Measurement and simulation of the propagation of impulsive acoustic emission sources in cylinders, with potential application to pipeline monitoring

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Abstract

Acoustic Emission (AE) monitoring of processes, machines and structures consists of using one or more surface-mounted sensor to listen for sources, which could come from structural degradation, process conditions or machine operation. Since real AE sources have a temporal structure, often over the millisecond range or longer, it is of general interest to examine what can be recovered of this temporal structure using an array of sensors of known positions relative to each other.

Experiments and simulations were carried out with impulsive sources (pencil-lead breaks) and the propagating AE resulting from these sources was recorded over a period of around 2 seconds for both experiments and simulations. Two test objects were used; a solid steel cylinder to provide a relatively simple and well-studied platform to examine a number of essential principles, and a 2m length of pipe to provide some conclusions relevant to impact monitoring of pipelines.

Comparison of the simulated and experimental results indicates that the frequency content of the resulting wave is not very sensitive to unloading rate at the source, although the amplitude of the simulated signal is. Comparison of the first few tens of microseconds of the simulated and experimental waveforms suggests that the first arrival is consistent with a wave speed of around 5000ms$^{-1}$. In addition, both simulations and experiments indicate that, in the sizes of the objects examined, reflections at interfaces quickly introduce interference, so the nature of the impulsive part of the source can only reasonably be preserved in the fastest-moving components of the propagating wave and before arrival of any reflections from interfaces.

1. Background

Pipelines play a significant role in the transport of both gases and liquids, particularly in the oil and gas industry. There is a continuing interest in improved levels of monitoring of these structures, as pipeline accidents are quite often disastrous to both people and the environment. A good number of studies have recommended Acoustic Emission Monitoring (AEM) for the surveillance of pipelines [1, 2, 3], mostly for leak detection or disturbances in fluid flow. This work combines an experimental and computational study of AE propagation in pipes and so the relevant background is twofold.

1.1. Experimental AE background

Whereas AE has been suggested as a method for detecting and locating leaks in pipelines, this has been as an inspection technique, rather than a monitoring (surveillance) technique. Consequently, much of the literature on AE in pipelines addresses this application, concentrating on methods for noise rejection, improved specificity and source location for continuous or semi-continuous sources. Amongst the last of these methods, Shehadeh et al. [4, 5], have examined the effects of internal and external environment on the attenuation of AE propagating in pipes, although that work was confined to impulsive sources. In a full-scale trial, Giunta et al. [6] carried out hydraulic tests to failure of buried sections of pipeline
containing artificial surface defects with water as the internal medium and concluded that AE has a role in monitoring the growth of defects that have already been identified. Mostafapour and Davoudi [7] have calculated the expected vibration frequencies associated with pipeline leaks and compared these with the measured ones, citing good agreement between the two, although there was very little change in the calculated or measured frequencies for the four different leak conditions investigated, making specificity questionable. Liang et al. [8] have also used vibration analysis to improve signal to noise ratio in pipeline leak detection, claiming improved detection rate for small leaks with reduced false alarm rate by reducing noise using spectral filtering.

Although the work of Shehadeh et al. [4, 5] was carried out using impulsive sources, the majority of the foregoing authors have considered continuous sources, as would be expected from leaks. Relatively few articles have addressed other applications of AE in pipelines, in which the source(s) might be impulsive or semi-continuous. Shehadeh [4] carried out a series of tests on scaled-down pipelines for damage due to dropped objects and tearing open of artificial defects finding a relationship between the damage energy and the resulting AE energy recorded at adjacent sensors. Al-lababidi et al. [9] have found that AE energy is a good predictor of gas void fraction in liquid-gas slug flow in pipes, although they acknowledge the limitations that an unknown source-sensor attenuation can place on practical applications of such findings.

The work reported here is aimed at assessing the fidelity with which a step surface unload is reproduced at a sensor a known distance from the source. The Pencil Lead Break (PLB) (Hsu Nielsen source) is widely accepted as a reproducible step-unload AE source [10, 11, 12]. Generating the event involves the breaking a 0.3mm diameter pencil lead by pressing it on the surface of the test structure and applying a bending moment until fracture. Although the fracture of the lead is effectively a natural source, the generated AE is highly reproducible [13] and approximates an impulsive source.

1.2. Background on calculation and simulation of AE in cylinders

Over the past two decades, finite element analysis (FEA) has been used increasingly for simulating elastic wave propagation associated with acoustic emission phenomena, initially as an aid for calibrating AE sensors and understanding propagation phenomena [14, 15].

Prosser et al. [16] were amongst the first researchers to attempt the use of FEA for AE source identification, modelling Lamb waves on a plate using 3D Finite Element Modelling (FEM) with different source types. They argued that the use of a model was better than using experiments to establish sensor placement strategies because parameters such as point source location in three dimensions, source rise time and magnitude were more easily controlled. Of direct relevance to the current work, Sause [17] has used FEA to model the interaction between the Hsu- Nielsen source (pencil-lead break) and a metal surface; he evaluated the differences in surface displacements from the source while varying the length of the pencil lead and angle of inclination. As part of this work, Sause measured the forces at fracture of pencil leads to be in the range of a few N and calculated the unload time to be around 1µs.
A number of other approaches have also been used, particularly for structures where the distance from the source to the nearest surface is relatively large as in the reference object used here. Nadal et al. [18] (in the context of developing acoustic microscopes) have modelled analytically the propagation of Rayleigh waves on cylindrical half-spaces in response to an impulsive spherical source and have published experimental and calculated time series consisting of a short (around 200ns) low amplitude component, followed (around 300ns later) by a short (again around 200ns) component of higher amplitude. Although these authors considered much higher frequencies (5-25MHz) than those to which the current sensors respond, their observations indicate that it is possible that both the low and high amplitude components observed in the experiments are associated with the Rayleigh wave arrival, and that the second-high amplitude event, along with its associated low amplitude precursor are due to the wave returning after having been reflected from the edge of the cylinder.

Ceranoglu and Pao [19, 20], in a series of papers, have suggested a relatively simple analytical approach to a solution for the displacement function time series in a solid cylinder. Rather than attempting a full-field solution of the wave equation, their approach was based on ray-tracing, identifying paths to reach the sensor for three basic types of wave, which they call pressure waves, and two types of shear waves, one vertically polarised (perpendicular to the surface) and one horizontally polarised (parallel to the surface). Since each type of wave has a distinct velocity, focusing on the early times allows a relatively small number of components to be taken into account, reducing the calculation burden. This approach is potentially useful for long hollow objects such as pipelines where multiple reflections from the inner and outer walls are likely.

El–Shaib et al [21] have carried out a different type of simulation using ray-tracing within a solid model. They fired rays into the model and created a series of rules for reflection at boundaries, which depended on the nature of the medium at the boundary (air, water or sand), the object being to understand the effect of phase boundaries on attenuation of AE. For pipes, El-Shaib [22] was able to reproduce the effect of different internal and external environment on the attenuation of AE measured by Shehadeh et al [4].

This work focuses on the early part (first few hundred µsec) of the wave packet resulting from an impulsive source as it propagates in a steel structure. The objective is, by comparing simulation (where there is no damping or attenuation) with experiment, to understand the fidelity with which an impulsive source propagates in a cylindrical structure. This is a precursor to a further assessment using sources which are extended in time.

2. Methodology

To pursue the main objective, a matched series of experiments and simulations were carried out to establish the fidelity with which an impulsive AE source can be propagated and measured at a remote sensor along a pipe. Two test objects were chosen; a reference object (solid steel cylinder) and the main test object (a 2-m length pipe). The configuration for the reference object was chosen because, aside
from its simple geometry, it had already been well studied and was known [4, 5, 21, 22] to propagate Rayleigh waves when source and sensor were placed on the same surface.

2.1. Experimental procedure:

For both experiments, a standard Hsu-Neilson source, pre-amplifiers (PAC-1220A) and broad band piezoelectric AE sensors (PAC Micro U80D-93) were used for generating the AE and acquiring the resulting signals. The preamplifiers were set at a gain of 40dB and, once the trigger was activated, the system acquired 50,000 points at a sampling rate of 5Msamples/s with a pre-trigger of 1000 points.

The reference object used was a steel solid cylinder 0.166m long and 0.307mm diameter and was used standing on one of the circular faces, with the opposite circular face being used as the test surface. Two sensors were mounted on the test surface, both placed at a distance of 0.0785m from the edge while the AE source was at the middle (Fig. 1a).

The main test object was a steel (ASTM A106/99) pipe of nominal length 2m with internal and external diameters of 0.08 m and 0.1m respectively simply supported at both ends. The external pipe cylindrical surface was used as the test surface with both source and sensors being mounted on it (Fig. 1b).

Signals from a total of 20 lead breaks were acquired at each of the sensors mounted on the reference and test objects without removing and replacing the sensors (thus avoiding any variability due to the coupling of the sensors onto the surface). In order to have a consistent way of identifying arrival, a thresholding algorithm [5] was adopted using S₁ (the trigger sensor). This consisted of calculating the mean and standard deviation (SD) of the first 1000 points (pre-trigger) and defining arrival as the point at which the amplitude first crosses the pre-trigger mean ± 5SD. A first-in-first-out buffer system was used to capture the short pre-trigger record, so this can be used to establish the signal to noise ratio in a way that allows comparison of recorded waveforms with simulated ones.

2.2 Finite Element Simulation

Finite element simulations of the above experimental configurations were carried out in ABAQUS (Dassault Systemes, Vlizy- Villacoublay, France) using its dynamic explicit solver. For the reference object, a 3D elastic steel cylinder subjected to a pressure unload similar to that from a PLB located at the centre of the upper surface was modelled with the lower surface fully constrained. The results were extracted from a location in the FE model at a distance of 0.0785m from the left hand edge of the upper surface (Fig. 1a). For the main test object, an elastic steel pipe was fixed at both ends and subject to pressure loading one metre from one end, and the results were extracted from the S₁ and S₂ postions (Fig. 1b).

The proprietary commercial software Abaqus was specifically chosen for this work because it offers accurate analysis techniques to determine the local element failure and can then adjust the element stiffness to precede damage analysis e.g. it has the capability to predict element failure by the most common failure criteria such as those from the theories of maximum stress and maximum strain, and
thus quite suited for linear and nonlinear explicit dynamics problems such as those involving impact [23, 24].

In this work, Abaqus’ explicit dynamic analysis was applied to obtain the transient stresses resulting from rapid changes in pressure. The ultimate objective of the FE simulations carried out here is to be able to predict the time and frequency distortion of a non-instantaneous source as the AE it generates propagates along a pipeline.

Both FE models were simulated as a dynamic explicit system made from steel with a Poisson’s ratio of 0.3, Young modulus 210GPa and density 7800kg/m³ subjected to a 100N force spread over a surface area of 0.003m².

The simulation of the stress wave propagation on the both the reference cylinder and pipe were modeled using the linear hexahedral type C3D8R elements. The general approach used was to refine the mesh size until acceptable behaviour (results stay consistent between meshes) was obtained and a mesh size of 0.01mm was chosen as, beyond this mesh size, there were no appreciable differences recorded in the resultant stress waves generated.

The force and unloading rates \(2.46 \times 10^{-6} \text{s}\) were chosen to be in the region of the estimated time it would take a fracture, propagating at the speed of sound, to cross the diameter of a 0.5mm pencil lead. This time (about 0.3µs) is reasonably close to that reported in AE simulation literature. As the area of interest here was the propagation of the stress waves generated as a result of the PLB source, it was important that the stress wave was kept as sharp as possible, therefore the Quadratic bulk viscosity parameter was set to zero throughout. To capture the AE dynamics of the model, a time step of \(1 \times 10^{-9} \text{s}\) was used for all the FE simulations in this work.

For the FE models, the input acceleration at the source is given by:

\[
\ddot{u}^{(i)} = M^{-1} \left( P^{(i)} - I^{(i)} \right)
\]

where \(M\) is the mass matrix, \(P\) is the vector of applied loads and \(I\) the vector of internal forces. Eq. 1 can be used to obtain the accelerations at the start of an integration. The Courant–Friedrichs–Lewy (CFL) was used to determine the maximum allowable size of the time increment \(\Delta t\):

\[
\Delta t \leq \Delta t_{cr} = \min \left( \frac{L_e}{c_d} \right)
\]

where \(L_e\) is the element length and \(c_d\) is the dilatational wave speed and is given by

\[
c_d = \sqrt{\frac{(\lambda + 2\mu)}{\rho}}
\]
where $\lambda$ and $\mu$ are the first and second Lame constants and $\rho$ represents the density of the material.

**3. Results And Discussion**

The experimental results were recorded as time series, which starts 1000 points (pre-trigger) before the disturbance caused by the source arrives at the trigger sensor. The simulation results were also “recorded” as time series, which, at a given virtual sensor position, starts when the source is activated, so that time-correlation of the measurements and simulations depends on the precision with which the measurement arrival time can be determined. Also, for the simulations, the output data base files were acquired as stress time text files for ease of analysis and comparison with the experimental results. The proprietary package MatLab was used for signal processing because of its capacity to handle and display the large arrays of data from both the experiments and simulations.

**3.1 Experiments on reference object**

Figure 2 shows full records for typical raw AE time series generated by a pencil-lead break, recorded at both sensors on the solid cylinder. As can be seen, the maximum amplitude is reached very quickly and is followed by a more gradual ring-down which lasts for the entire duration of the record (10 ms).

Figure 3 shows the first 300µs (excluding part of the pre-trigger) of the records shown in Fig. 2 at which resolution the waveforms can be clearly seen. It might be noted here that the two sensors are nominally equidistant from the source, so it is a matter of chance whether $S_1$ or $S_2$ acts as trigger. The waveforms display a clear similarity, each consisting of a low amplitude component which is the first to arrive (labelled A in Fig. 3a), followed by a higher amplitude component which contains the highest positive peak (labelled B in Fig. 3a). The higher amplitude component appears to be of higher frequency and attenuates more sharply than the lower amplitude component, which appears to persist over the entire portion of the record (A') shown in Fig. 3a. There are some subtle differences in the relative amplitudes of these features between $S_1$ and $S_2$, and it is unclear if these are sensor-related or constitute a random variation, hence the need to analyse all 40 records separately to determine causes of variation statistically.

First, the thresholding algorithm was applied to determine the arrival time of the low-amplitude feature, labelled as $t_1$ on Fig. 3. Assuming this feature to correspond to a ray travelling parallel to the surface a distance of $7.5 \times 10^{-2}$ m, the expected first arrival would be at $1.2 \times 10^{-5}$ s for a P-wave travelling at a speed of $6240 \text{ms}^{-1}$, or at $2.4 \times 10^{-5}$ s for an S-wave travelling at a speed of $3143 \text{ms}^{-1}$. The thresholding technique was again used the obtain the first arrival time for the high amplitude wave at $S_1$ and $S_2$ for each of the pencil lead breaks labelled as $t_2$ on Fig. 3.

A number of other investigators (e.g., [25, 26], have noted that practical AE signals often consist of a lower amplitude faster “wave” with low attenuation, followed by a higher amplitude, slower “wave” with high attenuation, which appears to be happening here. In each case, the pulse is presaged by a downward
spike (labelled C and C’ on Fig. 3a), so a return time ($\Delta t_1$ in Fig. 3a) can be identified. Two methods were developed for locating the times at C and C’, using thresholding and time frequency analysis. Taking the second of these as the more likely, the arrival time difference ($\Delta t_2$ in Fig. 3b) can be calculated as the time taken for a P-wave to travel 0.075m, i.e., $1.2 \times 10^{-5}$sec, less the time taken for either an S-wave to travel 0.075m, i.e., $2.38 \times 10^{-5}$s which seems to be approximately in accord with the observation.

The time difference $\Delta t_1 = 5 \times 10^{-5}$s corresponds to a distance of 0.3m at P-wave speed and 0.16m at S-wave speed. This implies that the pulses arriving at C and C’ are P-waves, which have travelled vertically through the cylinder reflecting back from the lower surface. A second possible explanation is that the pulses arriving at C and C’ are S waves which have travelled across the surface and reflected back from the edge.

Figure 4 shows power spectra of the time series segments highlighted in Fig. 3 for S$_1$ and S$_2$ on the solid cylinder. The two examples shown suggest that there are some features within the spectra that are not merely associated with the sensor response.

The speeds of the two waves in the simulation can be easily estimated to be around 3000ms$^{-1}$ and 1250ms$^{-1}$ if both are travelling across the surface from source to sensor. The first of these speeds corresponds closely to the Rayleigh wave speed, but the second does not correspond to any pure modal wave speed. For the experimental records, since the sensors are similarly positioned, a comparison of energy (as the RMS of the complete record) and the power spectrum can be used to indicate the consistency of the 20 pencil lead breaks and the consistency in response of the two sensors.

Therefore, to further analyse the spectra shown in Fig. 4, three new bands were chosen (by inspection); below 200 kHz (low frequency, LF), 200–500 kHz (medium frequency, MF) and above 500 kHz (high frequency, HF), giving three power values; $P_{LF}$, $P_{MF}$ and $P_{HF}$, and three indicators as proportions of the total power:

$$f_i = \frac{P_i}{P_{LF}+P_{MF}+P_{HF}}, \text{ where } i \text{ is LF, MF or HF}$$

### 3.2 Simulation of Reference Object

The simulations described here examines how the AE signal recorded at two virtual sensor positions on the surface of the solid cylinder changes as the unloading rate at the source changes, the objective being to determine the extent to which a PLB can be regarded as a step-unload. The choice of the most appropriate unload rate depends on carrying out a comparison with the experiment.

Figure 6 shows the power spectra of the entire simulated time series shown in Fig. 5 for all the unload rates for sensor S$_1$. Two key frequencies are present at the position of S$_1$, one at around 200 kHz and the other at around 350 kHz. There is a sharp frequency cut-off at 400 kHz, but this is artificial, and is associated with the effective sampling rate brought about by the time step used in the simulations.
Figure 7 shows higher resolution segments of simulated displacement time series for all the unload rates at position $S_1$ only, as the simulated AE wave for the first 300$\mu$s is the same for both sensors. As can be seen, the different unload rates are rather difficult to distinguish except in terms of the amplitude already noted.

Figure 8 shows the power spectra corresponding to Fig. 7. These spectra are a lot cleaner than those for the entire record, indicating that the waves are somewhat simpler. Two peaks at around 190 kHz and 310 kHz persist in all of the spectra, the height of the lower frequency one increasing systematically with unload time.

A summary of the total power frequency structure of all of the experimental and simulated data on the solid cylinder for sensor position $S_1$ is shown in Table 1. The experimental values are based on the average power values for the 20 measurements. Correspondingly, fractions have been calculated for the simulations for $S_1$ and each of the unload rates. As sensors $S_1$ and $S_2$ are nominally equidistant, the total power frequency structure for $S_1$ and $S_2$ are exactly the same but slightly different for the experiments.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Code</th>
<th>$f_{\text{LF}}$</th>
<th>$f_{\text{MF}}$</th>
<th>$f_{\text{HF}}$</th>
<th>$P_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment, sensor 1</td>
<td>ES$_1$F</td>
<td>0.3881</td>
<td>0.4328</td>
<td>0.1791</td>
<td>3.2289</td>
</tr>
<tr>
<td>Experiment, sensor 2</td>
<td>ES$_2$</td>
<td>0.3785</td>
<td>0.4882</td>
<td>0.1333</td>
<td>4.0682</td>
</tr>
<tr>
<td>Simulation, unload rate 1</td>
<td>Sim1S$_1$R</td>
<td>0.3891</td>
<td>0.5681</td>
<td>0.0428</td>
<td>0.0257</td>
</tr>
<tr>
<td>Simulation, unload rate 2</td>
<td>Sim2S$_1$R</td>
<td>0.3935</td>
<td>0.565</td>
<td>0.0415</td>
<td>0.4193</td>
</tr>
<tr>
<td>Simulation, unload rate 3</td>
<td>Sim3S$_1$R</td>
<td>0.408</td>
<td>0.5548</td>
<td>0.0373</td>
<td>0.754</td>
</tr>
<tr>
<td>Simulation, unload rate 4</td>
<td>Sim4S$_1$R</td>
<td>0.4338</td>
<td>0.5336</td>
<td>0.0326</td>
<td>0.9985</td>
</tr>
<tr>
<td>Simulation, unload rate 5</td>
<td>Sim5S$_1$R</td>
<td>0.4693</td>
<td>0.5007</td>
<td>0.0299</td>
<td>1.1389</td>
</tr>
<tr>
<td>Simulation, unload rate 6</td>
<td>Sim6S$_1$R</td>
<td>0.5121</td>
<td>0.4578</td>
<td>0.0301</td>
<td>1.1835</td>
</tr>
</tbody>
</table>

### 3.3 Experimental Pipe Model
In fairly small pipe lengths, it would be expected that the waves would be reflected several times within the record, and so the focus was on the first few tens of microseconds so as to avoid the complexities of (largely unknown) reflection coefficients.

Figures 9 and 10 show typical raw AE records and the corresponding power spectra at the two sensors. An S-wave will travel the full length of the pipe in around $6 \times 10^{-4}$ s, so it is clear that the system’s ring-down time corresponds to around 20 traverses of the length of the pipe. The power spectra for the entire record appear to show a shift from lower frequencies to higher frequencies as source-sensor distance increases with a major peak at just below 200 kHz. There are several other peaks, the most noticeable of which is at just below 400 kHz, although there is also some activity at around 150 kHz. To obtain a rough measure of this, the spectra were divided into two bands; low frequency between 100 kHz and 400 kHz and high frequency between 400 kHz and 1 MHz and the relative power calculated by integrating the spectra and determining the ratio between the two bands. The ratio of high-frequency to low-frequency power for the two sensor positions over the 20 records was 0.1516 with an SD of 0.0554 for $S_1$ and 0.1702 with an SD of 0.0507 for $S_2$.

Figure 11 shows the 250µs around first wave arrival for each of the two sensors for a typical example PLB on the pipe. It can be seen that the first arrival at $S_1$ is characterized by a low amplitude component, followed by a high amplitude component, which contains the peak amplitude ($t_p$), whereas an apparently similar feature at $S_2$, also labelled, is preceded by a medium amplitude component. The low amplitude component increases in length between $S_1$ and $S_2$, showing that it is traveling faster than the medium amplitude, and the medium amplitude component also seems to be moving faster than that carrying the peak.

Again, the thresholding technique was adopted using $S_1$ (the trigger sensor) as shown as $t_{arr}$ on Fig. 11a. Applying this same thresholding technique to $S_2$ gives a point ($t_{arr}$ on Fig. 11b) which, as expected, is later than the corresponding arrival at $S_1$. Dividing the distance between the two sensors by the arrival time difference for each of the 20 lead breaks yielded an average apparent wave speed of 5076 ms$^{-1}$ with a standard deviation of 189 ms$^{-1}$, somewhat lower than the P-wave speed and somewhat higher than the S-wave speed (ms$^{-1}$) but consistent with the first arrival speed for the pipe experiments and with first arrival speed on the cylinder.

To provide a good comparison with the simulations, it was necessary to condition the $S_1$ and $S_2$ signals to have the same time-base. As time in Fig. 11 was measured from the start of the pre-trigger and that for the simulation was measured from when the source was activated, it was essential first to assess the departure time (from the source) for the arrivals at $S_1$ and $S_2$, and this was achieved by subtracting the time taken for the wave to travel from the source to the sensor, using the speed determined from the arrival time differences at the two sensors. Figure 12 shows the re-based time series (corresponding to Fig. 11) where time, $t'$, is now measured from departure from the source.
Since the simulations did not incorporate any mechanism for damping or for loss of energy on reflection, separating the effects of damping from those due to losses on reflection was achieved by ensuring that both time-series were truncated before any reflection arrived at the real or virtual sensor.

Assuming circular symmetry of the source, it was expected that the first reflected wave will arrive at a given sensor after travelling the (shorter) distance to the end of the pipe, back again, plus the distance from the source to the sensor, i.e. a total of 0.7m, giving an arrival time since departure from the source for the particular example considered of $1.35 \times 10^{-4}$ sec for $S_1$ and a total of 1.2m, giving an arrival time of $2.32 \times 10^{-4}$ sec for $S_2$, shown as $t'_{\text{refl}}$ in Figs. 8a and 8b, respectively.

However, this analysis has brought up a new issue as it is obvious that the portion of the signal which included the peak for $S_2$ ($t_p$ in Fig. 12) was not the same feature identified as the peak in Fig. 11b ($t_p$). Therefore, in order to attain a compromise between characterising these different components and reducing the effect of reflections, a second wave speed was determined using the time difference between the two $t_p$ values, as identified in Fig. 11b, giving a mean "slow" wave speed of $2000\text{ms}^{-1}$ with a standard deviation of 478. This allows the time of arrival of the first reflection of the component containing $t_p$ in Fig. 11 to be determined. For example, this second return time is shown as $t'_{p,\text{refl}}$ in Fig. 12. Accordingly, two segments of the time series were identified for diagnostic purposes; the segment between $t'_{\text{arr}}$ and $t_p$ (which includes mostly the faster-moving component) and the segment between $t_p$ and $t'_{\text{refl}}$ (which includes both the faster-and slower-moving components).

The RMS values for the “fast” and “slow” segments are shown in Table 2

<table>
<thead>
<tr>
<th></th>
<th>Fast segment ($t'_{\text{arr}}$ to $t_p$)</th>
<th>Slow segment ($t_p$ to $t'_{p,\text{refl}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>0.0705 ± 0.012</td>
<td>0.1325 ± 0.0426</td>
</tr>
<tr>
<td>$S_2$</td>
<td>0.1340 ± 0.039</td>
<td>0.1201 ± 0.039</td>
</tr>
</tbody>
</table>

Figure 13 shows the corresponding spectra for the segments shown in Fig. 12. Notwithstanding the low resolution for the fast segment at $S_1$ (due to its short duration), the spectra are similarly narrow to Fig. 10, although there is a little more high-frequency content, again with $S_2$ showing a slightly higher power in the $200–400$ kHz range. A division of the spectrum into two bands did not capture some of the differences in the spectra visible in Fig. 13. Therefore, by inspection, three new bands were chosen; below $200$ kHz (low frequency, LF), $200–500$ kHz (medium frequency, MF) and above $500$ kHz (high frequency, HF), giving three power values, $P_{\text{LF}}$, $P_{\text{MF}}$ and $P_{\text{HF}}$, and three indicators as proportions of the total power:
3.3 Pipe simulation model

Figure 14 shows a typical plot of the simulated stress time series at the two virtual sensor positions for the first 20ms. As anticipated, this shows none of the damping seen in the equivalent experiment (Fig. 9).

Figure 15 shows a magnified view of the part of the simulated time series corresponding to the key events identified for the experiment. There is a certain consistency in both time series, although the simulated wave is much "cleaner". The spectra for the simulated segments (Figs. 12 and 8) are similar to those shown in Fig. 15, but there are major differences between the sensor positions, albeit less so for the unload rate.

The experimental values for the three fractions are based on the average power values for the 20 measurements and the corresponding fractions have been calculated for each of the sensors and each of the segments. It should be noted that the experimental power values can be compared with each other, and the simulations can be compared with each other, but the simulations are not amplitude calibrated relative to the experiments.

Figure 17 shows the spectral content for the average of the experimental measurements for each position and each segment, compared with the average of the simulations across all of the unload rates. This comparison confirms the observation made earlier that higher frequency elements are generally less evident in the simulations than in the experiments. Coupled with the different appearance of the first wave arrival in the simulations, this would suggest that the experimental source is more complex than a step direct compressive stress unload, as it is in the simulation.

Notwithstanding this, and despite the differences in measured spectral components across the 20 tests, some similarities between experiment and simulation can be seen in Fig. 17. First of all, the HF band is most prevalent in the "fast" segment as "seen" at S₁, signifying that the lower amplitude, first arriving wave is of higher frequency. Secondly, the HF power in the "fast" segment is considerably reduced by the time it reaches S₂. This is due to selective attenuation of the higher frequency components, although the attenuation mechanisms in the simulations are confined to the geometric ones. More likely, the "fast wave" has a more complex time-frequency structure which becomes more evident as more of it overtakes the slower components.

Also, both simulation and experiment exhibit a lower HF content in the slow segment, despite the possibility that it contains some reflected fast elements. The shifts in spectral content between LF and MF bands are highlighted in Fig. 18, where it can be seen that, again, the fast components behave consistently between experiment and simulation, with the LF band becoming more prevalent with distance from the source.

4.0 Conclusion
In the reference object, with sensors equidistant, and on the same face as the source, the first wave to arrive was a lower amplitude, lower frequency Rayleigh wave, followed by pulses of higher frequency corresponding to subsequent reflections of a P-wave from the lower surface of the cylinder.

In both experiments and simulations, the measured AE in the block quickly became contaminated with reflection for the edges of the block and its bottom surface. The simulated and measured signals on the reference object exhibited similar behaviour in the first 25–30 µs. Thereafter, the measured signals were much cleaner, and this is associated with the energy losses associated with reflections, for which there is no provision in the simulations. This finding indicates that the simulations, as they stand, are helpful in interpreting the structure of the source only in the early stages of event arrival for such small objects.

It was also observed from both experiments and simulations that a low amplitude wave travelling at around 5500ms\(^{-1}\) was the first to arrive at any surface sensor. The structure thereafter was complex, involving reflections from the inner wall of the cylinder and geometric interference as the wave spreads around the circumference of the pipe. The simulation showed that the AE line structure of an impulsive source can be reproduced by simulation for short times, for longer times, the damping associated with reflections would require to be measured and introduced into the simulations in order to fully represent the real practical simulation. The degree of damping is important in making a cumulative assessment of multiple impulsive sources.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

Not applicable

Competing interests

Not applicable

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Authors' contributions
The Authors confirm contribution to the paper as follows:

Authors 1 and 5 conceived of the original idea presented in the work and developed the theory.

Author 1 carried out the experiments, Autor 4 planned the rig design and set up.

Authors 1, 4 and 5 aided in interpreting the experimental results.

Authors 1, 2 and 3 performed the FEA simulations and analysed the simulation results.

Author 1 wrote the manuscript, all the authors provided critical feedback, discussed the results, and contributed to the final manuscript.

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References


**Figures**

**Figure 1**

Schematic representation of sources and sensor configurations on reference a) and test b) objects.
**Figure 2**

Typical raw AE time series generated by a pencil-lead break, recorded at (a) $S_1$, (b) $S_2$ on the solid cylinder (full record)

**Figure 3**
Typical raw AE time series recorded at (a) $S_1$, (b) $S_2$ on the solid cylinder (first wave arrival).

Figure 4

Power spectra of time series segments highlighted in Figure 3 for $S_1$ and $S_2$ on the solid cylinder.
**Figure 5**

Raw time series of displacement at $S_1$ and $S_2$ (0.4M samples per second) for virtual sensors at 0.157m from the simulated source on a solid cylinder unloading in: a) $2 \times 10^{-8}$ s b) $5.11 \times 10^{-7}$ s c) $1 \times 10^{-6}$ s d) $1.5 \times 10^{-6}$ s e) $1.98 \times 10^{-6}$ s f) $2.47 \times 10^{-6}$ s

**Figure 6**

Power spectrum of entire simulated time series shown in Figure 5.8 for a) $2 \times 10^{-8}$ s b) $5.11 \times 10^{-7}$ s c) $1 \times 10^{-6}$ s d) $1.5 \times 10^{-6}$ s e) $1.98 \times 10^{-6}$ s f) $2.47 \times 10^{-6}$ s
Figure 7

Segments of simulated stress time series from first arrival at position $S_1$ for a) $2 \times 10^{-8}$ s b) $5.11 \times 10^{-7}$ s c) $1 \times 10^{-6}$ s d) $1.5 \times 10^{-6}$ s e) $1.98 \times 10^{-6}$ s f) $2.47 \times 10^{-6}$ s
Figure 8

Power spectra of time series segments in Figure 5.9 for $S_1$ for a) $2 \times 10^{-8}$ s b) $5.11 \times 10^{-7}$ s c) $1 \times 10^{-6}$s d) $1.5 \times 10^{-6}$ s e) $1.98 \times 10^{-6}$s f) $2.47 \times 10^{-6}$s
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Comparison of measured (E) and simulated (Sim) low-frequency power spectral ratio (PLF/PMF) for each of the sensor positions ($S_1$ and $S_2$) and each of the time series segments (S) and (F). (For configuration code, see Table 1)