a group velocity at 92 kHz of 1.47 mm/µs. This result was obtained ignoring data from the sensor with a significant “water path” pulse. These CWD determined arrival times originate from a flexural mode portion of the signals with nearly the maximum SNR.

References