Acoustic Emission Source Identification in Pipes Using Finite Element Analysis

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Abstract. Stress waves propagate through a structure when it experiences rapid changes in loading, which can come about from a number of phenomena of interest in mechanical and process engineering. One class of applications is in structural health monitoring, where the challenge is to deduce the characteristics of the generating source from one or more signal recorded at one or more sensor, often located at some distance from the source on a large or long structural element. Several methods have been proposed to analyse these signals and relate their characteristics (energy, frequency etc.) to the state of the structure, particularly in the structural health monitoring of pipes as well as civil engineering structures such as bridges and dams. In practical situations, a key aspect of source identification is the loading rate, which can potentially distinguish between, say, an impact and a leak. Current AE research techniques tend to rely mainly on experiments which can be costly and difficult to carry out and in which it is difficult to control the nature of the source, it being common to use step-unload sources, such as the Hsu-Nielson pencil lead break source.

In this work, the effect of unloading rate at a source on the surface stress at a sensor is investigated using a finite element simulation. A range of different pipe sizes were modelled with a fixed source position, unloading from a fixed force at rates which varied over three orders of magnitude. The resulting stress wave versus time was "recorded" at various locations along the pipe and the characteristics of the recorded AE were determined. It is shown that arrival times are consistent with longitudinal stress waves and the frequency structure is broadly as would be expected in practically-recorded AE from pencil lead breaks. Some preliminary analysis is carried out on putative reflections as a preparation for a more systematic study of the effect of source temporal structure on AE recorded in practical situations.

Introduction

Pipelines are the safest and most cost-effective system for conveying large quantities of oil and gas over long distances. Despite this, pipelines are subject to both mechanical and environmental loading as well as other potentially damaging mechanisms such as corrosion and fatigue. Mechanical damage to pipelines is a key threat to pipeline integrity and, statistically, the average pipeline will experience about one obvious leakage event per year [1].

The main damage mechanisms in operating pipelines are; corrosion, direct mechanical damage, geotechnical problems, stress corrosion and degradation (e.g. fatigue) developing from construction flaws [2].

AE, in the form of high-frequency (0.1 to 1MHz) elastic stress waves, can be generated in pipelines as a result of pipeline failure by rupture [3] or leakage [4], but the actual degradation events, such as stress corrosion cracking [5], particle erosion [6] and fatigue crack propagation [7] are also know to generate AE.

One of the most important aspects of AE monitoring technique is source identification and one way of achieving this is by source location, which has been widely studied in pipes and other long linear structures [e.g. 8, 9]. Another, less common method of source identification is to characterise the temporal structure of the source, and this can be particularly useful for complex sources, such as occur in machinery. Combining source location with temporal structure identification leads to the idea of spatially-located time series, which has been used to good effect in analysing multi-source, multi-sensor data such as might be acquired in an engine [10]. Sources which involve low-speed impact pose particular challenges for AE monitoring, because the detailed structural dynamics of the impactor-target interaction will influence the generation of AE [11, 12].

The use of Finite element analysis (FEA) to simulate acoustic emission wave propagation has been a subject of research for around two decades. Prosser *et al.* [13] were amongst the earliest showing that FEM was effective in the evaluation of the far field structure of wave propagation in thin plates. Over the years, FEA has proven to be a reliable way of simulating elastic wave propagation associated with acoustic emission phenomena [e.g. 14-16]. Most relevant to the current study, Sause [17] has modelled the interaction between the pencil lead break and a metal surface including the contact stresses and lead fracture and has explained the sensitivity of the Hsu-Nielsen (H-N) source to handling by the operator.

In this paper, we tackle the more general issue of the effect of unloading rate on the AE recorded after a wave has propagated into the material. For this, a rather simpler AE generation mechanism is adopted for the sake of focusing on a single variable. Nevertheless, the simulations are grounded in an estimate of the step unload of an H-N source as this provides a touchstone for comparison with actual experimental observations.

Overall approach

ABAQUS 6.10 finite element software was used to simulate steel pipes fixed at both ends and subject to pressure loading one metre from one end, (Figure 1). The pipe model is simulated as a three dimensional elastic deformable solid with an inner and outer diameter of 0.08 and 0.1m, respectively, and lengths of 2.5, 5 and 10 metres. The source was simulated as a 100N force spread over a surface area of 0.003m^2 with three different time profiles as shown in Figure 2, the key variable being the rate of unloading, which varies over three orders of magnitude, unloading from 100N in 10^{-9}s, 10^{-8}s and 10^{-7}s, respectively. The unloading rates 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 in order that the simulated responses could be compared with observed responses to pencil lead breaks. This time (about 0.3μs) is reasonably close to that simulated by Sause [15] although the forces (chosen to give a reasonably strong response at all sensor positions) are around 50-100 times those measured and calculated by him for pencil lead unloads. Each length of pipe had three sensor positions, chosen to cover the pipe length on the far side of the sensor from the source. Table 1 summarises the sensor positions on each pipe simulation.

The FEA simulation was used to calculate the stress-time history at each of three sensor positions for each of the three pipes and each of the three unloading rates, giving a total of 27 stress-time histories.

Pipe length (m)	Sensor positions (m from source)		
2.5	0.5	1	1.5
5	1.5	2.5	4
10	4	5	9

Table 1. Summary of simulated pipe lengths and sensor positions

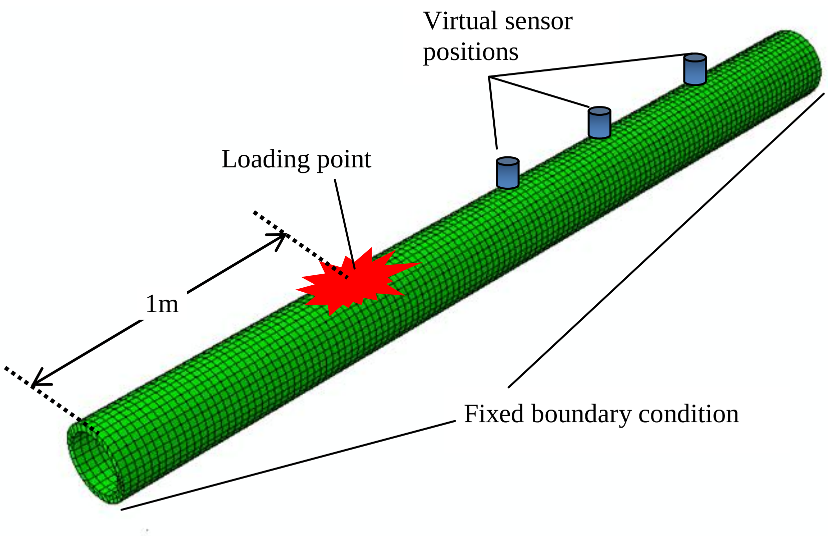


Figure 1. Schematic diagram of pipeline model

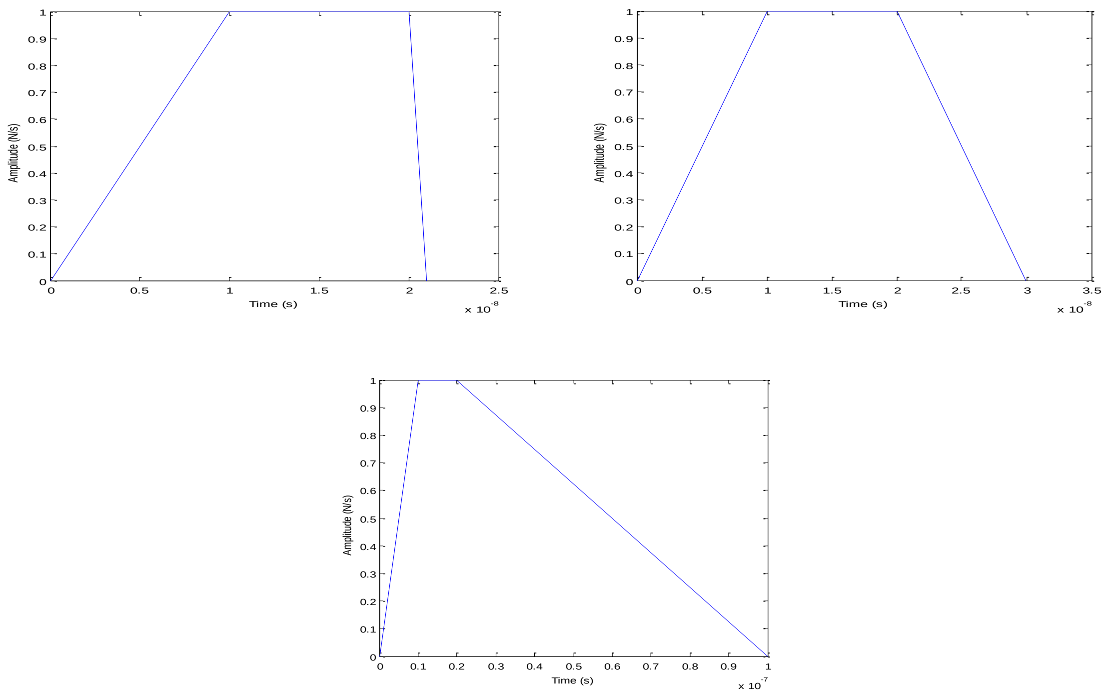


Figure 2. Amplitude *vs* time profiles for source simulation

Results and analysis

Figure 3 shows the time series response for the fastest unload with a source-sensor distance of 1m, with the time-base set at zero for the end of the unload. As can be seen, the arrival time of the first AE peak is at 0.194 ms, so the wave speed can be calculated to be around $5000ms^{-1}$, which accords well with the speed of longitudinal waves in steel which can be calculated from the modulus and density, and also matches with one of the propagation speeds measured for pencil lead breaks on pipes [8]. The remaining sensor locations and unloading rates for the 2.5m pipe gave a consistent wave speed.

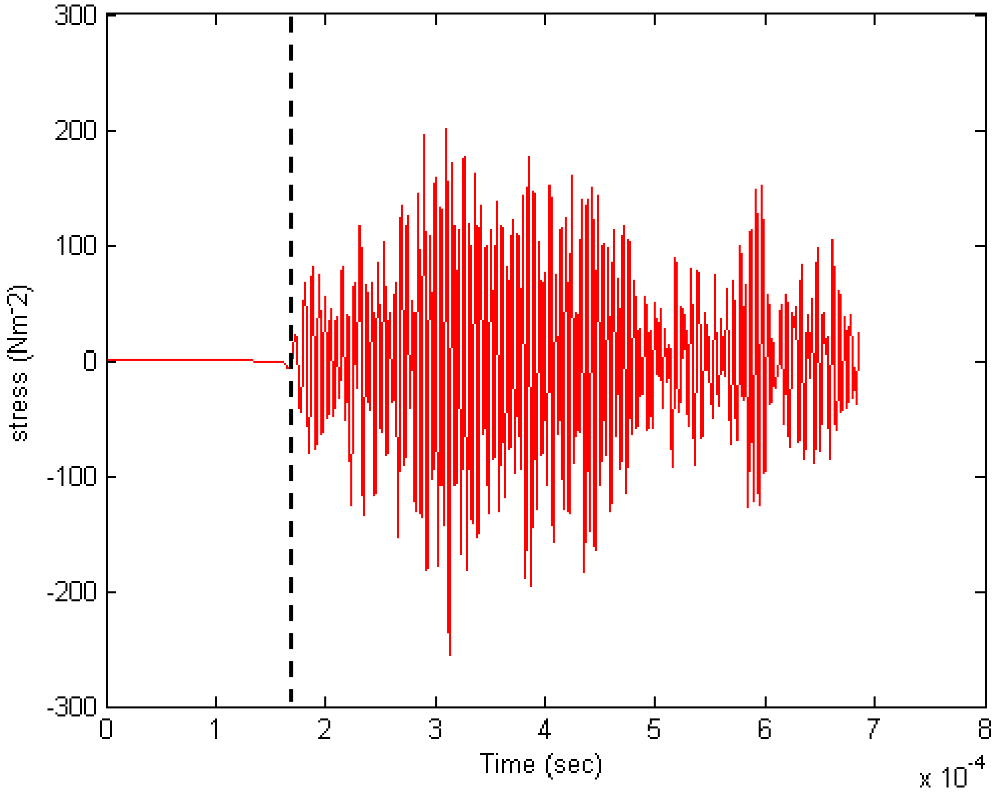


Figure 3. Time series of stress at virtual sensor 1m from source unloaded in 10^{-9}s on 2.5m pipe, showing arrival time estimation (dotted vertical line)

The raw time series were next processed to yield power spectra using a proprietary FFT algorithm, an example of which is shown in Figure 4. As can be seen, the expected response between 0.1 and 1MHz is seen for the fastest unloading rate, but this shifts to lower frequencies and becomes a smaller proportion of the total spectral power as the unloading rate decreases. Aside from this, there is a significant amount of power in the very low frequency part of the spectrum, and it is thought that this is associated with reflections from the fixed ends of the pipe giving pseudo-frequencies with periods equal to the return time of the disturbance. In order to investigate this phenomenon (which is of potential interest in real applications), the power spectra were divided into two (unequal) parts above and below 7kHz and the ratio of power in the low to high frequency parts calculated from each spectrum.

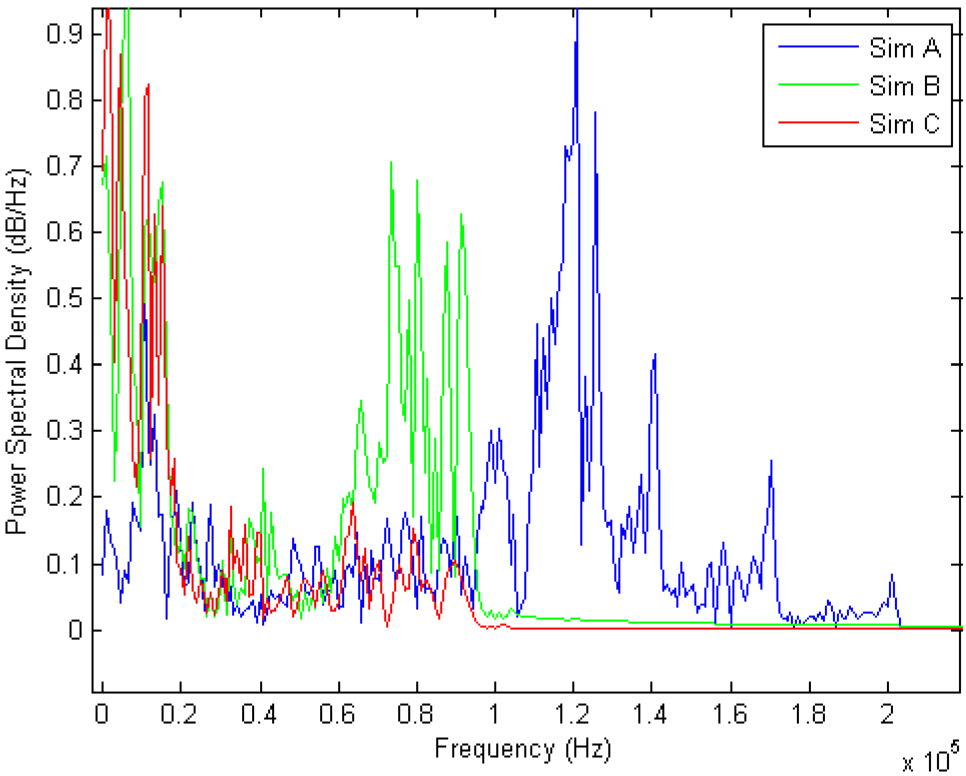


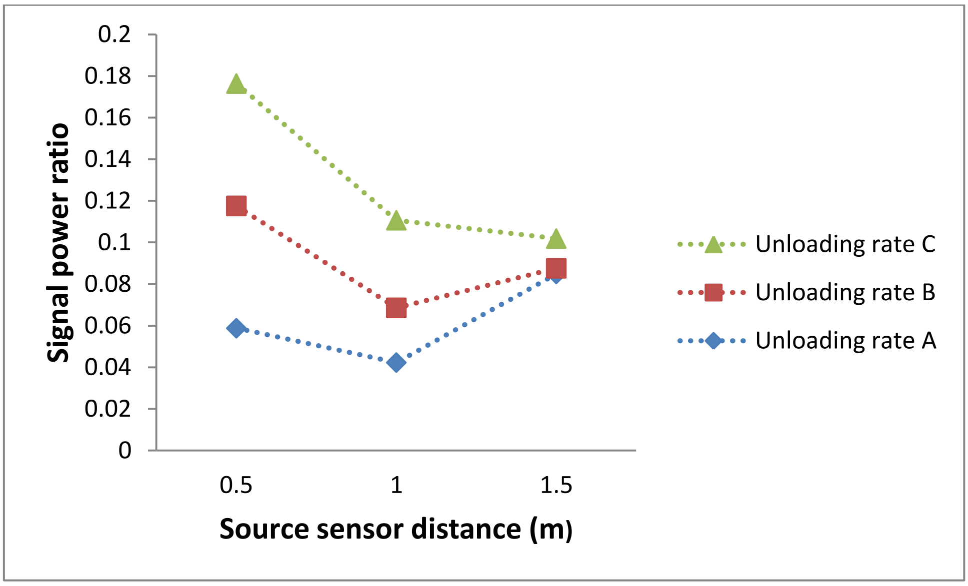
Figure 4. Normalized power spectra for signals acquired at 1.5m from the source on 5m pipe (A, unloaded in 10^{-9}s; B, unloaded in 10^{-8}s; C, unloaded in 10^{-7}s)

The power ratios are shown in Figure 5 for each of the pipe lengths and a number of interesting observations can be made. First of all, for each pipe length, there is a tendency for the ratio to fall off with source-sensor distance, but to rise again at the sensor distance closest to the end of the pipe. This would be consistent with the reflection hypothesis since the return time form the pipe end would be very short, so the pseudo-frequency associated with this part would be relatively high. Remembering that the choice of 7kHz was somewhat arbitrary, it is not too surprising that the patterns are not consistent in the magnitude of these effects.

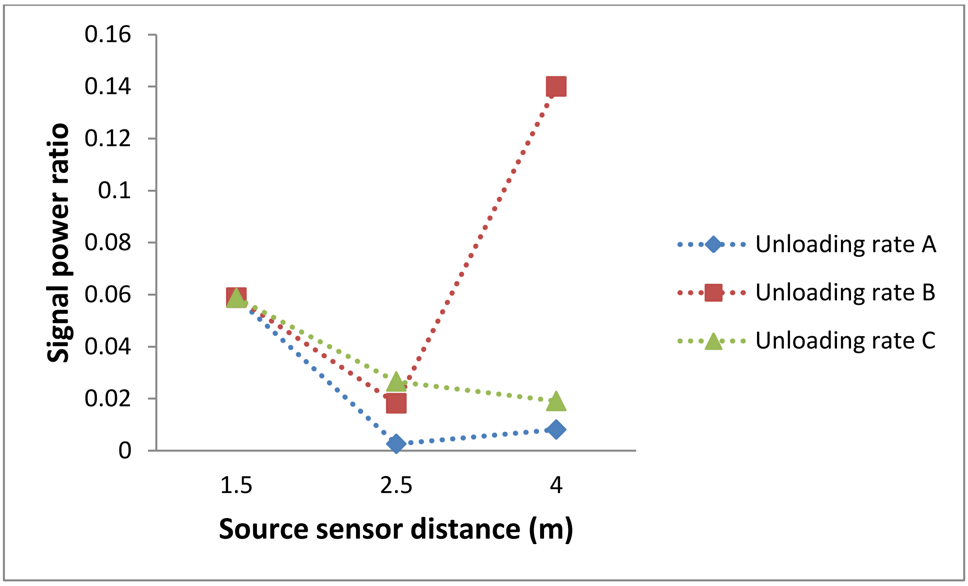
It is also apparent that there is a consistent fall with source-sensor distance in power ratio between the pipes. This is notwithstanding the apparently anomalous point for the 5m pipe at the position closest to the end, which can be explained in terms of the end effect observed above. Since the model used is linear elastic, the only type of attenuation inherent in the simulations is geometric spreading, which would be expected to increase, albeit at a decreasing rate, as the pipes get longer, meaning that the reflections will constitute a smaller proportion of the total recorded energy. The actual attenuation has not been measured in the current work since the spectra have been normalized for comparison purposes.

The division into high and low frequency components was focused on the analysis of the cause of the very low frequency components, although the separation in practice would be influenced by two key factors, namely the analogue filter(s) used in the data acquisition and the sampling rate, neither of which is present in the simulation. It is, however, possible to introduce these, and future work includes digital filtering of the outputs along with analysis which follows more the kinds which are done in practical AE monitoring on non-hit-based AE signals.

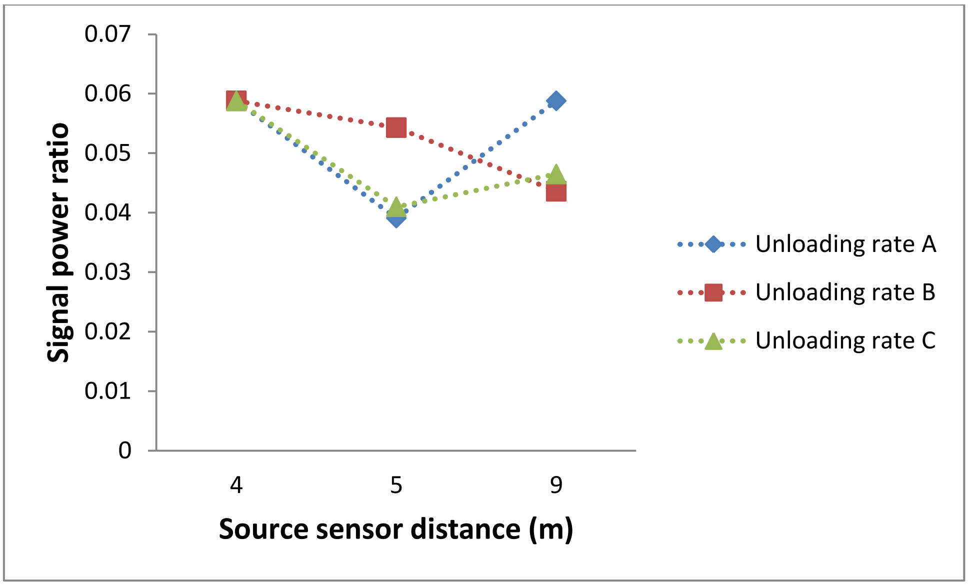
Another key question to be answered in future work on the present simulations is the effect of unloading rate on the high-frequency structure of the recorded response. At present, relatively high unloading rates have been investigated, but, once the reflection effect has been eliminated, it should be possible to examine the structure of the first arrival wave in terms of unloading rate prior to the investigation of more realistic loading functions, for example those typical of impacts.



(a)



(b)



(c)

Figure 5. Spectral power ratio (low frequency : high frequency) for (a) 2.5m long pipe, (b) 5m long pipe and (c) 10m long pipe (A, unloaded in 10^{-9}s; B, unloaded in 10^{-8}s; C, unloaded in 10^{-7}s)

Conclusions

A set of simulations has been carried out where a step-unload source was introduced in to a given pipe size of fixed diameter and wall thickness, but of varying length. The time series of stress was recorded at a number of sensor positions at varying distances from the source.

The following were found:

- The stress time series gave arrival times consistent with a longitudinal stress wave in steel
- The power spectra contained a response broadly in the frequency range expected for sources such as pencil lead breaks, consistent with the unloading rate
- The power spectra contained low frequency elements, tentatively identified as being associated with reflections from the ends of the pipes

The following future work is required on the existing simulations:

- Digital filtering of the time-series to accord with practical analogue filters
- Re-analysis of spectra in the AE response range to reveal effect of unloading rate
- Re-analysis of times series to examine reflection patterns and to determine real attenuation

Future simulations will introduce other types of attenuation, different, more practical loading functions and variable reflection conditions

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