MODELED TRANSVERSE SURFACE AE SIGNALS FROM BURIED DIPOLE SOURCES IN A POLYMER ROD

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Abstract
Finite element modeling (FEM) was used to study the AE type signals generated from internal dipole sources in a 600 mm long by 8.5 mm polyvinyl chloride (PVC) rod. A pencil lead break on a rod end was used to demonstrate the accuracy of the FEM results. Out-of-plane AE signals (u_r) versus time were obtained from 16 pseudo sensors equally spaced around the circumference at 90 mm and also at 120 mm from the sources. Group velocity curves were calculated. Filtering was applied to correspond to expected results from experiments. Along with the signals, fast Fourier transform and Choi-Williams distribution results were obtained for radially-oriented dipoles. Three dominant modes in the u_r signals were identified: L(0,1) symmetric, F(1,1) antisymmetric and F(2,1) antisymmetric. The relative dominance of these modes changed significantly with the angles to the sensors. The multiple sensors defined the modal displacement patterns of the circumference along with the significant changes in amplitude as a function the angles. Also, the dependence of the signal amplitudes of the modes were determined as a function of the source distance from the axis of the rod.

Keywords: Finite element modeling, dipoles, PVC rod, many sensors, modes

1. Introduction
In the past, extensive finite element modeling (FEM) of wave propagation signals has been done (by the author and co-authors) using dipole sources (to simulate acoustic emission sources), for example in steel [1] and aluminum [2] plates. These studies examined the effects of variables such as source orientation, source location through the thickness, rise time and type of source (using more than one dipole). The results focused on waveforms, fast Fourier transforms (FFT), and frequency/time analysis (with superimposed group velocity curves) of the signals. This author is not aware of such comprehensive studies on rods. This work represents the initiation of FEM studies with buried dipole sources of the wave propagation signals in an isotropic rod.

2. Material, Rod Geometry, Group Velocities and Pencil Lead Breaks
To allow use of a current desktop computer, a polymer rod was selected for this initial study. This decision was made since higher frequencies would experience substantial material-based attenuation. Thus, very short source rise times and an extremely small mesh size were not required to be able to model a long rod (so end reflections would not arrive during the major direct signal arrival). Hence, a polyvinyl chloride (PVC) rod was selected with diameter of 8.5 mm and length of 600 mm. The rod properties, except for the density (measured at 1500 kg/m^3 [3]), were taken from published values [4] that reported bulk longitudinal and shear velocities of 2330 m/s and 1070 m/s respectively. Due to the guided wave propagation, group velocities were calculated after modifying a code developed by Seco and Jimenez [5]. Figure 1 shows the results for the longitudinal modes as well as some flexural modes. In referring to these modes, the notation put forward by Rose
[6] has been adopted. Later it will be established, for the selected signal filtering, that the relevant modes observed were the fundamental longitudinal and flexural modes $L(0,1)$ and $F(1,1)$ respectively and a higher flexural mode $F(2,1)$.

![Graphs showing group velocities for various modes](image)

Figure 1. Group velocities for a 8.5 mm diameter PVC rod, red rectangles indicate the modes observed, velocity (m/s) on vertical scale and frequency 0 to 0.5 MHz horizontal scale.

To examine the appropriateness of the selected properties and to examine the accuracy of the FEM results, axial pencil lead breaks (PLBs) were modeled and experimentally applied to the end of a 1 m long actual PVC rod with the same diameter. For this experiment, conical-design broadband sensors (model KRNBB-PC) were placed on the rod circumference at 120 mm from the end PLBs.

### 3. Sensor Locations, Description of Dipoles, FEM Code and Mesh Structure

In the case of the buried dipole sources, two rings of 16 point-contact “pseudo” sensors were equally spaced around the rod circumference (spaced at 22.5° increments) at 90 mm and 120 mm from the plane of the centers of the dipole sources. These “sensors” provided the out-of-plane displacement ($u_r$) from mesh points versus time for runs of 280 µs. Initially four dipole source types were examined. These included single dipole sources aligned in the axial, radial and tangential directions as well as three simultaneous mutually perpendicular dipoles in these three directions. Since the radial and tangential dipoles results were found to be similar and included an additional mode not present in the other two dipole cases, it was decided to focus on radial dipoles with their centers located at a series of distances from the rod axis.

The FEM code used was that developed by Gary [7, 8]. It was validated in the past on metal samples both by comparison with analytical results as well as by experimental results using PLBs with an absolutely calibrated National Institute of Standards and Technology (NIST) secondary standard sensor. The FEM mesh structure is shown in figure 2(a) as well as the directions of the reference angles to the sensors from 0° to 360°. The figure also shows the radius at 90° where the dipole sources as well as the PLBs were centered. The mesh structure in the axial z-direction repeated that shown in the figure by a series of slabs of 0.2 mm thickness. The maximum variable cell size in the $r$, $\theta$ plane was 0.209 mm. The repetition of the mesh structure in the z-direction resulted in a very efficient FEM code. Each slab had
3072 cells and the total number of cells was $9.2 \times 10^6$ for the rod. For the dipole sources and the PLBs, the rise time was 2 $\mu$s with a cosine-bell time dependency [8]. The time step used was $0.0429$ $\mu$s, and the FEM displacement signals were resampled to a time step of 0.1 $\mu$s for the data analysis.

The dipole sources were made up of two monopoles (cells with body forces) separated by two cells without body forces. As shown in figure 2(b), the monopoles, with net force of 1 N, were two cells wide to preserve symmetry about the radius from the rod axis to the $90^\circ$ direction. For the dipoles oriented in the other directions, the same two cells without body forces were separated by the appropriate monopoles. The centers of the dipoles (relative to the rod axis) were taken to be located at the mid-points of a line from the center of each of the monopole cells.

4. Results PLB versus FEM

Figure 3(a) demonstrates a comparison between the FEM calculation and the experimental signal for a PLB (monopole) located on the rod end at 1 mm from the rod axis. For both the FEM model and PLB experiment the sensor was located on the rod circumference in the $90^\circ$ direction. The signal is in mV and the FEM result is in nm, since no absolute calibration is available for the broadband sensor on a polymer. Since the real sensor does not respond down to 0 Hz, the FEM signal was high-pass filtered (Butterworth) at 6 kHz (5 pole). It was also low-passed at 100 kHz (8 pole) to approximate the material-based attenuation of higher frequencies in the polymer rod. No filtering was done on the broadband sensor experimental signal. Given the limitations of the comparison (unknown material damping as a function of frequency, material bulk velocities not measured and lack of absolution calibration of the sensor), the results indicate a reasonable accuracy of the FEM model versus the experimental axial PLB result for the two fundamental modes that are present. Figure 3(b) schematically shows the dipole source plane and the sensor planes.
5. Filtering for FEM-Based Dipole Results

Since surface PLBs are known to generate larger flexural modes compared to the case of buried dipole sources, it was necessary to establish a different filtering scheme for the dipole-based results. For the initial filtering a high-pass 8 kHz (6 pole) filter was selected so as to represent what might be obtained with a near flat with frequency sensor that went down to near 8 kHz. This high-pass filter was followed by a 120 kHz (8 pole) low-pass filter, but as figure 4(a) illustrates this selection resulted in a dominance of what will be shown later to be the F(2,1) mode at 100 kHz. Since it is expected that a dominance at 100 kHz would not be present in the polymer material (due to material-based attenuation), a low-pass filter at 80 kHz (8 pole) was selected to reduce the 100 kHz dominance, as illustrated in figure 4(b). This filter allowed all three modes to be observed in a more amplitude-balanced way for the radial dipole.
6. Analysis of Initial Arrival Mode

To allow determination of key aspects of the initial arrival region of the $u_r$ signals, the signals shown in figure 5 at 90 mm from a radial dipole located at 1 mm above the axis were examined. First as illustrated in part (a), up to about 92 µs, the amplitudes and phase of $u_r$ are identical at all angles to the sensors. Examining the signals at the vertical lines labeled A and B in figure 5(b), it is clear that as the wave passes the sensors the rod circumference is uniformly vibrating in and out from the static diameter of the rod at a frequency of about 66 kHz (based on the 7.6 µs spacing of lines A and B). Thus, the large number of sensors allowed a direct determination of the full modal shape of the AE wave. Figure 6 (a) shows the $u_r$ signal for the above radial dipole for the sensor at $0^\circ$ and propagation distance of 90 mm, and (b) demonstrates the Choi-Williams distribution (CWD) ([9] parameters default values) for the signal. Due to the match with the group velocity curve for the L(0,1) mode in part (b), it is clear that the initial arrival mode is the L(0,1) mode. Also, the CWD results show the signal has peak intensity of 61 kHz at 75 µs. Additional runs made as the distance from rod axis to the center of the radial dipole source varied from 0.2 mm to 3.2 mm demonstrated only a small decrease (about 1.7 dB) in the $u_r$ peak amplitude of this mode from a source near
the axis to one far from the axis. The small difference may be related to the small change in geometry (figure 2(a)) of the source cells as the sources were moved further from the axis.

Figure 7. Focus on radial displacement from later arrival low frequency mode for a radial dipole 1 mm off axis and 90 mm propagation.

7. Analysis of Low Frequency Later Arrival Mode

Figure 7(a) shows (in the first quadrant) for a radial dipole (off-axis 1 mm and propagation distance of 90 mm) at a fixed time (see green vertical line) the amplitude of this mode varies significantly with the angle to the sensors. Clearly, the amplitude is essentially zero at 0° and it is a maximum at 90°. In figure 7(b), by examining the signal at the vertical lines A and B, it is clear that the phase of this mode in the upper half of the rod (45° and 90° sensors) is opposite to that in the lower half (270° and 315° sensors). Further, the out-of-phase amplitudes are essentially of the same absolute magnitude for the pair at 45° and 315° as well as the pair at 90° and 270°. These out-of-phase pairs are at the same absolute angle difference from the 0° to 180° line where the amplitude is zero. Also, the time difference of 45 µs from A to B implies a frequency of about 11 kHz.

In figure 8(a), a rough end-view sketch is shown of the vibration from A to B of this mode relative to the static circumference of the rod. The 0° to 180° line represents what is called the neutral axis in static bending. As might be expected, figure 8(b) demonstrates for the u, signal at 0° and 90 mm and it’s CWD with superimposed group velocity that this mode is the fundamental anti-symmetric mode F(1,1). Based on this CWD result the peak frequency is about 12 kHz with arrival at about 177 µs. When the distance of the center of this radial dipole from the rod axis was varied as before, the peak amplitude (pm) at the 90° sensor depended linearly on the source distance (mm) from the rod axis with a slope of 39 pm/mm. Further, when the angular dependence of the normalized peak amplitude (normalized by the 90° value) was examined from 0° to 90°, it was determined to vary as the sine of the angle to the sensor locations (from the radius to 0°). The character of these two amplitude aspects was the same in the other quadrants with adjustments per the illustrated modal vibration shape.
Figure 8. (a) End view sketch of radial vibration of later arrival low frequency mode relative to dashed static circumference. Red at time A and black at time B in fig. 7(b). (b) Signal and CWD for $u_r$ at 90° and 90 mm propagation distance for radial dipole 1 mm off axis. Peak frequency 12 kHz at 177 µs (orange line).

Figure 9. Radial displacement $u_r$ signals for later arrival high frequency signal. Radial source at 1 mm of axis and 90 mm propagation.

8. Analysis of Later Arrival High Frequency Mode

The high frequency region has an interesting behavior with respect to its modal shape. Figure 9(a) for angles in the first quadrant demonstrates (use vertical black line to compare) that $u_r$ has the same phase at 0° and 22.5°, no amplitude at 45° and opposite phase at 67.5° and 90°. For another set of angles to the sensor, figure 9(b) shows (use vertical lines A and B) the phase is the same at 0° and 180° and opposite at both 90° and 270°. The time gap of about 5 µs between lines A and B indicates an approximate frequency of about 100 kHz for this mode. By use of the above observations and similar observations for the other quadrants, the modal shape (end view) of the vibration at the sensors is roughly sketched in figure 10(a) for the motion relative to the static circumference at the two times A and B. This figure shows that $u_r$ for this mode remains zero at the sensors angles of 45°, 135°, 225° and 315°.
Additional modeling, examining $u_r$ at interior diameters verified that the radii to these four angles have zero radial displacement for this modal vibration. Figure 10(b) which shows the signal at the 0° sensor and the corresponding CWD result with superimposed group velocity demonstrates that this high frequency mode is F(2,1). Also, it is apparent that the frequency corresponds to the cut-off frequency (see figure 1) of this mode at about 101 kHz. Figure 10(b) shows the amplitude slowly increases with increasing time out to the modeled signal length of 280 µs. When the peak-to-peak amplitude at the 0° sensor of this mode was examined as a function of the source distance from the rod axis at a fixed propagation time, it was determined that the amplitude was largest when the source was nearer the axis, and it decreased in a non-linear fashion as the distance from the axis increased. It was found without an explanation, that this amplitude increased nearly linearly with the horizontal distance (parallel to the 0° to 180° line) from the source centers (along the 90° radius) to the circumference of the rod. To examine the angular dependence of this mode a special FEM run was done with nine sensors equally spaced from 0° to 45°. As a function of the angle to these sensors the normalized (by the 0° sensor magnitude) amplitude decreased directly with the cosine of two times the angle to the sensor.

10. Analysis Results from Other Dipole Cases

The $u_r$ results for the three single dipoles cases (radial, axial and tangential) and the three simultaneous dipoles (dilatation) (with source positions on the axis to 90° line) are best demonstrated in figure 11 using the CWD results for first quadrant signals (at 90 mm) with all the source centers off axis at 1 mm. These results illustrate that the radial and tangential dipoles have very similar intensities of all three modes as the angle locating the sensors changes. On the other hand, the axial dipole and the dilatation case are similar but only show intensity of the two fundamental modes. For all four source cases the fundamental modes change in a similar fashion as the angle to the sensors changes.
Figure 11. CWD results for $u_r$ for first quadrant of four different source cases showing modes and the variation of the intensity as the angle to the sensors changes. All at 1 mm off axis.

11. Conclusions

Based on use of flat-with-frequency pseudo sensors on the circumference of a 8.5 mm PVC rod; long enough that end reflections do not appear in the $u_r$ filtered signals (HP 8 kHz followed by LP 80 kHz):

- For the radial dipole cases, three modes for $u_r$ are significantly excited
- Modal shapes of the signals for the radial sources vary:
  - L(0,1) uniform radial vibration about static circumference
  - F(1,1) normalized vibration varies in amplitude in sinusoidal fashion as the angles to the sensors changes from $0^\circ$ to $90^\circ$ (or $180^\circ$ to $90^\circ$) and it has opposite phase above and below the $0^\circ$ to $180^\circ$ line
  - F(2,1) vibration has nodes at lines from $45^\circ$ to $225^\circ$ and $135^\circ$ to $315^\circ$.

- Amplitudes as radial source center moves further from the rod axis:
  - L(0,1) no significant change
  - F(1,1) increases linearly with distance increase
  - F(2,1) decreases with distance increase
- Different source cases:
  - Radial and tangential sources similar behavior for all three modes
  - Axial and three dipole source similar, only fundamental modes
- Except for signs, the first quadrant provides examples that translate to other quadrants

The inexpensive use of 16 sensors from FEM modeling and group velocity curves results in easy mode identification and verification of modal shapes on the circumference. Also, the results demonstrate that the signals obtained depend strongly on the location of the sensors relative to the source location in the rod.
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References

3. Personal communication, L. Vergeynst, University of Ghent, Belgium, 2014.
4. Kaye & Laby, Tables of Physical and Chemical Constants, National Physical Laboratory and Online, 2005
   http://www.kayelaby.npl.co.uk/general_physics/2_4/2_4_1.html