Some Recent Research Results on the use of Acoustic Methods to Detect Water Leaks in Buried Plastic water Pipes

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1. Introduction

Water leakage from buried pipes is a concern in Britain because of changing rainfall patterns, deterioration or damage to the distribution system, and an ever increasing population. A leak from a water supply pipe generates noise, which can be used to locate and detect the leak. Acoustic leak detection techniques have been shown to be effective [1,2], and are in common use in the water industry. Other methods of leak detection which have been used with varying degrees of success are tracer gas. thermography [3], flow and pressure modelling [4], and ground penetrating radar [5]. The potential of several non-acoustic technologies has been evaluated by Hunaidi *et al.* [6,7]. In leak detection surveys using acoustic methods, the most widely used approach involves the cross-correlation of the measured acoustic signals. This has proved to be reasonably effective in detecting and locating metal pipes, but has been problematic when used on plastic pipes [8]. Recent work at the University of Southampton, funded by the EPSRC, has focussed on trying to determine the reasons why this is so, and to investigate ways of improving the technique for plastic pipes. In this article the findings of the research are summarised; the reader is referred to the references for further technical details.

A typical measurement layout to determine the location of a leak in a buried plastic pipe is shown in Figure 1.

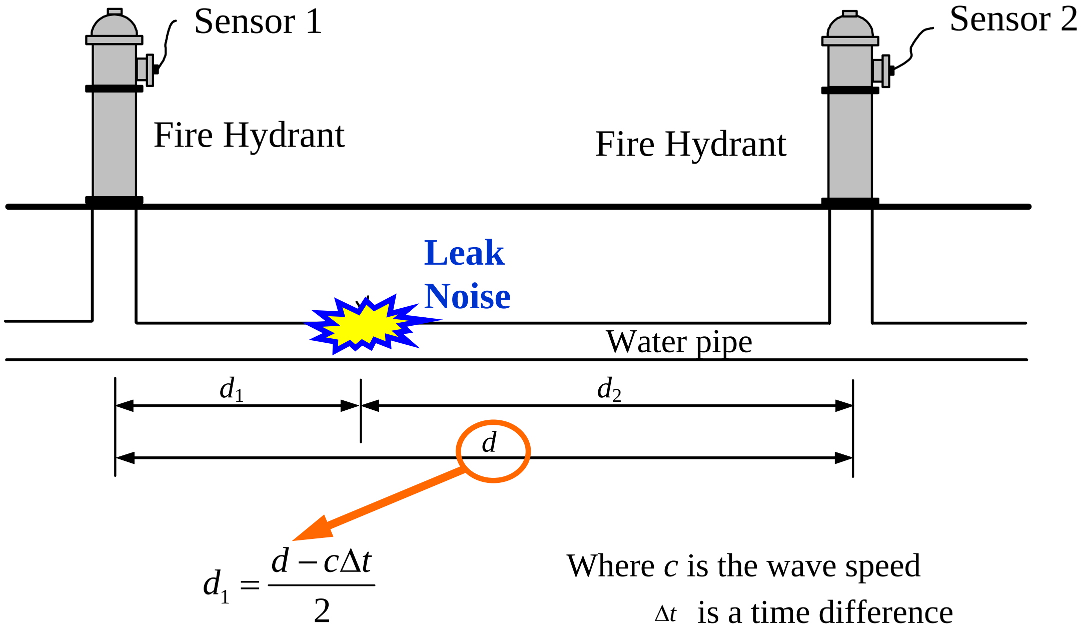


Figure 1. A typical set up to determine the position of a leak from a buried water distribution pipe

If a leak is suspected, the acoustic sensors (typically accelerometers or hydrophones) are placed either side of the leak at convenient access points, for example hydrants. The aim is to determine the position of the leak, which in this case is the distance d_1 from sensor 1 to the leak. This distance is related to other variables by [9]

$$d_1 = \frac{d - c\Delta t}{2} \tag{1}$$

where d is the distance between the two sensors, c is the speed at which the leak noise propagates through the pipe, and Δt is the difference in arrival times of the noise at the two sensors. Thus to accurately determine the leak these three variables need to be known. The distance between the sensors d, can be measured reasonably accurately using a variety of methods, for example GPS. The wave speed c, is difficult to measure and remains an area for further research. However, there is now a reasonably good understanding of the factors that affect this, and these are discussed in the next section. To estimate Δt, the cross-correlation of the signals from the sensors is generally used. However the quality of this estimate depends upon the type and positioning of the sensors and the processing of the signals. Some developments in this area are discussed in section 3.

2. Factors Affecting the Propagation of leak Noise

It is observed in practice that the wave speed (speed of leak noise propagation through the pipe) varies considerably from case to case, and that this noise does not propagate long distances in *plastic* pipes. These two properties are governed by the behaviour of the wave responsible for the propagation of the noise along the pipe. Although there are many waves in a buried fluid-filled pipe, there is only one that generally plays a dominant role in the propagation of leak noise. For a 170 mm diameter MDPE water distribution pipe, the energy associated with this wave is mainly carried in the fluid. It propagates at a much slower speed than in a corresponding metal pipe, typically being around 400 m/s. An experiment was carried out at a special test site, shown in Figure 2, at the University of East Anglia [11].

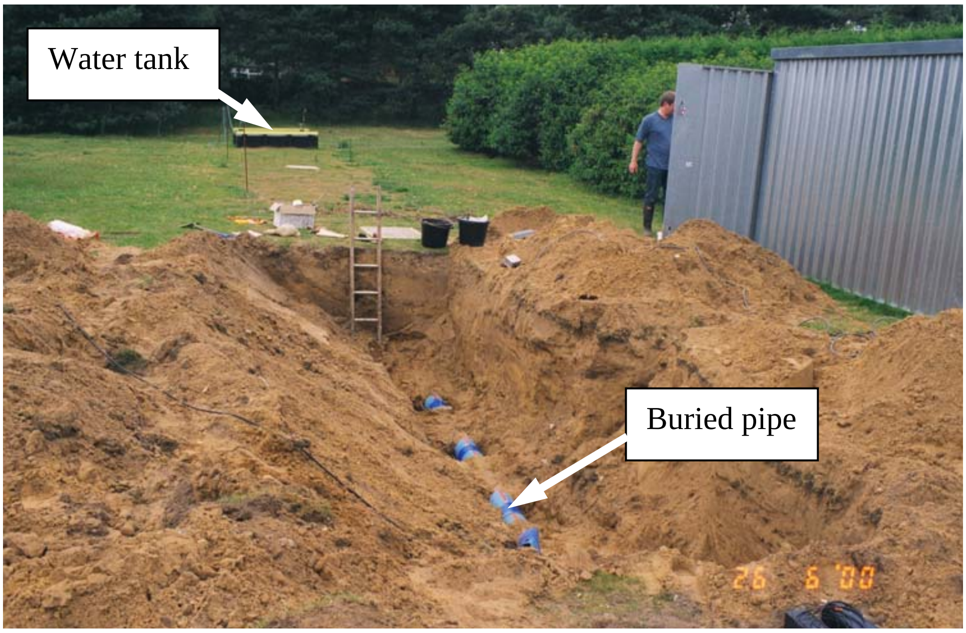


Figure 2. Test Facility at the University of East Anglia used to measure the wave propagation properties of a buried water filled plastic pipe

The water was excited by a specially adapted loudspeaker at one end of a buried pipe and the wave speed and attenuation of the wave were measured using a number of hydrophones positioned along the pipe. The measured and calculated wave speed are shown in Figure 3.

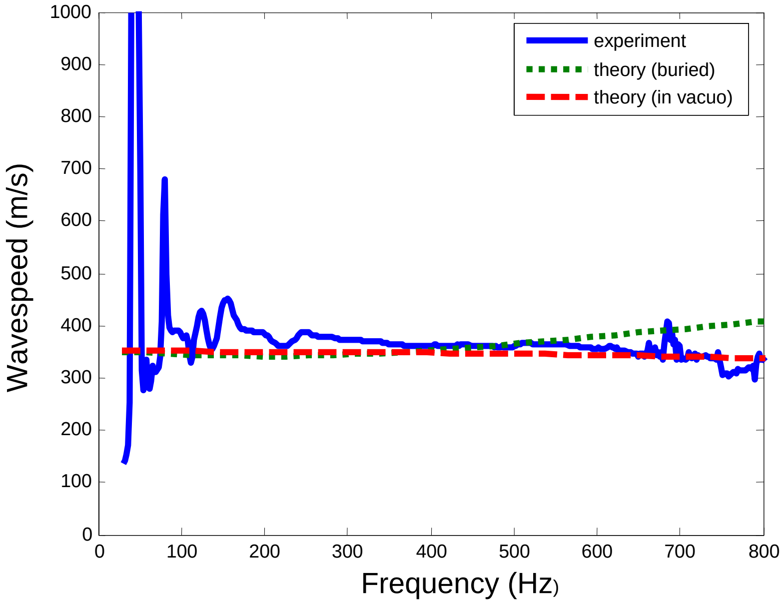


Figure 3. Measured and predicted wave speed in a fluid-filled pipe. The buried pipe is that depicted in Figure 2.

It can be seen that the ground has very little effect on this at frequencies up to about 500 Hz, however the wave speed is highly dependent upon the pipe thickness, diameter and material properties [10,11]. Moreover, the material properties of the pipe are dependent upon temperature, so the wave speed can change from day to day. If the geometry and material properties of the pipe are known, however, the wave speed can be predicted quite accurately. Unfortunately these data are often not available, and so an estimate has to be made.

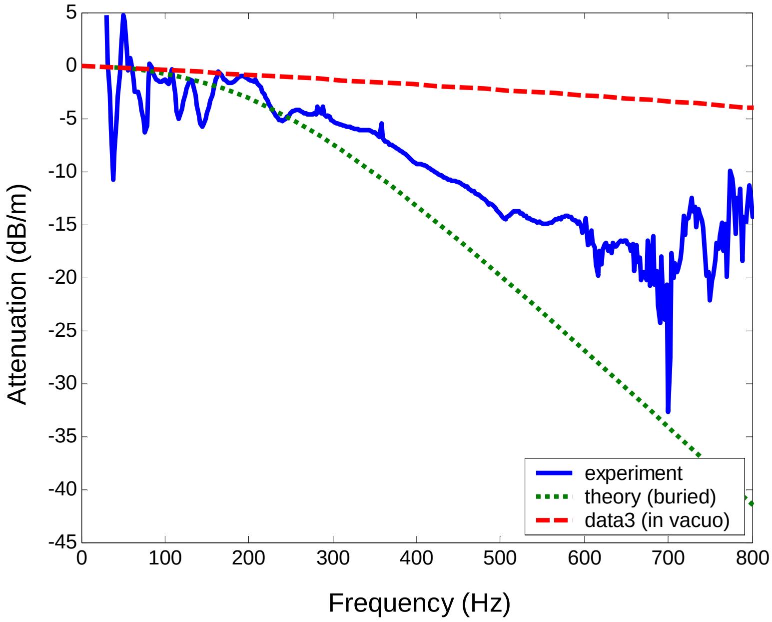


Figure 4. Measured and predicted attenuation of the wave amplitude in a fluid-filled pipe. The buried pipe is that depicted in Figure 2.

The main effect of the ground on the wave responsible for the propagation of leak noise is that it causes the amplitude to decay with distance from the leak and with increasing frequency. This can be seen in Figure 4, which shows the wave attenuation in the buried fluid-filled plastic pipe at the experimental facility at the University of East Anglia compared with a similar pipe in air. The reason for this is that the energy radiates into the ground rather than propagating along the pipe. It should be noted, however, that in the frequency range where the leak noise is generally detected (up to about 100 Hz), the dominant loss mechanism is material damping in the pipe wall. The effect of a different external medium on the wave speed was also investigated by inserting a fluid-filled pipe into water rather than the ground [12]. It was found that in this case the wave speed decreases marginally with a corresponding small increase in the wave attenuation.

If a length of pipe consists of mixed media, for example if a damaged section of metal pipe is repaired using a section of plastic pipe, then the wave speed will be modified accordingly, making it much more difficult to locate a leak accurately. If there is a change in pipe cross-section, then there could be considerable reflection of energy, significantly reducing the distance over which a leak could be detected [13]. Side-branches can also cause reflections which will also have the same effect.

3. Choice of Sensors and Signal Processing

Because the amplitude of the wave responsible for the propagation of leak noise decreases both with distance and frequency, the pipe effectively acts as a low pass filter, with the cut-off frequency decreasing as the distance from the leak increases. Thus if two sensors are placed, one each side of a leak, but at different distances from the leak, then the leak noise passes through two different filters. This means that the degree of correlation between the signals will change as the relative distance between the leak and each sensor changes. The worst situation is when one sensor is placed at the leak and the other is placed at some distance from the leak [9]. A typical cross-correlation function calculated from two leak noise signals is shown in Figure 5.

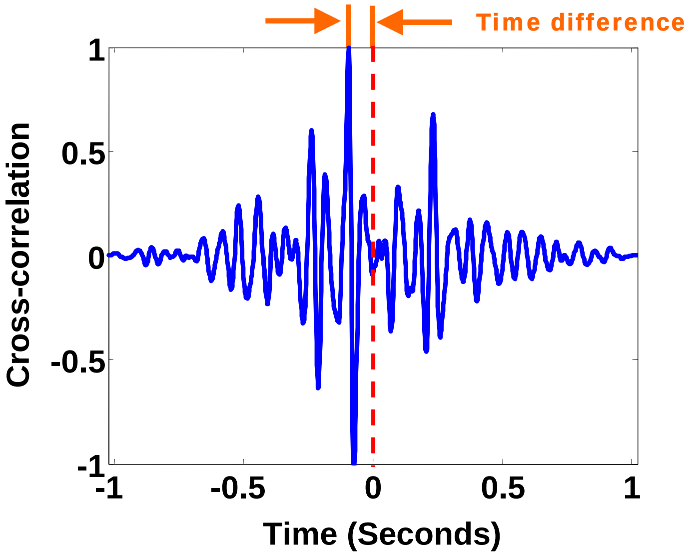
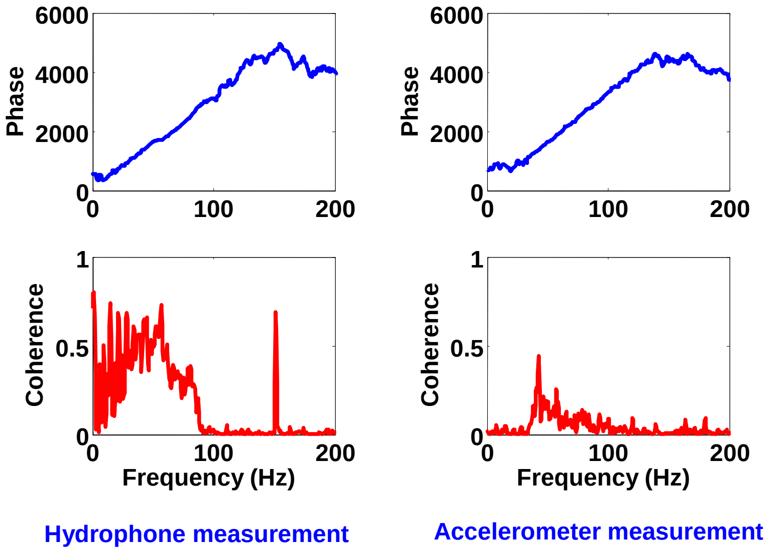


Figure 5. A typical cross-correlation of two leak noise signals made in a measurement system similar to Figure 1 [7].

The position of the largest peak indicates the time difference between the leak noise arriving at the two sensors, and is the variable Δt in equation (1). Clearly a peak that that is large compared with other spurious peaks is desirable. A peak value of one would indicate perfect correlation and only occurs if there is no background noise, and if the sensors are equidistant from the leak. Provided that the background noise at each sensor is uncorrelated, then increasing the time over which the measurement takes place will increase the signal-to-noise ratio (at the rate of 3 dB per doubling of data acquisition time). The other quantity of interest in the cross-correlation function is the accuracy of the time difference estimate and the width of the peak (discrimination). It has been shown that the signal-to-noise ratio has only a marginal effect on the accuracy of the estimate [14]. However, the positioning of the sensors and the type of sensor used can have a significant effect on the width of the peak [14,15]. Clearly, as the distance from the sensor to the leak increases, the higher frequency components of the signal will be significantly attenuated, resulting in a much smaller signal to noise ratio; this will reduce the height of the peak in the cross-correlation function. Also, because the higher frequency content of the signals is diminished, the ability to accurately locate a leak will be adversely affected because the width of the peak increases.

The acoustic pressure inside the pipe is related to the radial displacement of the pipe integrated around the circumference, and a sensor that measures this will indirectly measure the pressure. A sensor has been developed based on this principle a few years ago [16], and has been recently modified with the application of leak detection in mind [17]. If an accelerometer is used instead of a pressure or displacement sensor then the filter that the leak noise passes through is modified, because acceleration is proportional to the product of displacement and square of frequency. Thus an accelerometer will amplify high frequencies compared to a hydrophone. So, for better discrimination of the leak location, an accelerometer is preferable provided that it is positioned to sense the fluid wave; a hydrophone or integrated displacement sensor is preferable, however if the signal to noise ratio is small [15].

The time difference information in the cross-correlation function can be represented as a phase difference in the corresponding cross-spectrum. Examples of the phase together with the coherence between the two signals are shown in Figure 6 for hydrophone and accelerometer measured signals.



Hydrophone measurement

Accelerometer measurement

Figure 6. Comparison between the phase of the cross-spectra and the coherence of two leak noise signals measured on a NRC test facility, Canada [7][15].

The useful information in these plots is the straight-line characteristic of the phase. In both phase plots it can be seen that there is significant background noise for the first few Hz (environmental noise) and also at high frequencies (due to the filtering properties of the pipe). There is always a limited range of frequencies which contains the information on the location of the leak. It should be noted that the coherence is less for the accelerometer measured signals, but the bandwidth is much greater, because of the reasons discussed above.

Figure 7 shows the cross-correlation plots for the signals in Figure 6, and illustrates the improvement that can be achieved by some additional signal processing. Four graphs are depicted, two for the hydrophone measured signals and two for the accelerometer measured signals. It should be noted that these are normalised by setting the maximum to unity.

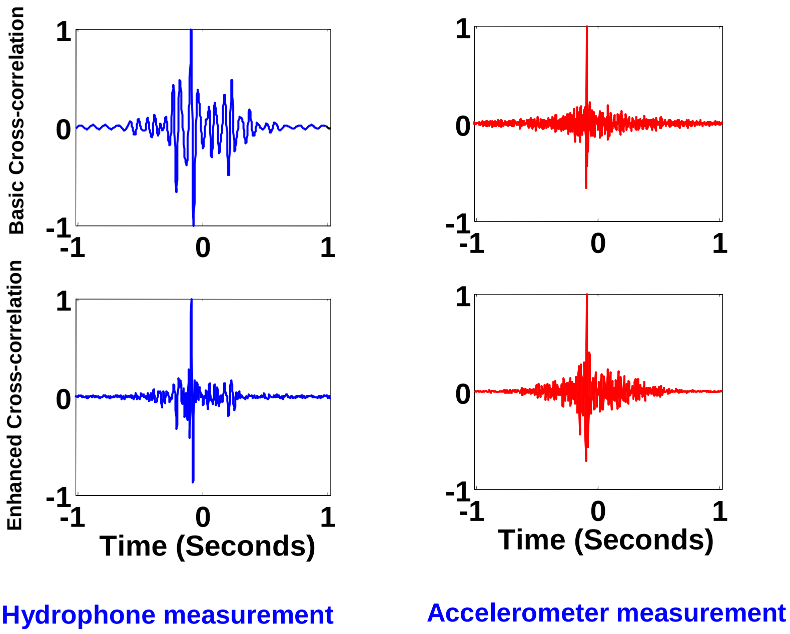


Figure 7. Comparison of the ordinary and enhanced cross-correlation functions for leak noise measurements made using hydrophones and accelerometers at an NRC test facility, Canada [7][15].

For each case the basic cross-correlation function has been calculated and for comparison and enhanced cross-correlation function has also been calculated. The enhancement process involves pre-whitening the signals to remove the amplitude filtering effects of the pipe and weighting the signals at each frequency according to their coherence [14]. The difference between the results from the accelerometer measured signals and the hydrophone measured signals is clear; the higher frequency components from the accelerometer measured signals is evident. Perhaps the most striking feature is the enhancement in the cross-correlation function of the hydrophone measured signals by the additional signal processing.

4. Conclusions and Some thoughts on Future Research

The research conducted over the past fours years or so at Southampton has resulted in:

- A much greater understanding of the way in which leak noise propagates in buried plastic water distribution pipes [10-13].

- A clear understanding of when different sensors should be used and the effects of their positioning [9,15].

- The development of a signal processing procedure that is a significant improvement on the standard cross-correlation technique [17].

To further improve the efficacy of leak detection using acoustic means, it is necessary to develop simple and robust techniques to measure the wave speed in buried plastic water distribution pipes. It is also recommended that the findings from the research summarised in this article be validated by a programme of measurements in a variety of field conditions.

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