Leak detection and location in polyethylene pipes

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Leak Detection & Location
in
Polyethylene Pipes

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A Thesis submitted for the Degree of
Doctor of Philosophy
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To the Almighty...
Acknowledgement

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July, 2008

Maninder Pal
Abstract

This thesis is focused on the application of cross-correlation technique for leak detection and location in medium density polyethylene (MDPE) pipes. A leaking water pipe generates noise that depends primarily on water pressure, pipe characteristics and the leak size and shape. This noise, commonly called leak signals, can be used for the purpose of leak detection and leak location in MDPE pipes. A correlation technique is typically employed to detect, position and characterise these water leaks and is proved to be very efficient for metallic pipes. However, the same is not true for MDPE pipes where the attenuation rate with distance of the leak/source signal is very high, and the generated leak signals are of low frequency and narrow bandwidth. In order to locate leak with good accuracy in MDPE pipes, the correlation process relies on the estimation of speed of leak signals in water/pipe and the time delay between leak signals measured at two locations.

For time delay estimation, a correlation function is used. Its accuracy depends upon the sharpness of the correlation peak, type and positioning of sensor, and the processing of signals obtained, which in turn further depends upon the characteristics of leak signals. In MDPE pipes, leak signals are of low frequency and narrow bandwidth; however, their frequency response is not well characterised. Therefore, this thesis presents an analytical model to explain the acoustic characteristics of leak signals in MDPE pipes. The model is used to study the effects of the cut-off frequencies of low, high and band pass digital filters and the selection of acoustic/vibration sensors for the correlation technique. It detailed the importance of the cut-off frequency of the high pass filter and the insensitivity of the correlation function to the cut off frequency of the low pass filter.

Various correlation functions and the time delay estimators are compared for their ability to locate leaks in MDPE pipes. For leak detection purposes, generalised cross-correlation (GCC) function with the smoothed coherence transform (SCOT) estimator is theoretically found to be an optimum choice as it eliminates the uncertainty involved in selecting filter cut-off frequencies. In contrast with the cross correlation in time domain, GCC with SCOT can easily pick up the main peak while suppressing additional false peaks. Followed by these theoretical predictions, experimental work on MDPE pipes with and without backfill is carried out to validate the accuracy and effectiveness
of the theoretical predictions and to characterise leak signals. From the experimental studies, it is found that leak signals in MDPE pipes lie in the frequency range 20Hz to 350Hz. An approximately linear phase-frequency relationship is observed for the frequency range 20Hz to 250Hz. With these results, it is possible to achieve better performance of existing correlators by means of using appropriate filters, amplification and choice of sensors.

The second parameter, propagation speed of leak signals depends upon the dimensions and material properties of the pipe section under survey between the two sensor positions. The information about these properties are difficult to obtain in practise, as the water distribution network has many discontinuities in dimensions and material properties of pipe. Therefore in this thesis, a new method for the calculation of propagation speed of leak signals in MDPE pipes is proposed and experimentally verified. This method is based on the linear phase-frequency relationship of the leak signals. The advantage of this method is that it is stable and does not need any prior information on the physical properties of pipe.

Finally, the choice of sensors also significantly affects the accuracy with which the correlation method locate leaks. From the theoretical predictions, it is found that hydrophones are effective for measuring signals with a small signal to noise ratio (SNR), however, a relatively sharp and clearer correlation peak can be achieved using accelerometer measured leak signals. Hydrophones are found difficult to use in practise, therefore, an optimum accelerometer sensor is specified in this thesis for the purpose of measuring the low frequency and narrow bandwidth leak signals in MDPE pipes. It is highly sensitive, which makes it more susceptible to noise, therefore appropriate signal processing techniques are also specified. A choice of a combination of high order (>7) Bessel low and high pass filter with root mean square averaging is both experimentally and theoretically found suitable for processing leak signals before being correlating. The complete system is validated experimentally.

Keywords: Correlators, Leakage, Leak detection, Leak Location, Medium Density Polyethyelene Pipes and Water Shortage.
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B.1 A small cube of fluid suffers a change in density if the displacements $\xi(x)$ of its left face and $\xi(x + \Delta x)$ of its right face are not equal (Donald, 1987). 225
### NOTATIONS & ABBREVIATIONS

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<thead>
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<tr>
<td>*</td>
<td>Complex conjugate</td>
</tr>
<tr>
<td>$E, B_f$</td>
<td>Young's modulus and fluid bulk modulus</td>
</tr>
<tr>
<td>$E[ * ]$</td>
<td>Expected value</td>
</tr>
<tr>
<td>$E_f$</td>
<td>Water borne leak energy</td>
</tr>
<tr>
<td>$E_s$</td>
<td>Shell borne leak energy</td>
</tr>
<tr>
<td>$G(\omega), g(\tau)$</td>
<td>Frequency and time domain characteristics of an ideal band-pass filter</td>
</tr>
<tr>
<td>$H(\omega, x)$</td>
<td>Frequency response of the transfer function</td>
</tr>
<tr>
<td>$H$</td>
<td>Transfer function</td>
</tr>
<tr>
<td>$H_p(\omega, x)$</td>
<td>Frequency response function between the pressure measured at the sensor location and at the leak location</td>
</tr>
<tr>
<td>$L_1, L_2$</td>
<td>Distances of sensors relative to the leak position</td>
</tr>
<tr>
<td>$P_s$</td>
<td>Pressure amplitude of the s wave</td>
</tr>
<tr>
<td>Notations &amp; Abbreviations</td>
<td></td>
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<tr>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td>$R_{s_1s_2}(\tau), R_{n_1n_2}(\tau)$</td>
<td>Correlation function of $s_1(t)$ and $s_2(t)$, $n_1(t)$ and $n_2(t)$</td>
</tr>
<tr>
<td>$R_{x_1x_1}(\tau), R_{x_2x_2}(\tau)$</td>
<td>Auto-correlation functions of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$R_{x_1x_2}(\tau)$</td>
<td>Cross-correlation function of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$R_{x_1x_2}^G(\tau)$</td>
<td>Generalised correlation function of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$S_{x_1x_1}(\omega), S_{x_2x_2}(\omega), S_{ll}(\omega)$</td>
<td>Auto spectral densities of $x_1(t)$, $x_2(t)$ and $l_0(t)$</td>
</tr>
<tr>
<td>$S_{x_1x_2}(\omega)$</td>
<td>Cross spectral density of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$S_{x_1x_2}^m(\omega)$</td>
<td>Cross spectral density of $x_1(t)$ and $x_2(t)$ for the modified correlation function</td>
</tr>
<tr>
<td>$T$</td>
<td>Total observation time</td>
</tr>
<tr>
<td>$U_s$</td>
<td>Axial displacement amplitude of the $s$ wave</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Radial displacement amplitude of the $s$ wave</td>
</tr>
<tr>
<td>$X_1(f), X_2(f)$</td>
<td>Fourier Transforms of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$\Delta\omega, \omega_0, \omega_1, \omega_c$</td>
<td>Frequency bandwidth, lower, upper cut-off frequencies and centre frequency of the band pass filter</td>
</tr>
<tr>
<td>$\Psi_M$</td>
<td>Frequency weighting function of maximum likelihood estimator</td>
</tr>
<tr>
<td>$\Psi_P$</td>
<td>Frequency weighting function of phase transform estimator</td>
</tr>
<tr>
<td>$\Psi_S$</td>
<td>Frequency weighting function of smoothed coherence transform estimator</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Attenuation with distance of leak signals</td>
</tr>
<tr>
<td>$\delta(\tau)$</td>
<td>Dirac delta function</td>
</tr>
</tbody>
</table>
**Notations & Abbreviations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$\eta$, $\nu$</td>
<td>Loss factor of the pipe wall and Poisson ratio</td>
</tr>
<tr>
<td>$\hat{R}_{x_1x_2}(\tau)$</td>
<td>Biased correlation function of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$\omega$, $\Omega$</td>
<td>Frequency and normalised frequency</td>
</tr>
<tr>
<td>$\otimes$</td>
<td>Convolution</td>
</tr>
<tr>
<td>$\phi_{m,x_1x_2}(\omega)$</td>
<td>Phase spectrum of modified cross-correlation function</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Phase of leak signals</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>Density of fluid</td>
</tr>
<tr>
<td>$\rho_{x_1x_2}(\tau)$</td>
<td>Normalised correlation coefficient of $x_1(t)$ and $x_2(t)$</td>
</tr>
<tr>
<td>$\sigma_x$, $\sigma_0$</td>
<td>Axial and circumferential normal stress</td>
</tr>
<tr>
<td>$\tau_{\text{shift}}$</td>
<td>Time delay at the peak</td>
</tr>
<tr>
<td>$\xi$, $\xi_r$</td>
<td>Displacement of fluid element</td>
</tr>
<tr>
<td>$a$, $h$</td>
<td>Pipe radius and wall thickness</td>
</tr>
<tr>
<td>$a_i$, $b_i$</td>
<td>Filter coefficients</td>
</tr>
<tr>
<td>$c$, $c_f$</td>
<td>Wavespeed and fluid wavespeed</td>
</tr>
<tr>
<td>$c_w$</td>
<td>Wavespeed of the impulse wave</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Sampling frequency</td>
</tr>
<tr>
<td>$k$, $k_f$</td>
<td>Wavenumber and fluid wavenumber</td>
</tr>
<tr>
<td>$k_l$</td>
<td>Axial wavenumber of a compressional wave</td>
</tr>
<tr>
<td>$k_s$</td>
<td>Axial wavenumber of the $s$ wave</td>
</tr>
<tr>
<td>$k'_s$</td>
<td>Radial wavenumber for the $s$ wave</td>
</tr>
<tr>
<td>Notations &amp; Abbreviations</td>
<td></td>
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<tr>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td>( l_s(t) )</td>
<td>Leak signal at leak position</td>
</tr>
<tr>
<td>( n_1(t), n_2(t) )</td>
<td>Background noise at sensor position 1 and 2</td>
</tr>
<tr>
<td>( p(\omega, x), P_0(\omega) )</td>
<td>Acoustic pressure and its amplitude at ( x = 0 )</td>
</tr>
<tr>
<td>( s_1(t), s_2(t) )</td>
<td>Attenuated leak signals at sensor positions 1 and 2</td>
</tr>
<tr>
<td>( t, \tau )</td>
<td>Time and lag of time</td>
</tr>
<tr>
<td>( t_L )</td>
<td>Journey time of the reflected impulse wave</td>
</tr>
<tr>
<td>( u, v, w )</td>
<td>Displacement in axial, circumferential and radial direction</td>
</tr>
<tr>
<td>( v_r )</td>
<td>Radial velocity of the fluid</td>
</tr>
<tr>
<td>( v_x )</td>
<td>Axial fluid particle velocity</td>
</tr>
<tr>
<td>( v_{sr} )</td>
<td>Shell radial velocity</td>
</tr>
<tr>
<td>( x, \theta, r )</td>
<td>Axial, circumferential and radial coordinates</td>
</tr>
<tr>
<td>( x_1(t), x_2(t) )</td>
<td>Measured signals</td>
</tr>
<tr>
<td>( x_L )</td>
<td>Distance of leak from valve</td>
</tr>
<tr>
<td>( z_{Mpipe}, z_{Kpipe} )</td>
<td>Impedance of the pipe wall inertia and stiffness</td>
</tr>
<tr>
<td>( z_{fluid}, z_{pipe} )</td>
<td>Impedance of the contained fluid and the pipe wall</td>
</tr>
<tr>
<td>AC</td>
<td>Asbestos cement</td>
</tr>
<tr>
<td>ASD</td>
<td>Auto-spectral density</td>
</tr>
<tr>
<td>AWWA</td>
<td>American water works association</td>
</tr>
<tr>
<td>CSD</td>
<td>Cross-spectral density</td>
</tr>
<tr>
<td>Notation</td>
<td>Definition</td>
</tr>
<tr>
<td>----------</td>
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</tr>
<tr>
<td>D</td>
<td>Total distance between sensors, $D = L_1 + L_2$</td>
</tr>
<tr>
<td>DMA</td>
<td>District meter area</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FT</td>
<td>Fourier Transform</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground penetrating radar</td>
</tr>
<tr>
<td>GRP</td>
<td>Glass reinforced plastic pipes</td>
</tr>
<tr>
<td>HDPE</td>
<td>High density polyethylene pipe</td>
</tr>
<tr>
<td>IFT</td>
<td>Inverse Fourier Transform</td>
</tr>
<tr>
<td>IT</td>
<td>Infrared thermography</td>
</tr>
<tr>
<td>ITA</td>
<td>Inverse transient analysis</td>
</tr>
<tr>
<td>IWSA</td>
<td>International water supply association</td>
</tr>
<tr>
<td>LD</td>
<td>Leak detection</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low density polyethylene pipe</td>
</tr>
<tr>
<td>LL</td>
<td>Leak location</td>
</tr>
<tr>
<td>LNC</td>
<td>Leak noise correlator</td>
</tr>
<tr>
<td>MDPE</td>
<td>Medium density polyethylene pipe</td>
</tr>
<tr>
<td>ML</td>
<td>Maximum likelihood transform</td>
</tr>
<tr>
<td>PCCP</td>
<td>Prestressed concrete cylinder pipes</td>
</tr>
<tr>
<td>PHAT</td>
<td>Phase transform</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and advisory system</td>
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### Notations & Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SCOT</td>
<td>Smoothed coherence transform</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>ST</td>
<td>Severn Trent</td>
</tr>
<tr>
<td>WDN</td>
<td>Water distribution network</td>
</tr>
<tr>
<td>WSS</td>
<td>Water supply system</td>
</tr>
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</table>
Chapter 1

Introduction

This chapter presents the importance of medium density polyethylene (MDPE) pipes in water distribution systems. It summarises the problems associated with leak detection and location in MDPE pipes; along with the aim, research objectives and the outline of thesis.

1.1 Leaks and their importance

Worldwide the shortage of drinking water is a subject of increasing concern. This is because of the increasing demand for water and decrease in water supplies. A partial solution to this problem can be obtained by controlling the amount of water loss in distribution networks. Water loss mainly occurs due to leakage in distribution networks. The volume of leaking water may constitute a significant portion of the water fed into the networks. For example in 1991, International Water Supply Association (IWSA), reported a water loss in between 20 to 30% of production, with leakage being the main component (Cheong, 1991). Severn Trent¹ (ST) and Thames Water², UK water companies, lost an average of 505 megalitres/day and 905 megalitres/day respectively in 2004-2005, which is a large volume of water; however, lost somewhere on its way to customer (OFWAT, 2005). Leaks occur due to damage or

¹www.stwater.com
²www.thameswater.co.uk
deterioration of the network caused by several factors such as corrosive environment, soil movements, poor construction standards, excessive traffic load and fluctuations in the water pressure (AWWA, 1987). Leaks not only cause water loss but also pose a risk to public health, by making a potential entry for contaminants if a pressure drop occurs in the distribution system. Leaks also result into economical losses due to the high cost of energy, wasted on the treatment and pumping action of leaking water (Colombo & Karney, 2002). In addition to these, leaking water may represent a risk to building foundations, roads and other structures.

Thus, water leakage reduction from distribution networks is a vital strategy in the improvement of sustainable use of water, the most fundamental of our natural resources.

1.2 Current leak detection techniques and equipments

There are several methods available to detect and locate leaks in water distribution pipes. These are based on interpreting:

- the noise produced by the leaking pipe.
- the changes, made by leaking water, in the characteristics of soil surrounding the pipe.

A leaking pipe produces vibro-acoustic noise, which depends primarily on water pressure, pipe characteristics, and the leak size and shape. The vibro-acoustic noise, commonly called leak signals, travels both in the pipe and soil surrounding the pipe. Acoustic devices such as listening sticks and leak noise correlators (LNC's), measure and process these signals to detect and locate leaks. Their accuracy in detecting and locating leaks depends upon the material properties and physical dimensions of the pipe.

In recent years, MDPE pipes are increasingly being used because of their inherent advantages over metallic pipes such as low cost, ease of handling and high resistance to corrosion. Acoustic equipment gives good result for metallic pipes; however, due to high attenuation with propagation distance of leak signals in MDPE pipes it is difficult to detect and locate leaks using currently available acoustic devices (Hunaidi et al., 1999, 2000).
Water leaking through pipes also changes the characteristics of the soil surrounding the leaking pipe. Leaks can be detected by identifying these changes using various non-acoustics methods such as thermography (Weil, 1993), tracer gas (Sensistor, 1997) and ground penetrating radar (Graf, 1990). The potential of non-acoustic techniques has been evaluated by several researchers such as Hunaidi (1998, 2000) and water professionals such as Divit (2005). They found non-acoustic techniques giving promising results when use on difficult non-metallic pipes; however, at the expense of high cost, being more time consuming, high complexity and requirement of highly skilled staff. Because of high cost and need for skilled staff, water professionals such as Divit (2005) found these techniques not to be suitable for practical use in MDPE pipes. Therefore, there is a need to develop a detection system and monitoring procedure with application to the growing percentage of installed MDPE pipes, that can provide information on the leak location for efficient maintenance operations.

1.3 Leak detection and location in MDPE pipes

Leak noise correlator is the only credible option for leak detection and location in MDPE pipes. The advantages of leak noise correlators over other leak detection methods have been appreciated and accepted within the UK water industry (UKWIR, 1999) and many other countries worldwide. LNC's are proved to be very efficient for metallic pipes. However, the same is not true for MDPE pipes where the attenuation rate with distance of the leak signal is very high.

In order to locate leaks with good accuracy in MDPE pipes, correlators rely on the frequency range of leak signals, estimation of the speed of leak signals in water/pipe and the time delay between two measured leak signals. The speed of sound and the estimation of time delay depends upon the type of sensor, their positioning and the processing of signals obtained. However, due to poor knowledge about the characteristics of leak signals in MDPE pipes it is difficult to make a selection of the sensors and appropriate filter frequencies.

Therefore, the research work reported in this thesis is focused on the characteristics of leak signals in MDPE pipes, choice of sensors and optimisation of signal processing techniques, with the aim to provide better solutions for leak detection and location in MDPE pipes.
Chapter 1: Introduction

1.4 Aim

To develop a method for detecting and locating leaks in medium density polyethylene pipes.

1.5 Research objectives

Leaks in metallic pipes can be located using LNC's based on the correlation technique. However, the effectiveness of existing technique for leak detection in MDPE pipe is not well established and some leak detection professionals such as Divit (2005) are skeptical about locating leaks accurately using correlators. Therefore, the purpose of this research is to optimize the variables of leak noise correlators to aid leak detection and location in MDPE pipes. The main objectives of this research are:

- To review existing information on distribution network pipe material properties in situ construction conditions and operational constraints.

- To investigate potential methods of leak detection and location such as water borne acoustic emission techniques, in use and under development.

- To develop an analytical model to predict cross-correlation of both the structure borne and fluid borne waves, for the purpose of leak detection and location in MDPE pipes.

- To produce a novel monitoring procedure, develop a test rig and conduct trials at the developed test rig and Severn Trent Lake House facilities.

- To characterize leak signals using simulated leaks under controlled conditions and to investigate the parameters affecting signal characteristics.

- To design a monitoring system, signal acquisition sensor and signal processing techniques for detecting and locating leaks in MDPE pipes.
1.6 Contributions to knowledge of the Thesis

In the achievement of the above research objectives, the following contributions are made:

- An analytical model to predict the cross-correlation function of leak signals in MDPE pipes is established.
- The characteristics of leak signals in MDPE pipes is determined using experimental studies and theoretical predictions.
- A new method for calculating the velocity of leak signals is proposed and experimentally verified.
- Using the characteristics of leak signals defined above, an accelerometer sensor is specified and tested successfully for measuring leak signals in MDPE pipes.
- An optimal criteria for the selection of signal processing techniques is made for the purpose of leak detection in all type of pipes including the traditionally difficult MDPE pipes.
- A novel monitoring procedure including the specification of accelerometer and signal processing techniques is developed and experimentally verified.

1.7 Thesis structure

The main body of this thesis comprises nine chapters. The outline of the chapters is provided below:

- Chapter 1: Introduction

  Chapter 1 gives an overview of the importance of detecting leaks in distribution pipes, especially MDPE. The current problems associated with leak detection and location in MDPE water pipes and the difficulties with leak detection correlators are briefly discussed. It summarises the aim, research objectives, contributions made and the thesis structure.
Chapter 1: Introduction

- Chapter 2: Literature Review
  This chapter presents the importance of MDPE pipes in the existing and future water supply systems. It gives a review of all the leak detection and leak location techniques, that can be used in MDPE pipes. A comparison of these techniques is done to determine their strength, weakness and use in MDPE pipes. Finally, this chapter summarises the problems associated with the effective use of correlators in MDPE pipes, which are further investigated in this thesis.

- Chapter 3: Correlating Leak Signals in MDPE Pipes
  This chapter presents an analytical model of cross-correlation method for leak detection and location in MDPE pipes. It explains the parameters that directly or indirectly affect the accuracy of the correlation method. Different types of correlation functions, that can be used for the estimation of time delay between leak signals are discussed and compared. At the end, it report the research methodology used in this thesis to optimize these parameters.

- Chapter 4: Characterising Leak Signals in MDPE Pipes
  This chapter explains the importance of the characteristics of leak signals in performing correlation on leak signals. It presents an analytical model to characterize leak signals in MDPE pipes. Finally in this chapter, the theoretical predications are validated with the experimental results obtained from the pilot stage tests on pipes without soil surround conducted on a MDPE pipe test rig at hydraulics laboratory, Loughborough University.

- Chapter 5: Leak Signals in Buried MDPE Pipes
  In this chapter, a series of pilot study tests were conducted on buried MDPE pipes and the results obtained are compared with tests conducted in Chapter 4 on MDPE pipes without backfill. From the results of these tests, this chapter determines the characteristics of leak signals in MDPE pipes.

- Chapter 6: Speed and Wave Propagation Theory
  In this chapter, a new method for the calculation of speed of leak signal propagation in water filled MDPE pipes is proposed and experimentally verified.
Chapter 1: Introduction

The currently used methods for the estimation of speed of leak signals are also discussed and compared with the proposed method.

• Chapter 7: Signal Processing for Leak Signals

This chapter discusses the various types of sensor and signal processing techniques. It explains the optimised accelerometer sensor designed and the signal processing techniques selected for the purpose of leak detection in MDPE pipes.

• Chapter 8: System Evaluation

Chapter 8 discusses the test set-up designed and manufactured at hydraulics laboratory, Loughborough University for the final stage of controlled experiments. It reports the experimental work carried out on this buried MDPE pipe test rig. In this chapter, tests were conducted to confirm the characteristics of leak signals, and to determine the efficiency and accuracy of the optimised system in detecting and locating leaks in MDPE pipes.

• Chapter 9: Conclusions and Recommendations

Finally, Chapter 9 summarises the main conclusions from the thesis and makes recommendations for future work.

This thesis also contains two appendices to support the main structure of the thesis. Appendix A gives the Matlab code used for various supporting examples used in the thesis. The dynamic behaviour of fluid-filled pipes is reviewed in Appendix B.
In recent years, MDPE pipes are increasingly being used in water supply systems (WSSs). This is because of their inherent advantages over previously used materials such as ductile iron and asbestos cement. However, it is challenging to detect and locate leaks in MDPE pipes.

This chapter presents the importance of MDPE pipes in the existing and future water supply systems. It gives a brief review of all the available leak detection and leak location techniques, which can be used for detecting and locating leaks in MDPE pipes. A comparison of these techniques is done and correlation is found to be the best technique for both detecting and locating leaks in MDPE pipes. However, for its effective use in MDPE pipes, certain parameters such as filter cut-off frequencies needs an optimisation. At the end, this chapter summarises all the problems associated with the effective use of correlators, which are further investigated in this thesis.

2.1 Introduction

WORLDWIDE the shortage of potable water is increasing day-by-day. It is becoming a subject of increasing concern with numerous articles appearing in news, magazines (Young, 2006) and journals about the shortage of drinking water especially in developing countries. There are a number of factors such as climate change, extended periods of drought, population growth and migration, that are putting
increasing pressure on existing water utilities to meet the demand for drinking water. However, a key factor which can help in reducing the shortage of potable water is control over water losses in water supply systems.

### 2.2 Water loss

Water loss, commonly called Un-accounted for Water (UFW), refers to the un-accounted water that leaves a water supply system. Hope (1996) rephrase the statement, originally made over a century ago, which is still to the point:

> "There is no water supply in which some unnecessary waste does not exist and there are few supplies, if any, in which the saving of a substantial proportion of that waste would not bring pecuniary advantage to the Water Authority."

In 1980, the international water supply association (IWSA) published the results of a survey carried out in 70 European cities (TWGWW, 1980). The study established an average amount of 15% losses in water supply networks. Cheong (1991) from his studies summarised that for a typical WSS, the amount of water loss is typical between 20-30% of production, with leakage being the main component. A typical range for water loss in Europe of 9–30% (Cheong, 1991), while rates for Malaysia of 43% and for Bangladesh of 56% (Chowdhury et al., 1999) have been reported. Brothers in 2001 mentioned that some utilities in North America experience water losses of 20–50%. For some distribution systems, the water loss can even be in excess of 50% (AWWA, 1987). BBC News (2005), reported that Thames Water, a UK based water company, loses an average of 915 megalitres a day. The studies demonstrating the amount of water loss in various parts of the world is summarised in Table 2.1. It can be seen from Table 2.1 that a minimum 15% of water loss is reported in most WSSs across the world. This is a large volume of water that does not arrive at the customer. Thus, reducing water loss is a vital strategy to minimise the shortage of drinking water. The three main factors responsible for water loss are authorized un-metered accounts, unauthorized connections and leaks. Authorized un-metered accounts are legal, un-metered connections often for special users (such as fire-fighting and parks) at no charge. Unauthorized connections refers to the theft of water from WSS (e.g. disconnected sources illegally reconnected and illegal taps on distribution lines) (Thornton, 2002).
A leak is any hole, crack or flaw in the WSS that permits an uncontrolled flow of water. Leaks can be classified into background leakage and bursts, depending upon their flow rate. If the leak flow rate is lower than a certain threshold value set by the water companies, then it is called a background leak; however, if it exceeds the threshold then it is classified as a burst. For most WSS’s, leakage is the hardest and most expensive form of water loss to control. Leaks not only cause water loss but sometimes may result in physical losses such as undermining of roadways by eroding the underlying soil (Price & Reed, 1989). Leaks also result in increased pumping energy, system rehabilitation costs and the risk of compromised water quality by allowing intrusion of polluted groundwater and contaminants from surrounding soil (Colombo & Karney, 2002, 2004a,b). For example, LeChevallier (1990) mentioned that at leak positions, higher velocities of leaking water influence water quality by promoting greater transport of disinfectants throughout the system, which increases the likelihood of biofilm detachment. Thus, if unauthorized connections and leaks can be completely avoided, then this is a high proportion that can help in reducing the shortage of drinking water.

To manage this water loss, water industries focus on two ways: pumping more water than required and/or detecting and repairing leaks. However, pumping more water than required makes leaking worse by increasing their size. Therefore, water companies engaged in an active programme of locating and repairing leaks (Fantozzi & Fontana, 2000). This implicit recognition that important savings can be achieved via locating and repairing leaks is highlighted by the appearance of numerous articles on leak detection and control by various researchers such as Hunaidi et al. (2000); Lahlou (2001), Žitkovský et al. (2000) and Vairavamoorthy & Lumbers (1998).

In general, leaks are expensive for a variety of reasons, including the loss of water and treatment chemicals, the increased risk of water quality deterioration, unnecessary capacity expansion and the increased energy expenditure required to feed the leaks. Thus, efforts put for locating and repairing leak helps not only in minimising water loss but also save energy and infrastructure.

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1Leak flow rate refers to the quantity of water exiting the leak per unit time.
Table 2.1: Studies demonstrating un-accounted for water and leakage rate in various parts of the world (after Lee & Schwab (2005)).

<table>
<thead>
<tr>
<th>Location</th>
<th>Summary of Findings</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makkah, Saudi Arabia</td>
<td>Estimated leakage rates are 56%.</td>
<td>Al-Ghamdi &amp; Gutub (2002)</td>
</tr>
<tr>
<td>North America</td>
<td>A typical range of 20-50% of water loss is reported.</td>
<td>Brothers (2001)</td>
</tr>
<tr>
<td>London, UK</td>
<td>Thames Water, a UK based water company loses 915 megalitres a day.</td>
<td>BBC News (2005)</td>
</tr>
<tr>
<td>Midlands, UK</td>
<td>Severn Trent, a UK based water company loses 505 megalitres a day.</td>
<td>OFWAT (2005)</td>
</tr>
<tr>
<td>Malaysia and Europe</td>
<td>An average rate of 43% water loss in Malaysia, while in Europe the amount of water loss between 9 to 30% is reported.</td>
<td>Cheong (1991)</td>
</tr>
<tr>
<td>Bangladesh and other parts of Asia</td>
<td>Average rate of un-accounted for water (UFW) estimated to range between 22% and 56% in Bangladesh. Other Asian cities range varies from 25% in Calcutta, India, to 58% in Manila, Philippines.</td>
<td>Chowdhury et al. (2002)</td>
</tr>
<tr>
<td>Mexico city, Mexico</td>
<td>Leakage rates estimated to be 37%.</td>
<td>Conger (1999)</td>
</tr>
<tr>
<td>São Paulo, Brazil</td>
<td>Occurrence of 35,000 leak situations per month.</td>
<td>Massato &amp; Thornton (1999)</td>
</tr>
<tr>
<td>Cebu, Philippines</td>
<td>Leaks in pipes resulted in contaminated water where pipes lay in open gutters.</td>
<td>Moe et al. (1991)</td>
</tr>
<tr>
<td>Hyderabad city, India</td>
<td>180 leaks reported each day.</td>
<td>Mohanty et al. (2003)</td>
</tr>
<tr>
<td>Venezuela, Latin America</td>
<td>UFW was 70% of the water supplied by the system.</td>
<td>Bank (1996b)</td>
</tr>
<tr>
<td>Various cities</td>
<td>Average rate of UFW in developing countries estimated to range from 17% in Abidjan, Côte d'Ivoire, to 62% in Bursa, Turkey.</td>
<td>Bank (1996a)</td>
</tr>
<tr>
<td>Minsk, Belarus</td>
<td>Pipe breaks estimated at 70 breaks per 100km per year.</td>
<td>Bank (1996a)</td>
</tr>
<tr>
<td>Bogotá, Colombia</td>
<td>Pipe breaks estimated at 187 breaks per 100km per year.</td>
<td>Bank (1996a)</td>
</tr>
<tr>
<td>Middle East and North Africa</td>
<td>Average rate of UFW ranges from 15% in Dubai, UAE, to 64% in Damascus, Syria.</td>
<td>Bank (2003)</td>
</tr>
</tbody>
</table>
2.3 Water supply system

The purpose of water supply system is to treat water from source and then deliver adequate quantity of safe water at sufficient pressure to customers. In practise, WSS is a complex combination of pipes made up of various materials and size. Its size and complexity varies from one place to another. However, the WSS can be classified into two groups: water transmission system and water distribution network.

Water transmission systems consists of large diameter (>300mm) transmission pipelines, designed to transport large volumes of water over long distances, usually from treatment facilities/storage reservoirs to smaller distribution networks or another reservoir. Its length can vary from a few kilometers to several hundred kilometers depending upon the area. The transmission pipes are required to have high strength, so these are mostly made of either ductile iron, steel, mild steel cement-lined (MSCL), prestressed concrete cylinder pipes (PCCP) or asbestos cement (AC). Cast iron is the dominating material for WSS transmission pipe, till 1970s.

Water distribution networks (WDNs) are an intermediate step to deliver water transported via transmission lines to customers, such as residential or industrial. WDNs are much more complex than water transmission systems and are built up of distribution mains and service pipes.

Distribution mains are used to transport water from transmission pipes to service pipes which are further connected to end customers. Distribution mains are mostly built of ductile iron, asbestos cement, polyvinyl chloride (PVC) and MDPE pipes with diameters less than 300mm. Service pipes are the smallest diameter (less than 50mm) pipes in WDNs, used to transport water from distribution mains to customers. These are mostly built up of steel, plastic (PVC and MDPE) and lead. For example, Weimer (2001) mentioned that 43% of service pipe in Germany are plastic, 36% are made out of steel and lead constitutes 8% of the service pipes.

In general, the most widely used materials for WSS pipes are cast iron, ductile iron, asbestos cement, steel, glass reinforced plastic (GRP), polyvinyl chloride, polyethylene (LDPE/MDPE/HDPE) and prestressed concrete cylinder pipes. The duration of usage of various WSS pipe materials is summarised in Table 2.2 and their comparison is done in Table 2.3. Among these, on an average, cast iron is the dominating pipe material forming 40-60% of the existing WSSs. Cast iron pipes were no longer installed after
Table 2.2: Periods for use of water pipeline construction materials (after Reed et al. (2004))

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Period of Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit cast iron</td>
<td></td>
</tr>
<tr>
<td>Spun cast iron</td>
<td></td>
</tr>
<tr>
<td>Ductile iron</td>
<td></td>
</tr>
<tr>
<td>Asbestos cement</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Glass Reinforced Plastic Pipe</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl Chloride Unplasticised (PVC-U)</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl Chloride Molecular Oriented (PVC-O)</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl Chloride Modified (PVC-A)</td>
<td></td>
</tr>
<tr>
<td>LDPE/MDPE/HDPE*</td>
<td></td>
</tr>
<tr>
<td>Pre-stressed Concrete Cyclinder Pipes</td>
<td></td>
</tr>
</tbody>
</table>

*Low/Medium/High Density Polyethylene

1970s because of their poor resistance to corrosion, high failure rates due to non-uniform wall thickness and low strength. The second most widely used material is ductile iron forming 25-30% of the whole system. Ductile iron has better resistance to corrosion, uniform wall thickness and higher strength than cast iron pipes. However, these are now depreciated because of the better non-corrosive plastic and asbestos cement pipes. Depending on the country, plastic and asbestos cement pipes can individually constitute 10-30% of the network. However in 1990s, plastic pipes were more common than AC pipes because of their better strength for all sizes than AC pipes that are comparatively weaker when used to form smaller diameter pipes. In 1970s, a new range of low, medium and high density polyethylene (LDPE/MDPE/HDPE) came on to the market. Due to the low tensile strength of LDPE and high ductility of HDPE, these are not preferred. However in recent years, MDPE is extensively used by water industries, because of several advantages over other pipe materials such as low cost, high resistance to corrosion, long life with low maintenance, ease of handling, flexibility, durability and high strength. This is the main reason why this thesis primarily focus on leak detection and location in MDPE pipes.
Table 2.3: Comparison of transmission and distribution pipe materials (after AWWA (2003))

<table>
<thead>
<tr>
<th>Material</th>
<th>Joint Type</th>
<th>Pipe Diameter (mm)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey cast iron</td>
<td>LeadBell socket &amp; spigot</td>
<td>75-1200</td>
<td>Variable wall thickness and strength. Easy to manufacture. Multi-phase material and composition. The cooling process and heat treatment during manufacturing affects its strength.</td>
<td>Non-uniform wall thickness and strength. Structurally weak, prone to corrosion, graphitisation can lead to problems with both structural integrity and water quality.</td>
</tr>
<tr>
<td>(Vertical cast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grey cast iron</td>
<td>Lead Bell socket &amp; spigot, Mechanical joints with elastomeric seal</td>
<td>75-1600</td>
<td>High strength, high density, more uniform pipe-wall thickness than above cast iron pipes. Better chemical composition and heat distribution due to spinning process.</td>
<td>Corrodes, use of graphitisation causes structural deterioration, non-uniform wall thickness but less than pit grey cast iron pipes.</td>
</tr>
<tr>
<td>(Spun cast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ductile iron</td>
<td>Push-on/Mechanical, Integrally cast joints, Bell &amp; spigot, Flanged, Flexible ball, Restrained</td>
<td>76-1625</td>
<td>Spheroidal/nodal graphite form increase strength and elongation at failure compared to previous cast iron pipes. Durable, strong, high flexural strength, good corrosion resistance, easier tapping and lighter weight than cast iron.</td>
<td>Subject to general corrosion if installed unprotected in a corrosive environment.</td>
</tr>
<tr>
<td>Steel</td>
<td>Butt welded, Mechanical sleeve coupling, Rubber gasket joints, Flanged joints, Expansion joints, Socket and spigot joints and mechanical joint systems with elastomeric seals</td>
<td>100-3048</td>
<td>Lightweight, easy to install, high tensile strength, low cost, good hydraulically when lined, adapted to locations where some soil/ground movement may occur.</td>
<td>Subject to electrolysis; external corrosion in acidic or alkaline soil; poor corrosion resistance unless properly lined, coated and wrapped; and subject to tuberculation when unlined.</td>
</tr>
<tr>
<td>Material</td>
<td>Joint Type</td>
<td>Pipe Diameter (mm)</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Asbestos cement (AC)</td>
<td>Push-fit joints with double seal arrangement, cast iron or steel couplings.</td>
<td>80-2500</td>
<td>Good flow characteristics, lightweight, easy to handle, low maintenance; can be used as an alternative to cast iron pipes.</td>
<td>Low flexural strength in small sizes when subject to impact damage; difficult to locate underground; deteriorates when used with certain aggressive soils or water.</td>
</tr>
<tr>
<td>Prestressed concrete cylinder pipe (PCCP)</td>
<td>Welded joints internally and externally applied and sealed. Flexible joint with an elastomeric seal.</td>
<td>406-3658</td>
<td>Durable with low maintenance, good corrosion resistance, good flow characteristics, O-ring joints are easy to install, high external load capacity, minimal bedding and backfill requirements.</td>
<td>Requires heavy lifting equipment for installation, may require special external protection in high chloride soil.</td>
</tr>
<tr>
<td>Polyethylene (LDPE MDPE HDPE)</td>
<td>Butt fusion, electrofusion, mechanical joints and Bell and spigot with rubber O-rings</td>
<td>16-1200</td>
<td>Easy to install &amp; handle, low cost, flexible, lowest leakage rates, long service life at low maintenance because of antioxidants, corrosion free and ability to resist extreme weather conditions.</td>
<td>Difficult to locate pipe, difficult to detect and locate leaks in polyethylene pipes. Lower tensile and high ductility of LDPE &amp; HDPE. MDPE is better than LDPE and HDPE.</td>
</tr>
<tr>
<td>PVC</td>
<td>Integral socket and spigot joints with elastomeric seal. Mechanical couplings.</td>
<td>16-914</td>
<td>Lightweight, easy to install, excellent resistance to corrosion, good flow characteristics, high tensile strength and impact strength. Modern jointing systems allow considerable flexibility.</td>
<td>Difficult to locate underground, requires special care during tapping, susceptible to damage during handling, requires special care in bedding.</td>
</tr>
<tr>
<td>GRP</td>
<td>Integral socket and spigot joints with elastomeric seal. Mechanical couplings.</td>
<td>25-3600</td>
<td>Light weight, corrosion resistant, fire resistant, low roughness, low installation costs and chemical resistant which means low maintenance costs.</td>
<td>Lack of standards and limited knowledge of design and manufacture techniques, needs better quality backfill.</td>
</tr>
</tbody>
</table>
2.4 Review of leak detection and leak location techniques

The definition of leak detection and leak location is given by several researchers such as Carlson (1993); Hunaidi & Chu (1999); Hunaidi et al. (2000); Liston & Liston (1992); Smith et al. (2000); Turner (1991) and Zhang (1997). Leak detection refers to the narrowing down of a leak or leaks to a section of pipe network, while leak location is the identification of a position of a leak or leaks along a length of pipe, prior to excavation and repair. The classification of different leak detection and leak location techniques is shown in Figure 2.1.

As discussed previously (section 2.3), the focus of this thesis is to detect and locate leaks in MDPE pipes. Therefore, this section reviews all the techniques that are already in use for leak detection and leak localisation operations in MDPE pipelines and techniques that are in the stage of research and development. Depending on the application and principle of operation, these techniques/devices are divided into two groups: Discrete time inspection devices and continuous monitoring devices.

2.4.1 Discrete time inspection techniques

Discrete time inspection devices are those leak detection/leak location devices, which are used to perform planned leak inspection actions at discrete time instances to detect and locate leaks that are already present. These can be divided into three groups: traditional, acoustic and non-acoustic techniques, depending upon their function and principle of operation (Figure 2.1).

In addition to these three groups, transient based discrete time leak detection/leak location methods are also reviewed in this section. Although not commercially available, transient based approaches have attracted substantial interest from the research community.

2.4.2 Traditional/mechanical methods

In traditional leak detection methods, an experienced person walks along the pipeline looking for unusual patterns made by leaking water near the pipeline and listening to noise generated by leaking water. It entails placing a rod with a diaphragm, in contact with access points (such as hydrant or valves) of distribution network pipes to listen for leak induced vibrations and acoustic noise. The results of such leak detection methods
Figure 2.1: Review of leak detection and leak location technologies
depend on an individual’s experience and whether a leak develops before or after the inspection.

In earlier days, mechanical methods of pipe leak detection were used, which involves visual inspection of leaks. In visual inspection, a series of holes are drilled at intervals (say 1m) along the ground surface above the pipe line (Farley, 2001; Farley & Trow, 2003). As the drilled holes approach the leak location, water spurts from the holes with increased height. The location with maximum spurt height is chosen as the point to excavate. This method though very old; however, is still used when other methods, based on instrument readings such as GPR and correlators, fail. This method is independent of the material of pipe so it can be used in MDPE pipes. However in recent years, drilling holes and visual inspection are no longer preferred and rarely used because of the intensive labour involved.

2.4.3 Acoustic devices

Water leaking from a pipe produces both acoustic noise and mechanical vibrations, which are commonly called leak signals. These leak signals travel for long distances in the pipe wall and water column inside the pipe. However, due to high attenuation with distance in soil, they travel comparatively shorter distances through the soil surrounding the leak. Acoustic devices such as listening sticks and correlators can detect these leak signals and subsequently several signal processing techniques such as correlation and coherence can be applied to gain information about the location of leak. Several researchers such as Gao et al. (2004); Hough (1988); Hunaidi et al. (1999, 2004); Klein (1993); Kurmer et al. (1993); Turner (1991) and Zhang (1997) found it easier, more economical and more efficient to detect leaks using acoustic devices in comparison to chemical testing and visual devices (See section 2.4.4 for details).

Acoustic devices detect these leak signals either by putting invasive hydrophone sensors inside the pipe or by connecting non-invasive accelerometer sensors to pipe access points such as a hydrant. Based on the type of sensors, acoustic leak detection devices can be broadly classified into two categories:

- **In-Pipe acoustic devices**: In these devices, hydrophone sensor is inserted inside the pipe to detect leak signals. At present, the Sahara leak detection and location
system is the only commercial in-pipe acoustic device available. It is discussed later in section 2.4.3.5.

- **Outside pipe acoustics devices**: Using these devices, leak signals are detected by connecting a non-invasive accelerometer/vibration sensors to access points such as hydrants and valves; or sometimes directly to the pipe surface if accessible. The most common outside pipe leak detection acoustic devices are:
  
  - Listening stick
  - Ground microphone
  - Leak noise loggers
  - Correlators

### 2.4.3.1 Listening stick

Listening for leaks has been popular since 1850s (Pilcher, 2003). The technique relies on using mechanical or electronic acoustic devices such as listening sticks and ground microphones that are sensitive to leak induced acoustic noise or vibrations.

Listening sticks are of two types: mechanical listening sticks (Figure 2.2(a)) and electronic listening sticks (Figure 2.2(b)). A mechanical listening stick, commonly called as basic listening stick, is made up of a steel bar (Figure 2.2(a)) which transmits the leak induced vibrations from the access point, such as hydrant, to a brass diaphragm within a resonance cavity. These vibration signals are amplified mechanically in the acoustic resonance chamber before passing to a diaphragm. The diaphragm converts these into audible signals. An electronic listening stick is a rather rudimentary acoustic device, based on a piezoelectric transducer. It detects the mechanical vibrations produced by a leak and converts these into electrical signals which are amplified and fed to a loudspeaker or headphones. It also incorporates an in-built noise filter to remove unwanted background noise.

Listening sticks are simple to use. The leak inspector walks along the pipeline and listens to the leak signals at various access points along the pipeline. The louder the noise, the nearer is the leak. However, leaks can make different sounds depending on pipe material, soil composition, leak size and leak shape. Smaller leaks under high pressure usually make louder noises than larger leaks under low pressure. In some
cases, large leaks under low pressure make almost no sound causing them to be very difficult to locate. Sounds can be misleading and are sometimes very confusing as these can also be produced by other sources, such as customer use (water offtake) and traffic. The efficiency and precision of listening sticks completely depends upon the individuals experience, as it gives no visual or alarm indication in the presence of leak. It depends upon the user whether he or she can differentiate between the noise produced by normal running conditions of a pipe and the noise produced by a leak.

2.4.3.2 Ground microphone

The principle of a ground microphone is similar to a listening stick, but in this case the sensor is in direct contact with the surrounding ground rather than the WSS itself. Leak detection using ground microphones involves placing the microphone on the ground at intervals along the pipe and observing changes in the loudness of sound as the microphone approaches the leak position. The ground microphone can be assembled for use in either contact mode or survey mode (Figure 2.3). The contact mode is for sounding on fittings, while the survey mode is used to locate leaks on shorter lengths of pipeline. Like listening sticks, the performance of ground microphones also depends upon an individuals experience. However, ground microphones give better sensitivity than listening sticks and can detect weak leak signals directly above on the ground surface and do not always require access points for connection.

The effectiveness of listening sticks and ground microphones (especially in MDPE pipes) depends upon several factors (Chastain-Howley, 2005). Leak signals attenuate with distance so the distance of the monitoring point from the leak position significantly
affects the precision of listening sticks and ground microphones. The noise attenuation rates in different soil types and in PVC pipes are discussed by Hunaidi & Chu (1999). However, the attenuation rate in MDPE pipes is still unknown. Hunaidi & Chu (1999) mentioned that acoustic leak detection using listening sticks and ground microphones is more efficient when listening is done on pipe fittings such as valves and hydrant. However, closely spaced fittings are not always found in WSS so leak detection using listening sometimes becomes difficult. Finally, the noise from traffic, water flow as well as the depth of survey influences the performance of leak detection and location using listening.

2.4.3.3 Leak noise loggers

Leak noise loggers typically make use of the piezoelectric accelerometers to detect the leak signals and a programmable logger to record the data (Hunaidi et al., 2004). Unlike listening sticks, loggers can be permanently or temporarily deployed to access points using magnetic mountings. In practise, loggers are deployed in groups on adjacent pipe access points such as fire hydrants and valves, usually 200m to 500m apart in
most WDNs. Loggers are usually programmed to record the acoustic noise\(^1\) at one second intervals for two hours during the night (usually between 2am and 4am), when background noise and customer use is likely to be a minimum. The amplitude (or loudness) of acoustic noise varies due to random effects, however if a leak exists then there will be a consistent minimum noise that is always present within the recorded time. The recorded data is either downloaded to a personnel computer or simultaneously transmitted to the operator site for further analysis. The logged data is analysed statistically, i.e. the frequency and amplitude of noise is compared at different locations to determine the presence of leaks. Unlike listening sticks, loggers give alarms and can record noise. Loggers are generally used to leak survey large areas, but they are not suitable for locating individual leaks.

However, the economic viability and leak detection effectiveness of temporarily or permanently deployed noise loggers is questionable. Vander-Kleij & Stephenson (2002) found from their experimental studies that both permanently and temporarily deployed loggers are not an economical alternative to skilled and well equipped leak inspectors. Vander-Kleij & Stephenson (2002) reported that for a typical network wide coverage, temporary mode loggers were found less than one-third efficient than acoustic surveys and for a similar number of surveys the permanently installed loggers failed to detect approximately 40% of leaks found in detailed listening surveys.

2.4.3.4 Leak noise correlator

Leak noise correlator (LNC) is the most sophisticated acoustic leak detection and leak location instrument (Fantozzi & Fontana, 2000; Hunaidi et al., 2000; Pudar & Liggett, 1992). It depends upon the speed of the sound instead of the loudness (decibel) of noise made by leak signals traveling along the pipe wall.

LNC equipment is based on the principle of cross-correlation of leak signals obtained from two sensors connected to access points such as fire hydrant and valve along the pipeline under survey, and shows a distinct peak if any leak exits. The location of this peak is used to determine the time delay between signals obtained from two sensors and hence the location of a leak. It is discussed in Chapter 3.

\(^1\)Acoustic noise refers to the noise produced inside a pipe. It can be the noise produced by pipes running under normal conditions or by leaks inside pipes or a combination of both.
Chapter 2: Literature Review

Like other acoustic devices discussed above, the efficiency and precision of correlators is highly influenced by background noise, pipe characteristics, sensors and distance of sensors position from leak. Another issue regarding the performance and accuracy of correlators is the sharpness and clarity of the correlation peak obtained for a leak. In practise, pipe network consist of a number of discontinuities such as bends, pipe section with different diameters and materials. This significantly effects the frequency characteristics of leak signals and may degrade the signals. These leak signals can be separated to some extent from unwanted signals/background noise by using filters. However, due to poor knowledge about the characteristics of leak signals, especially in MDPE pipes and large diameter pipes (all materials), it is difficult to choose appropriate filter cut-off frequencies and the selection of signal acquisition sensors.

However, despite these problems, several researchers and water industry professionals, such as Hunaidi et al. (1999, 2004) and Liston & Liston (1992) found correlators useful for both leak detection and leak location. For example, Hunaidi et al. (1999) found that correlators are very efficient in determining leak location with less than 1.0m accuracy in most sizes of cast iron, steel or asbestos cement pipe and can survey up to 500m using non-intrusive sensing devices (accelerometers) and up to 600m by intrusive sensing devices (hydrophones) in one time (Gao et al., 2005). However, due to high attenuation with distance of leak signals in plastic pipes (PVC or MDPE) and large diameter pipes, the effective range of correlators reduces to 50m when accelerometers were used and 120m when hydrophones were used.

Hunaidi & Wang (2000) reported the performance and precision of a commercial correlation based leak detection system, LeakfinderRT, developed by National Research Council (NRC), Canada and Echologics Engineering Inc¹. The authors indicated that Leakfinder incorporates an enhanced cross-correlation function² to determine the time delay between the two leak signals. Hunaidi & Wang (2000) found that for narrow-band leak noise, an enhanced correlation function improves the definition of correlation peaks and does not require filtering of leak signals as in traditional cross-correlation. This is important for plastic pipes, large diameter pipes, multiple-leak situations and in settings where leak sensors have to be closely spaced and for situations of high

¹www.echologics.com

²In the enhanced cross-correlation function, correlation of two signals is calculated using Fast Fourier Transform and it does not require filtering of leak signals as in traditional cross-correlation.
background noise. The authors claimed that LeakfinderRT can detect leaks as small as 0.85 l/min and 1.7 l/min using hydrophones and vibration sensors\(^1\) respectively, in plastic PVC pipes over a typical sensor spacing of 100 m. For metallic pipes, it is reported that it can locate leaks with spacing between sensors less than 500 m using low frequency vibration sensors.

However, Divit (2005), a water professional, found it not able to detect leaks in 125 mm MDPE pipes over distances more than 45 m. Also like existing correlators, it calculates the propagation velocity of leak signals using theoretical formula and has no provision to calculate it at the survey site. Thus, the application of correlators in MDPE pipes over longer distances is still questionable.

### 2.4.3.5 In-pipe acoustic technologies

In-pipe acoustic technologies refer to those leak detection and leak location techniques/devices in which the sensor is inserted inside the pipe.

According to Chastain-Howley (2005), the Sahara leak detection and location system developed by the Water Research Centre, UK is the only in-pipe technology currently available. The development and deployment of Sahara system is described by Bond et al. (2004).

Bond et al. (2004) reported that Sahara is designed to find leaks in 50 mm or above diameter WSS pipes of any material. The principle of operation is that a combined sensor (hydrophone with head unit size less than 25 mm) and tracking device are connected to a computer by a Kevlar covered umbilical (Figure 2.4). The sensor along with the umbilical is chlorinated\(^2\) and then inserted into the pipe at any tap point 50 mm or larger in diameter, while the pipeline remains in service. The sensor travels along with the flow by means of a drogue (parachute). As the sensor passes any leak, it detects the acoustic signals generated by leaks and gives an indication to the operator. Leak position is determined by a built in tracing device known as PipeSpy 2000. Sahara's umbilical can accommodate up to 135° of pipeline bends per survey.

Bond et al. (2004) claimed that Sahara possesses the capability to detect leaks as small as 1.0 l/hr in large diameter pipes (>250 mm diameter) of any material. Over

\(^1\)Vibration sensors are piezo-electric accelerometers with an in-built preamplifier and pull base magnetic mounting.

\(^2\)Chlorination is done for Health & Safety reasons. Chlorination is necessary to sterilize the equipment prior to insertion into a potable water supply.
1,000 individual surveys of large diameter water transmission mains have already been performed in which an average water loss of 134,000 l/day/km was eliminated and a maximum length of up to 2000m was surveyed in one pass using Sahara.

Sahara was tested by Severn Trent Water Company, UK (Divit, 2005) and the performance report about the system is as follows:

### 2.4.3.6 Review of Sahara – Severn Trent survey

One of the main operational conditions of Sahara is that it requires an insertion point of a minimum 50mm diameter inorder to insert the sensor. Severn Trent started the survey work on 31\textsuperscript{st} January 2004, on the first new insertion point at Lincoln Close, Tewkesbury (Divit, 2005). By 13\textsuperscript{th} May 2005, 19 points had been completed and 17 surveys conducted, giving a total of 16km of mains surveyed. The cost was in the order of£111,000 (£6,937 per kilometre), of which 76\% was incurred in enabling works and is the highest cost of any trunk main leak detection method used to date. According to Severn Trent expertise Divit (2005), this high cost is due to the installation of new insertion points.

Divit (2005) mentioned that for the effective use of Sahara, background information about the pipeline and the area to be surveyed is required. The author mentioned that water velocity is critical to the success of Sahara. If the water pressure or velocity is too high then this makes it difficult to retrieve the drogue thus limiting the distance which can be surveyed. On the other hand, if the pressure or velocity of water is low then there will be insufficient pull on the drogue to allow a reasonable distance to be surveyed. Any deviation in direction (greater than 135\textdegree) will cause friction on the cable.
and reduce survey distances dramatically. Similarly, acute bends in the pipe work are unlikely to be traversed. The maximum distance surveyed by Severn Trent in a single survey was 2006m at 1.15m/sec velocity with no deviation in the pipe and the shortest was 360m. In general, Divit (2005) recommended a distance of 800m for a straight pipeline in real world conditions. The final conclusion for the use of Sahara indicates the following:

- Sahara is not likely to be cost effective if used to survey large systems where many new insertion points are required.
- Where a system is suspected to have many small leaks which alone would not be effective to repair, Sahara could provide solid evidence of the need to replace a critical asset.
- Sahara can accurately indicate pipeline location and can detect leaks effectively when a number of pipelines are running parallel and close to each other under the ground.
- Sahara cannot be used in pipes less than 50mm in diameter and those running at very low or high pressures.

2.4.3.7 SmartBall

SmartBall, developed by Pure Technologies, uses the acoustic noise generated by leaking pipes for the purpose of leak detection and location in water distribution pipes (Fletcher, 2008). It is spherical (Figure 2.5(a)) in shape and is smaller than the pipe bore, which allows it to roll silently through the pipeline and detect quiet leaks. Its principle of operation is shown in Figure 2.5(b). It consists of a foam ball in which an aluminium core of 65 mm diameter is placed. This aluminium core contains the acoustic sensor called free swimming acoustic sensor, data acquisition system, power supply and others instruments. SmartBall uses only a single acoustic sensor that is deployed inside the pipeline, in comparison to traditional acoustic devices which employs two or more sensors. When deployed in pipe, the SmartBall passes through the pipe under survey and record the acoustic noise, which can be later post-processed to determine the presence and location of leaks. Leaks are detected by a combination of increased acoustic power and a characteristic frequency spectrum. The location of leak
relative to receiver positions is calculated by analysing the arrival times of the acoustic pulses emitted by the ball at receivers attached to pipe appurtenances. SmartBall is claimed to run up to 17 hours in a single deployment, which made it able to survey many kilometres of pipeline. For example, at a water flow rate of 0.5 m/s, the ball can travel almost 25 km in a single deployment. Its major advantage is that its principle of operation is independent of the material of pipes; however, it can only be used in pipes with diameter greater than 110mm. For its proper functioning and deployment, its size is usually restricted to less than one-third the diameter of the pipeline. Another advantage is that it requires only two access points, one for insertion and other for extraction for survey the entire pipe lengths and can be inserted and retrieved from a pipeline under normal operations. It can be used in MDPE pipes; however, it cannot be efficiently used in pipes with diameter less than 125mm and those operating at higher pressures, so it is not preferred in water industry.

![SmartBall internal view and principle of operation](image)

Figure 2.5: (a) SmartBall’s internal view and (b) its principle of operation (Fletcher, 2008).

The acoustic leak detection also requires that the background noise be as low as possible and that means that the ball needs to roll relatively silently through the pipe. Therefore, a resilient elastomeric coating is placed around the ball to control the noise from rolling. However, the noise of nearby pumps and other apparatus generates significant background noise, which can make leak signal analysis difficult. Another disadvantage of SmartBall is that it is not able to determine the leak size and it is extremely difficult to accurately track its position in pipe.
2.4.4 Non-acoustics methods

Non-acoustics methods can be classified into two groups:

- Underground imaging devices
  - Infrared thermography
  - Ground penetrating radar
- Chemical leak detection methods
  - Fluoride testing
  - Tracer gas

2.4.5 Underground imaging devices

Underground imaging devices detect leaks by identifying changes in properties, such as temperature, of soil in the immediate surroundings of a leak in comparison to the soil far away from a leak. The two underground imaging leak detection devices are infrared thermography and ground penetrating radar.

2.4.5.1 Infrared thermography

The infrared thermography method of locating leaks is based on the assumption that the water leaking from a pipe affects the thermal characteristics of the surrounding soil (Weigle, 2007; Weil, 1993; Weil & Graf, 1991). Soil in the immediate vicinity of a leak becomes saturated with leaking water, which makes it a more effective heat sink in comparison to the dry soil away from the leak. During the day time, thermal energy is stored in this water saturated soil which is released during the night time and is believed to be a major contributor to the warming of ground surface near a leak position. This temperature difference is reflected as a change in the infrared images (IR) and the leak can be detected as a warm spot in the visible IR images. Several case studies are reported in Weil & Graf (1991), which indicate the potential of this method to detect leaks in pipes. This method of leak detection can be used from moving vehicles, helicopters or portable systems and is able to survey hundreds of miles of pipeline per day. The recent development of advanced wide area temperature sensors, multi-temperature sensor electrical cable and optical time domain reflectometry using
fiber optics has made the infrared thermography technique even more promising for detecting leaks.

However, this method has several limitations such as the most appropriate survey time (day or night), effect of season, surface conditions of the test area, solar radiation and ambient conditions such as thermal noise in urban settings, cloud cover, wind speed and relative humidity. The major disadvantage of this method is that it is incapable of detecting leaks in regions where nearby soil is saturated with ground water or where a pipe passes through a large volume of water such as a lake. This method also requires expensive equipment and trained personnel to operate. However, in some situations it may be the most appropriate method such as where there are few access points, where the terrain is difficult and other circumstances where acoustic methods are impractical.

2.4.5.2 Ground penetrating radar

The application of ground penetrating radar (GPR) for leak detection has been given considerable attention during the last few years such as Graf (1990); Hunaidi (1998); Hyun et al. (2003); Smith et al. (2000); Stampolidis et al. (2003) and Nakhkash & Mahmood-Zadeh (2004).

GPR works in a similar fashion to seismic and ultrasound techniques. A transmitting antenna sends a short duration pulse of high-frequency electromagnetic energy into the ground. The pulse is partially reflected back to the ground surface by buried objects, pipes, voids in the ground or by boundaries between soil layers with different dielectric properties. Reflected radar signals are captured by a receiving antenna and the ground interior is scanned with radar waves in a similar manner to ultrasound to obtain cross-sectional images (Figure 2.6). The time lag between the transmitted and reflected waves corresponds to the depth of the reflecting object such as pipes and voids.

At leak position, soil surrounding the leak becomes saturated with leaking water which changes its dielectric properties. For some leaks, voids may form near the leak position depending upon the leak flow rate, leak size and soil properties. This water saturated soil and voids slows down the radar signals and makes the water pipe appear deeper in the visual display of GPR, than it should be. GPR detects leaks either by (a) identifying voids created by leaks in the soil surrounding the pipe, or (b) by detecting pipe sections that appears to be deeper than they actually are. Hunaidi & Giamou (1998) and Divit (2005) report some leak detection surveys using the pulse
radar system (Figure 2.6) and found it very useful for leak detection, especially for longer lengths of pipe with few access points. However, its main disadvantage is that it is very expensive and time consuming to operate and requires the detailed knowledge of the layout of pipes to be surveyed.

It is also incapable of detecting leaks in pipes passing through a large volume of water such as lakes, where the pipe is buried deep (e.g. hilly areas) or where it is not possible to position the GPR. The major advantage of IR and GPR is that they are independent of the physical properties such as material of the pipe, which makes them more effective and promising than acoustic correlators. However, they are highly dependent upon the layout of the pipe. Cist & Schutz (2001) mentioned that GPR can also be used to detect non-metallic pipes in some soils, but not in situations where the pipe is buried deep. As non-acoustic methods are independent of pipe material, so these are suitable for detecting leaks in MDPE pipes. However, because of their high cost of operation these are not commonly used.

2.4.6 Chemical leak detection methods

Chemical leak detection methods are based on the principle that if chemicals are inserted into the pipeline under testing, then they will come out with leaking water and reach to the ground surface which can then be tested further for the presence of these chemicals. There are two types of the chemical leak detection methods:

- Fluoride testing
- Gas injection (Tracer gas)
2.4.6.1 Fluoride testing

Fluoride testing is used in areas where there is a presence of substantial amounts of water from other sources such as agricultural irrigation or lake and the leaking water needs to be distinguished from other water (Farley, 2001; Smith et al., 2000). In order to do so fluorides are passed into the pipe and if there is a leak in a pipe then it comes out of the leak and mixes with the surface water which is then tested further for fluorides. If the test is positive, this indicates a leak in the pipe. This method is very expensive and can only be used for leak detection and is not capable of pinpointing leak if the quantity of water in the surrounding area is large.

2.4.6.2 Gas injection (Tracer gas)

Gas injection and tracing techniques are used mainly for leaks which are difficult to locate such as leaks in low pressure water pipes and non-metallic trunk mains. The pipe is first dewatered and a non-toxic, lighter than air water insoluble tracer gas like sulphur hexafluoride (SF₆) or industrial hydrogen (95% nitrogen, 5% hydrogen) is pressurised into the pipeline (Heim, 1979). The gas escapes through the leaks in the pipe and being lighter than air it rises to the ground surface where it can be detected with a portable gas detector. In this way, leaks can be located using this method. However, leaks can also be missed easily if the scanning for gas is not performed directly above the pipe or if the resolution of survey is too coarse. This method is preferred for use in:

- finding multiple small leaks in a single section of pipe.
- finding leaks in service pipes which are relatively close to the surface and which may contain unexpected loops or bends making accurate correlation difficult.

Because of the special equipment needed to inject and trace the gas, it is much more challenging to use than GPR and IR techniques. However, hydrogen gas is much easier to detect than SF₆ gas (Sensistor, 1997). It is because SF₆ needs bore holes to be made in the ground at intervals along the line of pipe to allow the gas to be collected and traced. Another disadvantage of this method is that the pipe needs to be de-watered before the test. Its wide application for leak inspection in pipelines is prohibited by the high cost of operation.
2.4.7 Transient based methods

In addition to the acoustic or non-acoustic methods discussed above, new approaches based on transient/waterhammer analysis are slowly emerging from research. These methodologies are still in their infancy and under testing; however, researchers are hoping these methodologies could provide a solution to detecting water loss in the future.

The transient leak detection methods are based on extracting information about the presence of leaks from a measured transient event. A safe artificial transient event under controlled conditions can be introduced in the water distribution network by either opening/closing a fire hydrant/valve; by starting up/shutting down a pump or by using special devices such as solenoid side discharge valves. The generated transient wave travels both upstream and downstream along the pipeline. The pressure is then measured at a number of locations in the network during the transient event, and is then further analysed to gain information about leaks. The various methods of analysing these measured signals are:

- **Leak reflection method**: The leak reflection method is based on measuring and analysing the transient waves reflected by a leak (Brunone, 1999; Brunone & Ferrante, 2001; Jonsson & Larson, 1992).

  Brunone (1999) found that leaks partially reflect the transient wave. The reflected wave can be seen when it arrives back at the section where the pressure wave is measured. The magnitude of the reflected wave depends on the ratio of the magnitude of the generated transient wave and the size of the leak orifice. It also depends upon its distance from leak position. A bigger sized leak produces a larger amplitude reflected wave. The location of a leak is calculated using the time difference between the incident transient wave and the measured reflected wave. This method gives the best results for leak detection if a large, sharp transient wave is used. However in practise, it is extremely difficult to detect the changes in the measured pressure caused by leak reflection; therefore, the application of leak reflection method in real pipe networks is still under development.

- **Inverse transient analysis**: Leak detection using inverse transient analysis (ITA) was first proposed by Liggett & Chan (1994). Since then, it has been
subject to intensive research by a number of research groups such as Covas et al. (2001); Kapelan et al. (2003); Vitkovský et al. (2000) and Stephens et al. (2004). In this method, a transient simulation model of the network is made and calibrated for the unknown effective nodal leak areas by comparing the model predicted pressures with the actual pressure measurements taken.

It uses least squares regression between modelled and measured transient pressure traces. The leak is modelled at discrete positions (usually nodes) in the network and the minimisation of the deviation between the measured and calculated pressures using the simulated model, gives a solution of leak location and size. The challenge for applying ITA is the accurate modelling of the transients and boundary conditions of the pipe system.

- Transient damping method: Wang et al. (2002) reported that leaks in a pipeline contribute to the damping of transient waves, which can be expressed in terms of Fourier series. All the Fourier components are damped uniformly by steady pipe friction; however, in the presence of a leak each component is damped differently. Leaks can be detected by comparing the frequency response of measured pressure containing the leak induced damping with the frequency response of the calculated pressure values for the same pipeline without a leak.

The magnitude of damping indicates the size of leak, whereas different damping ratios of the various Fourier components can be used to find the location of a leak. The rate of the leak induced damping depends on the leak characteristics, pressure in the pipe, location of the transient generation and pressure measurement point and the shape of the generated transient. In real situations, leaks and friction are not the only factors causing transient damping. Other physical elements such as joints, connections, fire hydrants and pipe wall can cause transient damping. The transient modelling of some of these elements is very complicated, which makes it difficult to accurately calculate the leak-free damping for a real pipeline.

- Frequency domain analysis: The frequency domain analysis method (Ferrante & Brunone, 2003a,b; Lee et al., 2005) is based on analysing the time domain characteristics of transient wave response in the frequency domain. The frequency response of transient waves travelling in a pipeline with a leak has additional high
amplitude peaks that are either low or do not exist in the frequency response of pipelines with no leaks. The presence of a leak can be detected by comparing the dominant frequencies of the transient frequency response of no leak and leaking pipelines. The performance of this method is strongly influenced by the shape of the transient wave and the location at which it is measured.

- **Impulse response analysis:** This method is based on analysing the pipeline’s response to a unit impulse input (Liou, 1998). For example, consider the opening/closing of a valve in a pipeline with a leak located at a distance $x_L$ from the valve. The movement of the valve introduces an artificial impulse down the pipeline. The impulse will be damped by steady and unsteady friction, and slightly dispersed by unsteady friction. At the leak position, a portion of the impulse is transmitted further, another into different directions while the remaining portion is reflected back. This reflected wave can be measured and if the total journey time of the leak reflected impulse (calculated using the cross-correlation techniques) is $t_L$ then the distance $(x_L)$ of leak from the valve is

$$x_L = \frac{1}{2} c_w t_L \quad (2.1)$$

where $c_w$ is the wave speed of the impulse wave. The size of a leak is determined by the magnitude of the reflected impulse. However, a similar response can be caused by pipeline discontinuities such as bends and joints, which may be difficult to identify in real practise.

The transient based methods for leak detection are only theoretical approaches and their practical validation in real pipe networks is still in progress. Therefore, these methods are not further discussed in this thesis.

### 2.4.8 Measurement based continuous leak monitoring techniques

In continuous leak monitoring techniques, the pipeline is continuously monitored whether a leak exists or not. These techniques continuously monitors the variables such as pressure and acoustic noise that can be directly related to a potential leak. A leak is indicated if there is any significant variation in these parameters. Based on different
variables such as pressure, there are several types of continuous leak monitoring techniques. However, most of them are used in the oil and gas industries. The two model based continuous leak monitoring techniques, which can be used for MDPE pipes are:

- Continuous acoustic monitoring
- District meter area (DMA) testing

2.4.8.1 Continuous acoustic monitoring

Continuous acoustic monitoring of a pipeline is done using data loggers in permanent mode (See section 2.4.3.3 for details). Data loggers are permanently installed in groups on adjacent access points (usually valves or hydrants) of the pipeline. A leak can occur anytime during monitoring. Loggers are set to switch on automatically for a fixed period at a predetermined time\(^1\). The loggers listen for and record the noise generated within the pipeline during this period. The noise is either produced by normal running conditions of the pipe or by leaks in the pipe or a combination of both. This noise is further analysed by comparing sound levels and sound spreads (frequency response) recorded at each logger. The proximity to a leak is typically represented by a continuous high noise (decibel) level and narrow noise spread.

Sanchez et al. (2005), presented the results of a pilot study of a permanent acoustic monitoring system. A total of 75km of distribution mains in three different areas in the autonomous region of Madrid, Spain were monitored using data loggers connected with a SCADA system\(^2\). The study was conducted over a period of six months and a total of 49 leaks were detected (excluding leaks that were already present in the network at the time of installation of the monitoring system). The cost benefit analysis performed in the study indicated that the high installation cost of permanent acoustic loggers can be justified if the number of leaks/bursts in the network is higher than 20 bursts per 100 km per year. In other words, continuous acoustic monitoring is beneficial in systems that have a high deterioration level. Therefore, it is not a cost effective method for use in non-corrosive MDPE pipes with a low deterioration level.

\(^1\)Most of the UK water industry records between 2:00 to 4:00am because of low background noise level and less customer use.

\(^2\)SCADA is the abbreviation for Supervisory Control And Data Acquisition system.
2.4.8.2 District meter areas testing

District meter areas (DMA) are well defined smaller parts of WDNs, that each can be supplied through a single pipe. The boundaries of a DMA\(^1\) can sometimes occur naturally (e.g. in small areas such as a village) but mostly these are created by closing appropriate valves. The most common technique practised by water companies for identifying leakage in a DMA is to conduct a water audit. Water audits\(^2\) account for all the water flowing into and out of a DMA. Any significant difference (between the volume of water flowing into and out of a DMA per unit time) above a threshold, set by the water companies, indicates the presence of one or more leaks. In practise, DMA testing is regularly done so as to monitor the DMA and to minimize further testing in an area to a smaller pipe network or a section of pipe if leakage is suspected. The techniques used to conduct leak detection surveys in a DMA are:

- **DMA testing by internal valving:** DMA testing by internal valving is carried out by sub-dividing a DMA into smaller areas by closing appropriate valves. The flow rate of each sub-area is monitored and compared at the end of the test period with the sequence of sub-division of the DMA. Any variation in flow rate indicates the probability of a leak.

- **DMA testing by metering:** In this method, meters (Farley, 2001; Smith *et al.*, 2000) are installed on the internal boundary to create two DMAs, one cascading into another. These meters are read normally unless DMA monitoring shows an increase in night flow, i.e. indicating the probability of a leak. This method is used for small sized DMAs (usually between 300-1000 properties).

- **Step testing:** Step testing involves designing step test areas in a DMA to identify sections of pipe with a probability of a leak. A flow meter is installed on the input main to each area (Farley, 2001; Smith *et al.*, 2000). Its principle is to systematically reduce the size of area by closing valves on each section of pipe, in turn, at the same time noting changes in flow rate at the meter. If there is a

\(^1\)Usually the area of a DMA is between 500 to 3000 properties; however, it may change depending upon the location.

\(^2\)Guidelines for conducting water audits have been published by the American Water Works Association (AWWA, 1999) and International Water Association (IWA, 2000).
large drop in flow rate then it indicates a leak in the section of pipe that has just been closed.

Step-test areas are generally small (500-1000 properties), so that there are less chances of pipe bursting in weaker and smaller pipes due to the change in pressure during the valves closing and opening actions. Step testing is no longer a popular technique as it requires expensive overtime working and regulatory requirements i.e. companies have to warn customers of their planned work in advance, which is time consuming and expensive and may cause bursts on weak mains.

- **Leakage monitoring using minimum night flow:** DMAs can be continuously monitored by measuring the minimum night flow on continual basis using SCADA system (Farley, 2001). The *minimum night flow rate* refers to the sum of flow rate of water used by all the night time users in the area and the unavoidable leakage rate (AWWA, 1987; Runophon, 2006). Leakage is suspected if the minimum night flow rate becomes greater than a previously measured level or if it exceeds a certain threshold set by the water companies. For example, the *Runoplot* leak detection system uses the minimum night flow rate and Archimedes principle to detect leaks in pipes (Runophon, 2006).

### 2.5 Comparison of leak detection and leak location techniques

The advantages and disadvantages of the leak detection and leak location techniques discussed above are summarised in Table 2.4. It is extremely difficult to find one suitable leak detection and location technique that can work in all case for MDPE pipes. A number of aspects are considered to make conclusions regarding the performance of a particular method. Some of the key attributes are:

- **False alarm rate:** False alarms refers to the ‘leak indication’ given by leak detection devices in the absence of leaks. These false alarms generate extra work and reduce the confidence operators have in a system. For example, water professionals such as Divit (2005) found that acoustic devices have comparatively higher false alarm rates when used in non-metallic pipes. GPR and fluoride testing gives comparatively less false alarms than acoustic devices; however, the false
alarm rate of infrared thermography and tracing gas techniques can reach to a very high value in some situations.

- **Sensitivity**: Sensitivity of leak detection devices depends upon their principle of operation. Sensitivity of acoustic devices depends upon their ability to detect quiet leaks, while the sensitivity of non-acoustic methods depends upon their ability to detect the smallest possible volumes of leaking water. The sensitivity of acoustic devices is highly influenced by the presence of background noise. The sensitivity of GPR and thermography is highly influenced by the type of soil and depth of burial of pipe. In general, for metallic pipes acoustic devices have much higher sensitivity; however, for non-metallic pipes visual devices and chemical devices are more sensitive than acoustic devices at present.

- **Precision**: Precision of the leak location devices is calculated in terms of how closely they can locate position of leaks. Of all the techniques discussed above, correlators, Sahara and GPR are the highly precise leak location devices and can locate leaks within 1m accuracy in most sizes and materials of pipe.

- **Cost**: Cost is one of the most important factor in selecting the leak detection and leak location equipment (AWWA, 1987, 2003). There are two types of costs associated: cost of equipment and the cost associated with its operation/usage in detecting and locating leaks. Basic listening sticks are the cheapest equipment, while the infrared thermography is the most expensive equipment. Sahara, infrared thermography, tracer gas and loggers in permanent mode are the most expensive to use. Correlators, ground microphones and loggers in temporary mode are intermediate both in terms of cost of equipment and operation.

- **Leak detection and leak location flexibility**: It is extremely beneficial if one type of equipment can be used for both leak detection and leak location. Correlators, Sahara, listening stick and GPR can be used for both leak detection and leak location. However, listening stick and GPR are very time consuming when used for leak detection and Sahara is very expensive if used for locating leaks in smaller pipe sections.
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- **Pipe and backfill characteristics**: There is no leak detection and leak location equipment available which can be used effectively without any restrictions of pipe characteristics such as material, size and depth of burial, and backfill soil type.

- **Health and safety**: Ideally, leak detection and leak location system should not have any health and safety issues. However, Sahara sensor and cable needs chlorination and chemical testing requires high quality chemicals in order to comply with water quality health and safety standards.

- **Physical work involved**: Mechanical methods are not preferred because of intensive physical work involved. It requires holes to be drilled in the ground which are not preferred. Similarly, chemical testing needs chemicals to be inserted into the pipeline and Sahara needs insertion points larger than 50mm diameter to insert a sensor inside the pipe. This requires significant physical work that can be very expensive, so these methods are not preferred.

- **Operational time**: Operational time refers to the time required to survey a unit length of pipeline. Out of pipe acoustic devices, GPR and Infrared thermography are much faster to use in comparison to Sahara and chemical testing. However, once installed Sahara can survey long distances in one process. Correlators are the most efficient methods in terms of operational time.

- **Discrete time and continuous mode**: It is very important that a leak detection and location device can be used as both discrete time inspection device and for continuous monitoring without disturbing normal pipe operation. As discussed above, only data loggers can be used for leak detection in both modes. However, the practical validation of correlators in continuous mode is still under trial.

Based on the discussion above, it can be determined that none of the existing technologies and devices offer good performance for all the applications. However, correlators and leak noise loggers are found to be satisfactory for most of the above mentioned points and thus can provide a solution for the problem of leak detection and location in MDPE pipes. But leak noise loggers can only be used as leak detection; therefore, correlator is the best equipment that can be used for both leak detection
and leak location in MDPE pipes. However, for its effective use in MDPE pipes certain parameters such as cut-off frequency of filters needs an optimisation. These parameters are discussed further in detail in this thesis.

2.6 Summary

In summary, MDPE pipes are increasingly being used in WSS in recent years, because of their advantages over existing pipes such as ductile iron and asbestos cement. However, due to poor knowledge about the characteristics of leak signals in MDPE pipes, it is difficult to detect and locate leaks in MDPE pipes.

A comparison of various leak detection and leak location techniques is presented and it is concluded that correlators are the most suitable methods for detecting and locating leaks in MDPE pipes. Other methods such as visual devices, chemical testing and Sahara can also be used but at the expense of additional cost and intensive physical work involved. However, for the effective use of correlators in MDPE pipes, certain parameters such as filter cut-off frequencies and hardware components such as sensors and wireless transreceiver system need an optimisation.
<table>
<thead>
<tr>
<th>Equipment or Method</th>
<th>Leak Detection or Location (LD/LL)</th>
<th>False Alarm</th>
<th>Comments and Application</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>LL</td>
<td>Low</td>
<td>No instrument readings so low false alarms. Simple to use. Holes are drilled in ground, which allow a release path for water. Holes with maximum spurt height is chosen as the leak position. Used as a backup method to support leak detection methods.</td>
<td>• Requires significant physical effort. • Can cause serious damages while drilling in areas where number of other pipelines are running in parallel. • Exact pipe location must be known. • Not suitable for large pipelines under high pressure.</td>
</tr>
<tr>
<td>Basic Listening Stick (BLS)</td>
<td>Both</td>
<td>Medium, High in non-metallic pipes</td>
<td>Cheap &amp; simple to use. The metal rod transmits the leak-induced signals from pipe fittings to diaphragm. The louder the noise the nearer is leak. Works best with hard surface and pipe fittings especially dry barrel type hydrant. Widely used in Blanket surveys and can detect leaks in most pipes.</td>
<td>• Exact pipe location must be known. • Its precision depends upon individual’s experience. • Not suitable in loose soil and high background noise. • Limited to depth less than 2 m. • Not suitable to detect smaller leak sounds in plastic and large diameter pipes and leaks under low pressure.</td>
</tr>
<tr>
<td>Electronic Listening Stick (ELS)</td>
<td>Both</td>
<td>Medium less than BLS</td>
<td>Better sensitivity than ‘Basic’ listening stick because of sound amplification and filtering unwanted background noise. Used to confirm ‘best leak sound’ position after correlation.</td>
<td>• Better than ‘Basic’ listening stick but not as good as ground microphone. • Low precision and efficiency in plastic &amp; MDPE pipes. • Unable to detect small and large leaks under low pressure.</td>
</tr>
<tr>
<td>Ground Microphone with/without filters (GM)</td>
<td>LL</td>
<td>Medium, High in grassy areas</td>
<td>More sensitive than ELS, powerful enough to listen leak sounds through ‘roadways’ and quiet leaks under low pressure. Can be used for general sounding with a probe screwed into microphone. Filters can be used to remove unwanted sounds.</td>
<td>• More ‘cumbersome’ to use than listening stick, especially when used with microphones. • Not suitable for leak detection in Blanket surveys. • Not able to record leak sounds.</td>
</tr>
<tr>
<td>Data Loggers</td>
<td>LD</td>
<td>Medium</td>
<td>Loggers are usually set to ‘record’ sounds within the pipes between 2:00 am and 4:00 am to detect leaks. Very effective in areas with high daytime background noise. Can be used as a permanent supervision system and in temporary mode for leak detection.</td>
<td>• Only gives probability that leak is taking place. • Very expensive to use in permanent mode in areas, where the number of leaks is less than 20 leaks/100km/year. • Not suitable for plastic and polyethylene pipes. • Time consuming and expensive to use in temporary mode.</td>
</tr>
</tbody>
</table>

Table 2.4: Applications and limitations of leak detection equipments (after Farley (2001))
<table>
<thead>
<tr>
<th>Equipment or Method</th>
<th>Leak Detection or Location (LD/LL)</th>
<th>False Alarm</th>
<th>Comments and Application</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| Leak Noise Correlators   | Both                               | Low, Medium in PVC & PE pipes | Highly versatile equipment used to detect and locate leaks. Easy to use, filters can remove unwanted noise signals. Sensitive enough for quiet leak sounds, can survey long lengths in one time rather than manual sounding of individual valves. | • Pipe must be accessible near the leak.  
• The material, diameter and length of pipe between the sensors must be known. Can cause errors in calculations if not accurately entered.  
• Difficult to use in plastic pipes. |
| Sahara                   | Both                               | Low         | Hydrophone is inserted into the pipe to detect the presence of leak. An insertion point greater than 50mm diameter is required. Can survey more than 2000m in one pass in all types of pipes. | • Very expensive to use if new insertion points are required.  
• Can violate Health & Safety rules.  
• Cannot be used in pipes less than 50mm in diameter.  
• Inefficient at low pressure. |
| Infrared Thermography (IT) | LD                                 | Medium     | IT locates temperature differences in soil caused by leaking water. Can survey hundreds of miles of pipelines per day using moving vehicles. No access points are required. Independent of pipe material. | • Expensive to use & requires training and experience.  
• Application limited by ambient weather conditions.  
• In capable of detecting leaks in regions where nearby soil is saturated with water. |
| Ground Penetrating Radar (GPR) | Both                               | Low, Medium in some soils | GPR detects leaks by identifying voids and boundaries between soil layers formed by leaking water. Can survey longer lengths of pipes with few access points. Independent of material of pipes. | • Expensive and time consuming to operate.  
• Require exact layout of the pipe to be surveyed.  
• Incapable of detecting leaks in pipes passing through a large volume of water or buried deep. |
| Fluoride Testing         | LL                                 | Low         | Specifically designed for areas where the pipes passes through a large volume of water and the leaking water needs to be distinguished from other water. Independent of material of pipes. | • Expensive and time consuming to implement.  
• Exact pipe location must be known.  
• Incapable of pinpointing leak if the quantity of water in surrounding area is large. |
| Tracer Gas Method        | LL                                 | Medium      | Best suited for locating leaks on smaller pipes, low-pressure and non-metallic pipes. Used to find multiple small leaks in a single section of pipe. Independent of material of pipes. | • Leaks can be missed if scanning is not done carefully.  
• Requires special equipments to inject and trace the gas.  
• SF6 gas needs bar holes to be made in ground.  
• Very expensive and time consuming. |
Chapter 3

Correlating Leak Signals in MDPE Pipes

As discussed in Chapter 2, correlation has been found to be the most efficient technique to detect and locate leaks in water distribution pipes. It is proven to be very efficient for metallic pipes. However, the same is not true for MDPE pipes where the attenuation with distance of the leak signals is very high because of the high stiffness of MDPE pipes compared to metallic pipes such as ductile iron.

This chapter explains the correlation method for detecting and locating leaks in MDPE pipes. It explains the three parameters: distance, propagation velocity and time delay which affects the accuracy with which the correlation method can locate leaks. In addition to these parameters, this chapter also discusses the parameters which indirectly affect the correlation method. The different types of correlation functions which can be used for the estimation of time delay between leak signals are discussed and compared. At the end, the research methodology involved in this thesis to optimise these parameters is discussed.

3.1 Introduction

A LEAKING water pipe generates noise which depends primarily on water pressure, pipe characteristics, and the leak size and shape. This noise, commonly termed
leak signals, consists of both acoustic noise and mechanical vibrations. These leak signals travel both in the pipe wall and through the water column within the pipe. The acoustic leak signals can be measured using invasive hydrophone sensors, while the non-invasive accelerometers/vibrations sensors can be used for measuring the vibrational leak signals.

As discussed in Chapter 2, correlation is the best technique to detect and locate leaks in water distribution pipes, using these leak signals. To locate leak/leaks in water distribution pipes, the correlation process relies on the estimation of propagation speed of leak signals in the water/pipe and the time delay between the two measured signals from a leak. The propagation speed is normally estimated either using theoretical methods based on pipe characteristics or measured on-site using a simulated leak. This is discussed in detail in Chapter 5. The time delay is estimated using correlation functions. Therefore in this chapter, various types of correlation functions that can be used for the estimation of time delay between measured leak signals are discussed and compared. This chapter also discusses the parameters on which correlation functions depend and the problems associated with their effective use in MDPE pipes.

### 3.2 Cross-correlation method for leak detection

The basic principle of detecting and locating leaks in water distribution pipes using a cross-correlation method is depicted in Figure 3.1. It is based on estimating the time delay between leak signals measured on two known access points (such as valves and fire hydrants) on either side of a leak. The non-invasive accelerometer sensors are used to measure vibrational leak signals while invasive hydrophone sensors are used to measure acoustic leak signals. The signals obtained from these sensors are transmitted wirelessly to a processing unit (correlator/PC). The processing unit then computes the cross-correlation function for these signals to determine the time delay between them.

In practice, leaks may not always be present between two access points. If a leak exists between the two measuring points, then the cross-correlation function will have a distinct peak (Hunaidi & Chu, 1999; Gao et al., 2004). The time shift ($\tau_{shift}$) corresponding to this peak will give difference in arrival times between the two measured signals.
To compute the leak location using the correlation process, it will be assumed that the signals measured at the sensor positions 1 and 2 be \( x_1(t) \) and \( x_2(t) \) respectively, from the leak source signals \( l_s(t) \). If the time taken by these leak signals to travel from leak position to sensor positions 1 and 2 be \( t_1 \) and \( t_2 \), then the time delay between measured signals \((x_1(t) \text{ and } x_2(t))\) is related to leak location by

\[
Time = \frac{Distance}{Speed} \quad \text{or} \quad \tau_{shift} = t_2 - t_1 = \frac{L_2 - L_1}{c} \tag{3.1}
\]

where \( c \) is the propagation speed of leak signals in pipe/water column, and \( L_1 \) and \( L_2 \) are the respective sensor positions 1 and 2 from leak. If the total distance \((L_1 + L_2)\) between two sensor positions is \( D \), then the position of leak relative to sensor position 1 is given by

\[
L_1 = \frac{D - c \tau_{shift}}{2} \tag{3.2}
\]

From eqn 3.2, the accuracy with which the position \((L_1)\) of leak can be computed using cross-correlation method depends upon three factors:

- **Distance \((D)\) between sensors position:** This can be measured on site using various instruments such as measuring wheel or tape. However, it may be difficult to accurately measure in some situations, such as in the presence of unexpected loops or bends in buried pipes. These circumstances may significantly affect the accuracy with which the correlator locate leaks. Therefore, a shorter length of pipe with less probability of loops is always preferred for performing correlation.
• **Propagation speed** \((c)\): The propagation speed (Hunaidi & Chu, 1999; Pudar & Liggett, 1992; Gao et al., 2004) of leak signals in pipe/water column is a critical factor in computing leak location using correlation process. It is highly influenced by the variations in pipe characteristics (material and size) and the presence of any discontinuities such as repaired joints between the two signal measurement positions. This is discussed in detail in Chapter 5 of this thesis.

• **Time delay** \((\tau_{\text{shift}})\): The time delay is estimated by correlating signals measured by the two sensors. The quality of this estimate depends upon the sharpness, clarity and the variance of correlation peak, which further depends upon several factors such as signal-to-noise ratio (SNR) and the processing of signals obtained. These parameters are discussed further in this chapter.

### 3.3 Time delay estimation using cross-correlation

The leak signals produced at the leak position, travel in both upward and downward directions along the pipeline (Figure 3.1). These signals get attenuated along the pipeline in both directions. While measuring leak signals, the sensor also picks up background noise. Thus, the measured signals can be represented by:

\[
x_1(t) = s_1(t) + n_1(t) \tag{3.3}
\]

\[
x_2(t) = s_2(t) + n_2(t) \tag{3.4}
\]

where \(s_1(t)\) and \(s_2(t)\) are the attenuated leak signals, and \(n_1(t)\) and \(n_2(t)\) represent the background noise at sensor positions 1 and 2 respectively. This background noise may be due to several sources such as traffic, running machinery, water pumps, customer use and human movements.

The background noise cannot be completely removed; therefore, to correlate measured signals \((x_1(t) \text{ and } x_2(t))\), some of the assumptions made are that:

- The signals \(s_1(t)\), \(s_2(t)\), \(n_1(t)\) and \(n_2(t)\) are stationary (ergodic), band limited zero mean signals.
- The signals \(s_1(t)\) and \(s_2(t)\) are uncorrelated with noise signals \(n_1(t)\) and \(n_2(t)\).
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- The noise signals $n_1(t)$ and $n_2(t)$ are uncorrelated with each other.
- The duration of correlation of the signals $s_1(t)$, $s_2(t)$, $n_1(t)$ and $n_2(t)$ are very small compared to the observation time $(T)$.

Besides these, the measured signals ($x_1(t)$ and $x_2(t)$) can be continuous analog signals or discrete digital signals depending upon the choice of sensors and data acquisition system used. Therefore, the cross-correlation can be performed in two domains:

- cross-correlation for continuous signals
- cross-correlation for discrete signals

3.3.1 Correlating continuous leak signals in the time domain

In this case, in addition to the assumptions made above, it is assumed that the measured leak signals ($x_1(t)$ and $x_2(t)$) are continuous random signals. The cross-correlation function (Taub & Schilling, 2002; Oppenheim & Schafer, 1975 and Abramowitz & Stegun, 1965) for these signals is given by

$$R_{x_1x_2}(\tau) = E[x_1(t)x_2(t+\tau)]$$

where $\tau$ is the time lag, which when maximises the cross-correlation function, provides an estimate of the value of time delay ($\tau_{shift}$) between the two measured signals, and $E[\cdot]$ denotes the expectation operator. In practise, the two signals $x_1(t)$ and $x_2(t)$ are measured for a fixed finite time interval, $0 \leq t \leq T$, thus the biased cross-correlation estimator $\hat{R}_{x_1x_2}$ is given by

$$\hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int_{0}^{T-\tau} x_1(t)x_2(t+\tau)dt \quad \tau > 0$$ (3.6)

$$\hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int_{-\tau}^{T} x_1(t)x_2(t+\tau)dt \quad \tau < 0$$ (3.7)

where $\frac{1}{T}$ refers to the normalisation scale factor. From eqns 3.6 to 3.7, it is clear that the correlation estimator $\hat{R}_{x_1x_2}(\tau)$ depends upon the product of the magnitude of two
measured signals. In practise, due to the noise (eqns 3.3 & 3.4) and attenuation, the measured signals may vary significantly with time, resulting in fluctuations in the value of correlation estimators. These fluctuations can sometimes be very large, making it difficult to identify the correlation peak responsible for leak signals. Therefore, it is advantageous to express the cross-correlation function in normalised (dimensionless) form i.e. on the scale of -1 to 1. The correlation coefficient $\rho_{x_1x_2}(\tau)$ in normalised form is given by

$$\rho_{x_1x_2}(\tau) = \frac{\hat{R}_{x_1x_2}(\tau)}{\sqrt{\hat{R}_{x_1x_1}(0)\hat{R}_{x_2x_2}(0)}}$$  \hspace{1cm} (3.8)$$

where $\hat{R}_{x_1x_1}(0)$ and $\hat{R}_{x_2x_2}(0)$ are the values of auto-correlation (Taub & Schilling, 2002; Oppenheim & Schafer, 1975) functions $\hat{R}_{x_1x_1}(\tau)$ and $\hat{R}_{x_2x_2}(\tau)$ at $\tau=0$.

An example of a biased correlation estimator is shown in Figure 3.2. Figure 3.2(a) shows a simulated signal, whereas Figure 3.2(b) shows the same signal delayed by 0.2 second. Signal one is correlated with the delayed signal two and the result obtained is shown in Figure 3.2(c). A sharp correlation peak is obtained and the 0.2 seconds shift of this peak from zero axis represents the time delay. This is an example to illustrate the correlation function and its Matlab code is outlined in Appendix A.1.

### 3.3.2 Correlating continuous leak signals in the frequency domain

The cross-correlation function can also be computed in the frequency domain using a Fourier Transform. A procedure for correlating signals in frequency domain is illustrated in Figure 3.3 (Gao et al., 2004, 2005).

The Fourier transforms (Oppenheim & Schafer, 1975) $X_1(f)$ and $X_2(f)$ of signals $x_1(t)$ and $x_2(t)$ are given by

$$X_b(f) = \int_{-\infty}^{\infty} x_b(t)e^{-j2\pi ft}dt \hspace{1cm} (3.9)$$

where $b = 1, 2$ and the inverse Fourier transform is given by

$$x_b(t) = \int_{-\infty}^{\infty} X_b(f)e^{j2\pi ft}df \hspace{1cm} (3.10)$$

Substituting the value of $x_2(t)$, using $b = 2$, from eqn 3.10 into the correlation function (eqn 3.6), produces:
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Figure 3.2: An example to estimate the time delay between two signals using a cross-correlation function (Appendix A.1).

\[ \hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int X_1(t) \int X_2(f) e^{j2\pi f(t+\tau)} df dt \]

(3.11)

This can be rearranged to give

\[ \hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int \int X_2(f) x_1(t) e^{-j2\pi(-f)t} e^{j2\pi f\tau} df dt \]

(3.12)

Or,

\[ \hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int X_2(f) X_1(-f) e^{j2\pi f\tau} df \]

(3.13)
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Figure 3.3: Schematic diagram of implementing cross-correlation of leak signals in frequency domain.

Now,

\[ X_1(-f) = |X_1(f)| e^{-j2\pi f t} = X_1^*(f) \]  

Substituting in eqn 3.13 gives the final result

\[ \hat{R}_{x_1x_2}(\tau) = \frac{1}{T} \int_{-\infty}^{\infty} X_1^*(f) X_2(f) e^{j2\pi f \tau} df \]  

where * denotes the complex conjugate. From eqn 3.15, the correlation of two signals \( x_1(t) \) and \( x_2(t) \) in the frequency domain is the inverse Fourier transform (Hunaidi & Chu, 1999; Oppenheim & Schafer, 1975) of the product of complex conjugate of Fourier transform of signal \( x_1(t) \) and Fourier transform of signal \( x_2(t) \) as depicted in Figure 3.3.

The advantage of performing the correlation in the frequency domain is two fold. Firstly, it involves less calculations as it does not require the usual time shifting and multiplications normally required in computing correlation in time domain. Secondly, it does not require filtering of the leak signals \( x_1(t) \) and \( x_2(t) \) prior to correlation. However, the disadvantage is that for a fixed sampling frequency \( f_s \), the maximum time delay which can be measured depends upon the length \( N \) of the Fourier Transform, i.e. \( \tau_{\text{max}} \propto N/f_s \). In practise, the Fourier Transform is calculated using Fast Fourier Transform (FFT) for a length of 1024 or 2048 discrete values. If it is calculated for longer lengths then its complexity and number of calculations increases dramatically. Thus, it is not suitable for measuring large values of time delay or where the difference between \( L_1 \) and \( L_2 \) is large.

3.3.3 Cross-correlation function for discrete leak signals

In some correlators (e.g. PC based), leak signals obtained from the sensors are digitised and then correlation is performed directly on these discrete digital signals. A procedure
for calculating cross-correlation of discrete digital signals is illustrated below. If the two, N-discrete value, leak signals are \( x_1(b) \) and \( x_2(b) \) for \( b = 0, 1, ..., N - 1 \), then the biased cross-correlation function is given by:

\[
\hat{R}_{x_1x_2}(m) = \frac{1}{N} \sum_{b=0}^{N-1-m} x_1(b)x_2(b+m)
\]  
(3.16)

\[
\hat{R}_{x_1x_2}(-m) = \frac{1}{N} \sum_{b=0}^{N-1-m} x_2(b)x_1(b+m)
\]  
(3.17)

Eqns 3.16 - 3.17 are very tedious to solve because of lots of time shiftings \((b+m)\), multiplications and additions. However, this can be made easier by performing correlation in frequency domain using Fast Fourier Transform (FFT) and convolution at the expense of some loss of accuracy.

The method for estimating cross-correlation functions for digital signals in the frequency domain is similar to that depicted in Figure 3.3 for the continuous leak signals. In this case, \( x_1(t) \) and \( x_2(t) \) are replaced with \( x_1(b) \) and \( x_2(b) \) and the FFTs are denoted by \( X_1(f) \) and \( X_2(f) \) respectively. The correlation function \( \hat{R}_{x_1x_2}(m) \) is computed by taking the inverse FFT of \( \hat{X}_1(f)\hat{X}_2(f) \) and scaled appropriately, where \( \hat{X}_1(f) \) denotes the complex conjugation of the FFT of \( x_1(b) \) and \( \hat{X}_2(f) \) is the FFT of \( x_2(b) \). However, it has also the same problem that its complexity and number of calculations increases if the FFT length \((N)\) is increased for measuring large time delays between leak signals.

### 3.4 Generalised cross-correlation for leak detection

In generalised cross-correlation (GCC), a weighting function/prefilter is applied to de-emphasises the portion of leak signal spectrum affected by the background noise. There are several types of weighting estimators (Knapp & Carter, 1976); however, the three estimators (Gao et al., 2006) which can be used for leak detection in MDPE pipes are:

- phase transform (PHAT)
- smoothed coherence transform (SCOT)
- maximum likelihood (ML) estimator
Similar to the cross-correlation functions discussed above, GCC can be computed in both the time domain and frequency domain. In the frequency domain, a weighting estimator is applied to the cross spectral density (CSD) function prior to performing the inverse Fourier transform (Figure 3.4). In the time domain, GCC is comparatively much more difficult to implement. In time domain, the signals are firstly passed through pre-filters prior to correlating them, with the aim to:

- enhance signals in the frequency bands with high SNR and suppressing signals outside these bands.
- pre-filter signals, which helps in sharpening the peak in the cross-correlation function.

Similar to section 3.3, it is assumed here that the background noise at each sensor position is uncorrelated with each other and with the leak signals (eqns 3.3 and 3.4). The biased GCC estimator, $\hat{R}_{x_1x_2}^G(\tau)$ for the finite time duration ($T$) signals $x_1(t)$ and $x_2(t)$, is given by

$$\hat{R}_{x_1x_2}^G(\tau) = F^{-1}\{\Psi_G(\omega)\hat{S}_{x_1x_2}(\omega)\} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Psi_G(\omega)\hat{S}_{x_1x_2}(\omega)e^{j\omega\tau}d\omega$$

(3.18)

where $F^{-1}\{}$ denotes the inverse Fourier Transform, $\Psi_G(\omega)$ the GCC weighting estimator and $\hat{S}_{x_1x_2}(\omega)$ represents the estimate of cross spectral density (CSD), which is given by:

$$\hat{S}_{x_1x_2}(\omega) = \frac{1}{2\pi n_n} T \sum_{b=1}^{n_n} X_{1b}^*(\omega,T)X_{2b}(\omega,T)$$

(3.19)
where \( n_a \) stands for the total number of averages over the duration \( T \). The three weighting functions (SCOT, ML and PHAT) of interest are mentioned in Table 3.1. It can be seen that all the weighting functions are real so they have no affect on the phase of CSD. For leak location in MDPE pipes, a good time-delay estimation is required. Therefore, \( \Psi_G(\omega) \) should be so chosen such that a large sharp correlation peak is obtained rather than a broad one. However, sharp peaks are more sensitive to errors introduced by finite observation time, particularly in cases of low SNR. Thus, the choice of \( \Psi_G(\omega) \) is a compromise between good resolution and stability.

Table 3.1: Various generalised cross-correlation weighting estimators

<table>
<thead>
<tr>
<th>PHAT</th>
<th>SCOT</th>
<th>ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Psi_G(\omega) )</td>
<td>( \frac{1}{</td>
<td>S_{x_1x_2}(\omega)</td>
</tr>
</tbody>
</table>

where \( \gamma_{x_1x_2}(\omega) = \frac{S_{x_1x_2}(\omega)}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}} \)

3.4.1 PHAT estimator

The frequency weighting function of the PHAT estimator is given by

\[
\Psi_P(\omega) = \frac{1}{|S_{x_1x_2}(\omega)|}
\]

where subscript \((P)\) stands for PHAT. Substituting in eqn 3.18 will give

\[
\hat{R}_{x_1x_2}(\tau) = F^{-1}\{\Psi_P(\omega)\hat{S}_{x_1x_2}(\omega)\} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{\hat{S}_{x_1x_2}(\omega)}{|S_{x_1x_2}(\omega)|} e^{i\omega \tau} d\omega = \delta(\tau + T)
\]

where \( \delta(\tau + T) \) represents the delta function delayed by time \(-T\). In this case, the output is a delta function so the correlation will result in a sharp, narrow spreading peak. This is beneficial for leak detection in MDPE pipes. However, this happens only when \( \hat{S}_{x_1x_2}(\omega) = |S_{x_1x_2}(\omega)| \). In practise, it is not always found that \( \hat{S}_{x_1x_2}(\omega) = |S_{x_1x_2}(\omega)| \), therefore the output \( \hat{R}_{x_1x_2}^{P}(\tau) \) may not always be a delta function. It can also be seen from eqn 3.21 that the output delta function is independent of the frequency of leak signals, thus independent of filters. However, the disadvantage is that it takes no
account of noise (eqns 3.3 and 3.4) in the signals \( x_1(t) \) and \( x_2(t) \). Another defect is that it is inversely proportional to \( |S_{x_1x_2}(\omega)| \), which accentuates the errors, especially when the SNR is low. Thus, overall the PHAT estimator results in a sharp correlation peak. However it may enhance the effect of noise, thereby giving errors in the estimate of time delay.

### 3.4.2 SCOT estimator

The frequency weighting function of the SCOT estimator is given by

\[
\Psi_S(\omega) = \frac{1}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}} \quad (3.22)
\]

Substituting in eqn 3.18 to have

\[
\hat{R}^{S}_{x_1x_2}(\omega) = F^{-1}\left\{ \Psi_S(\omega) \hat{S}_{x_1x_2}(\omega) \right\} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{\hat{S}_{x_1x_2}(\omega)}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}} e^{j\omega \tau} d\omega \quad (3.23)
\]

Or,

\[
\hat{R}^{S}_{x_1x_2}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{\gamma}_{x_1x_2}(\omega) e^{j\omega \tau} d\omega = h_s(\tau) \otimes \delta(\tau + T) \quad (3.24)
\]

where \( \hat{\gamma}_{x_1x_2}(\omega) = \frac{\hat{S}_{x_1x_2}(\omega)}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}} \) is the coherence estimate of signals \( x_1(t) \) and \( x_2(t) \), and \( h_s(\tau) = F^{-1} \left\{ \frac{\hat{S}_{x_1x_2}(\omega)}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}} \right\} \).

Substituting \( \hat{\gamma}_{x_1x_2}(\omega) \) in eqn 3.22 to have

\[
\Psi_S(\omega) = \frac{\hat{\gamma}_{x_1x_2}(\omega)}{\hat{S}_{x_1x_2}(\omega)} \quad (3.25)
\]

The SCOT estimator can be interpreted as two filtering processes: pre-filtering represented by the denominator \( |\hat{S}_{x_1x_2}(\omega)| \) and attenuation in the frequency regions where SNR is low, by numerator \( \hat{\gamma}_{x_1x_2}(\omega) \). The delta function in eqn 3.24 helps in sharpening the correlation peak, while the term \( h_s(\tau) \) helps to determine time delay under the influence of weakly correlated noise.

Thus in summary, the SCOT estimator can both sharpen the peak as well as attenuate the frequency region affected by noise, therefore it is potentially worthwhile to use it for leak detection in MDPE pipes.
3.4.3 ML estimator

The frequency weighting function of the ML estimator is given by

\[
\Psi_M(\omega) = \frac{\hat{\gamma}^2_{z_1,z_2}(\omega)}{1 - \hat{\gamma}^2_{z_1,z_2}(\omega)} \frac{1}{|\hat{S}_{z_1,z_2}(\omega)|}
\] (3.26)

Substituting in eqn 3.18 to have

\[
\hat{R}^M_{z_1,z_2}(\tau) = F^{-1}\{\Psi_M(\omega)\hat{S}_{z_1,z_2}(\omega)\} = h_M(\tau) \otimes \delta(\tau + T_0)
\] (3.27)

where

\[
h_M(\tau) = F^{-1}\left\{\frac{\hat{\gamma}^2_{z_1,z_2}(\omega)}{1 - \hat{\gamma}^2_{z_1,z_2}(\omega)} \frac{\hat{S}_{z_1,z_2}(\omega)}{|\hat{S}_{z_1,z_2}(\omega)|}\right\}
\] (3.28)

From eqn 3.28, there are two pre-filtering operations involved in the ML estimator, similar to as in the case of SCOT estimator above. The term \(\frac{\hat{\gamma}^2_{z_1,z_2}(\omega)}{1 - \hat{\gamma}^2_{z_1,z_2}(\omega)}\) acts as a pre-filter and helps to sharpen the correlation peak, when \(\hat{S}_{z_1,z_2}(\omega) = |\hat{S}_{z_1,z_2}(\omega)|\). However, this not always happens in practise.

The first term, \(\frac{\hat{\gamma}^2_{z_1,z_2}(\omega)}{1 - \hat{\gamma}^2_{z_1,z_2}(\omega)}\), in eqn 3.28 weights the CSD according to the variance of phase. It attaches most weight when the variance of the estimated phase error is least. Thus, the ML estimator weighs the cross-spectrum according to the SNR, giving most weight to the phase-spectrum that leads to the minimum variance of time delay estimate. However, in case of high SNR, \(\gamma^2_{z_1,z_2}(\omega) \rightarrow 1\), and \(\Psi_M(\omega) \rightarrow \infty\). Therefore, this processor is not preferable to the SCOT estimator for leak detection as it has the effect of overemphasizing as well as underemphasizing signals at certain frequencies.

3.5 Parameters affecting correlation of leak signals

As discussed in sections 3.3 and 3.4, the correlation method for leak detection depends upon three parameters: distance between sensor positions, estimation of time delay between leak signals and the propagation velocity of leak signals in the pipe/water column. In practise, the distance between sensor positions can be easily measured for the straight pipe lengths. The unexpected loops or bends can cause a reduction in accuracy with which length can be measured. However, as the attenuation of leak signals in MDPE pipe is very high; therefore, the correlation is usually performed
on shorter lengths (< 50m) and under these circumstances, the additional lengths of unexpected bends and loops may not be significant. Therefore, it is not a point of high concern in this thesis. However, the accuracy with which the other two parameters (time delay and propagation velocity) can be determined depends upon several other parameters. Therefore, the focus of research work contained in this thesis is to optimise these parameters, in order to aid leak detection and location in MDPE pipes using a correlation process. The research work is divided into two parts. One part focuses on the parameters affecting the estimation of time delay using the correlation process, while the second part deals with the parameters required for the calculation of propagation velocity of leak signals in MDPE pipes.

Table 3.2: Parameters affecting correlation of leak signals

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Frequency domain</th>
<th>Noise (dB)</th>
<th>Attenuation (dB/m)</th>
<th>Weighting factor</th>
<th>Observation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1(t), x_2(t)$</td>
<td>$X_1(f), n_1, n_2$</td>
<td>$\alpha$</td>
<td>$\psi_\sigma(\omega)$</td>
<td>$T$</td>
<td></td>
</tr>
<tr>
<td>$X_2(f)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The time delay between measured leak signals is estimated using the cross-correlation formulae discussed in sections 3.3 & 3.4. The variables involved in these formulae are listed in Table 3.2 and are discussed below:

- **Measured leak signals $x_1(t)$ and $x_2(t)$**: From eqns 3.6 and 3.7, the correlation function, at any instance, is directly proportional to the product of the temporarily displaced measured signals $x_1(t)$ and $x_2(t)$. The sharpness and magnitude of correlation peaks are affected by the characteristics of these measured signals. The four main characteristics are:
  - **Magnitude**: It can be interpreted from eqns 3.3 and 3.4 that the measured signals $x_1(t)$ and $x_2(t)$ are a combination of leak signals $s_1(t)$ and $s_2(t)$, and noise. Therefore, an adequate signal to noise should be present at both sensor positions in order to obtain a distinct, sharp correlation peak.
  - **Signal acquisition duration**: The signals measured at each sensor position travels different distances from the leak position. Consequently, the duration...
over which signals are measured should be long enough so that the measured signals contain sufficient time domain information to obtain a sharp correlation peak.

- **Frequency response:** Frequency response determines the frequency range of leak signals which helps in selecting filter cut-off frequencies, hardware components and sensors. Improper selection of frequency range can cause correlation error or even no correlation at all. A proper choice of frequency is required so that the leak signals obtained at both sensor positions lie in the selected frequency range.

- **Phase:** The phase of leak signals is important to determine whether the leak signals are a linear or non-linear function. This is important as the correlation function in both time and frequency domain involves a significant number of multiplications and time shift operations.

- **Fourier Transform:** In the frequency domain, correlation of leak signals is directly proportional to the product of the Fourier transforms of input signals. The Fourier transform is computed using FFT and the maximum time delay which can be measured depends upon the length of FFT. However, if the length of FFT is increased then its complexity and number of calculations involved will increase. Therefore, it is essential to optimise the length of FFT.

- **Level of noise:** From eqn 3.3, the measured signals are a combination of leak signals present at the sensor position and the level of noise present. This noise is assumed to be uncorrelated with both each other and the leak signals. In cases, if the noise level dominates the leak signals at either or both sensor positions, then noise may fade the actual leak signals making correlation difficult or even resulting in no correlation at all. This may result in a more complex situation if a significant level of noise is present in the frequency range of leak signals. It can be reduced using filters; however, to optimise filter cut-off frequencies, a priori knowledge of frequency range of leak signals is required.

- **Attenuation with distance of leak signals:** Attenuation with distance of leak signals along the pipeline depends upon the pipe characteristics. It limits the distance between sensors over which the signal acquisition and correlation
can be performed. It is required to optimise the maximum distance over which the correlation can be performed for different leaks.

- **Weighting factor**: As discussed in section 3.4, a weighting factor sharpens the correlation peak and minimises the extra frequencies in areas of low SNR. However, sharp peaks are more sensitive to errors introduced by finite observation time. Therefore, the choice of weighting factor is a compromise between good resolution and stability.

- **Measurement duration \((T)\) of leak signals**: The duration of correlation is significantly affected by the SNR. A too long correlation can lead to a large number of calculations, while a too short duration can lead to errors by missing the actual value of time delay between leak signals.

Thus, the variables discussed above significantly affect the correlation peaks and their optimisation is necessary to have a good time delay estimation. The second parameter on which correlation method for leak location depends is the propagation velocity of leak signals in pipe and water column. Generally, it is calculated using a theoretical formula (See Chapter 5 for details), which requires knowledge of the pipe characteristics. It can also be calculated on-site using a known simulated leak. However, this is not preferable as the velocity varies with pipe characteristics and with the presence of any discontinuities such as repaired joint inside the pipe length under survey. Therefore, it is cumbersome to calculate its exact value. Thus, the two parameters, propagation velocity and time delay, depend upon several other variables especially pipe characteristics and an optimisation of these parameters is required to obtain a sharp and clear correlation peak, which makes it easier to measure time delay.

In addition to the parameters discussed above, on which the correlation function directly depends, there are several other parameters which either indirectly affect the correlation peaks or directly affects one of the parameters discussed above. These are discussed below:

- **Sensitivity and frequency range of sensors**: This determines the ability of sensors to measure weak signals from the leaking pipes. A highly sensitive sensor picks up more background noise while a low sensitivity sensor can miss the weak signals. The frequency range of sensors is very important as different pipe
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materials produce signals of different frequencies and amplitude. Therefore, an optimum choice of sensors is required for the effective use of correlators in MDPE pipes.

- **Fluid pressure**: For a fixed dimensional leak (except very large leaks), increase in fluid pressure enhances the magnitude of leak signals. This helps in detecting quiet leaks. However, this may not happen for very large size leaks where the leak energy spreads over a large area.

- **Sharpness and variance of correlation peak**: It is preferable to have a sharp correlation peak with low variance because of the ease and accuracy of measurement of time delay. However, due to noise and finite measurement duration it is difficult to obtain a sharp correlation peak in practise.

- **Coherence of leak signals**: Coherence represents the degree of similarity between measured signals. It is expressed on a scale of 0 to 1. The closer its value is to unity, the more similar are the signals. Generally, leak signals measured over shorter distances are more cohered than signals measured over longer distances or in the presence of high noise.

- **In-bracket and out-bracket leak**: The correlation method discussed above is for in-bracket leaks in which leak/leaks exist in between the two sensor positions. However, in practise leaks may exist outside the two sensor positions (out-bracket condition). Thus, the direction/position of leak relative to sensor position is another important issue for leak detection and location using the correlation method. This can be done by comparing the measured time delay with the maximum time delay that it can measure. If the time delay exceeds the theoretical maximum value, then this indicates the out-bracket leak conditions, which can be further clarified by increasing the range of maximum value of theoretical time delay by increasing the length of window \((N_s)\), say, for digital correlators. Therefore, the correlators should have the ability to auto adjust the window length under these circumstances and thus can measure the time delay.

- **Filters**: Signals obtained from the sensors needs to be filtered to remove background noise. However, due to poor knowledge about the characteristics of leak
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signals, especially in MDPE pipes and large diameter pipes it is difficult to select appropriate cut-off filter frequencies.

- **Length of averaging**: The efficiency of correlators is highly influenced by background noise. Unfortunately this noise is not always detectable prior to capturing leak signals. However, for a given signal to noise ratio (SNR), increasing the length of time over which the cross-correlation is determined can reveal the presence of a previously masked signal. But in practice, the leak detection task is usually accomplished in a finite observation time, which sometimes increases the probability of missing the leaks, especially in case of low SNR. Thus, correlators should have the ability to store leak signals and perform long term signal averaging before it is clear if there is a correlation or not.

### 3.6 Research methodology

From the discussion made in section 3.5, it can be concluded that the correlation method for leak detection directly or indirectly depends upon several parameters. Therefore, the aim of this research work is to optimise these parameters so as to make effective use of the correlation technique for leak detection and leak location in MDPE pipes over long distances (greater than 50m). The research methodology involved in optimising these parameters is outlined in Figure 3.5 and the steps involved are discussed below:

- **Literature review**: The research work started with a review of currently used water pipes and the advantages of MDPE over other pipe materials. This priori knowledge of the specifications of MDPE pipes helps in computing various parameters such as propagation velocity of leak signals. It involves a review of the existing and upcoming leak detection and leak location techniques that can be used in MDPE pipes. These techniques are compared and their strengths and weaknesses are identified. A conclusion was made that correlation is the best technique for leak detection and location in MDPE pipes, which forms the basis of the research work in this thesis. Finally, the review mentions the problems associated with the effective use of correlation method in MDPE pipes.

- **Theory of correlation method**: Following the literature review, the second stage of research work is to theoretically solve the problem of leak detection using
correlation process. The theory behind the correlation method is explained and various types of correlation functions are compared. The variables involved in these theoretical formulae are tabulated. A decision is made that to effectively use the correlation method for leak detection in MDPE pipes, the key variables identified needs to be optimised using theoretical and experimental studies.

- **Optimising variables - A theoretical approach:** The next stage of the research work was to optimise these variables theoretically. As the correlation method is based on the noise made by the leaking pipe, thus most of the variables involved are associated with the characteristics of signals propagating inside the pipe. Therefore, in this step a theoretical model of the leaking pipe is presented to determine the characteristics of leak signals propagating inside the pipe. The theoretical approach is very complicated and is not able to completely model leaks in real networks. Therefore, a recursive experimental approach is proposed. This involves a study of different simulated and real leaks, and to optimise the variables using the measured leak signals.

- **Optimising variables - An experimental approach:** This step involves characterising leak signals in MDPE pipes using experimental studies. It involves measuring signals from MDPE pipes both in the presence of a leak and after the leak is repaired. These measured signals are compared with each other to find the dominating frequencies in the presence of a leak, which are either lower or not present in the case of no leaks. These signals are called leak signals, and are correlated to determine the position of leak. The key variables are optimised and the error between the actual and calculated leak location is computed. These steps are repeated for various combinations of leak characteristics (such as leak size and flow rate), pipe dimensions and water pressure. Finally, the characteristics of leak signals are optimised i.e. those characteristics (frequency response) which occur in all types of leaks but not in the case when there is no leak.

To do so, a series of pilot stage tests with simulated leaks in a MDPE pipe were conducted for various combinations of leak size, shape and flow rate. The tests on MDPE pipes without backfill were conducted at the hydraulics laboratory, Loughborough University and on buried MDPE pipes at Severn Trent Lake House facilities. Signals were measured both in the presence of a leak and when there
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Figure 3.5: Research methodology to detect leak in MDPE pipes using correlation.
is no leak. A preliminary set of conclusions are made on the characteristics of leak signals in MDPE pipes using these studies. This helps to design the signal processing techniques and selection of the sensors, data acquisition, transmission and analysis system.

- **Signal processing, hardware selection and design of algorithm:** Based on the results of the preliminary tests, a selection of signal processing techniques such as filtering and averaging, hardware components such as sensors and transmitters is made. The algorithm is designed and written using Matlab to acquire, analyse and correlate leak signals. Selection of the cut-off frequency from the results obtained is made so as to separate leak signals from background noise. The values of various parameters are chosen and a further series of more controlled experiments are conducted to optimise the parameters involved. A new method is proposed for the calculation of the velocity of leak signals.

- **System evaluation:** Based on the results of these preliminary experiments, a new test rig of buried MDPE pipes is built at the hydraulics laboratory, Loughborough University and a further series of controlled experiments are conducted. The aim is to study the effect of backfill on the generation and propagation of signals. Leaks with different characteristics (size and flow rate) are simulated and signals are measured along the pipeline using the selected sensors, data acquisition and transmission system. The signals are measured and compared both in the absence and presence of a leak to optimise the characteristics of leak signals and other parameters.

The steps mentioned above are repeated for different sizes of leaks at different flow rates and the results obtained are used to optimise the parameters and to determine which signals exist when the leak is present and when the leak is not present.

Finally the research will be concluded by developing a novel method for leak detection using trials at the test site of Severn Trent.
3.7 Summary

The correlation process for leak detection is based on the characteristics of leak signals in pipes. Due to limited knowledge of the characteristics of leak signals in MDPE pipes, correlation process is difficult to employ in these pipes. However, for its effective use in MDPE pipes, certain parameters such as filter cut-off frequencies and hardware components, such as sensors and wireless transreceiver system, requires optimisation.

In this chapter, a model for the calculation of the cross-correlation function for leak signals in time domain and frequency domain is presented. It is concluded that the frequency domain analysis eliminates the need for selection of cut-off frequencies required for the fine tuning of filters in time domain, but at the expense of a small loss of accuracy. It is also concluded that the maximum value of time delay which can be measured is limited by the length of FFT.

Various time delay estimators, used in generalised cross-correlation are also compared for the purpose of leak detection in buried MDPE water pipes. It has been shown that the PHAT, SCOT and ML estimators designed to pre-filter the leak signals prior to the cross-correlation, have the desirable feature of sharpening the peak in the cross-correlation function. Although the PHAT estimator is designed to give a delta function located at the exact time delay, in practice the SCOT and ML estimators additionally take account of the effect of background noise in the estimation procedure, which will probably be more beneficial to water leak detection. However, ML estimator has the effect of overemphasising and underemphasising at certain frequencies. Thus, SCOT is the most suitable weighting estimator for the purpose of leak detection. Finally, the research methodology used in this thesis to optimise the variables involved in the cross-correlation process has been presented.
Chapter 4

Characterising Leak Signals in MDPE Pipes

The accuracy with which the correlation technique detect leaks is highly influenced by the characteristics of leak signals. However in MDPE pipes, the frequency response of leak signals is not well characterised.

Therefore, this chapter presents an analytical model to characterise leak signals in MDPE pipes. The theoretical predications are further validated with the results of pilot stage tests conducted on a MDPE pipe. It has been found that most of the leak signals in MDPE pipes without backfill lie in the frequency band of 20 Hz to 350 Hz and extend upwards to 550 Hz and above, with increase in pressure and flow rate. With this knowledge, it is possible to achieve better performance of existing correlators in MDPE pipes using appropriate filters and amplification.

4.1 Source of leak signals

Leak signals are a combination of vibrations and acoustic signals produced by leaks, with the energy carriers transfer energy by vibrating in the vicinity of their original position. At a leak position, the three main factors which contribute to vibro-acoustic leak signals are:

1. Bedding and soil surrounding the pipe: At a leak position, leaking water
exit the pipe agitates the soil particles surrounding the pipe. The rate of 
agitation depends upon the type of soil, e.g. sand particles will be more agitated 
than the clayed ones. Some of these soil particles then hit the pipe with different 
forces, producing vibro-acoustic signals both inside the pipe boundary and soil 
surrounding the pipe. However, due to high attenuation with distance of these 
signals in soil, they propagate for only small distances in soil.

2. Leak aperture: Before exiting the pipe, leaking water touches the boundaries 
of the leak aperture (pipe edge) and pass a portion of its energy to the pipe and 
water column inside pipes, thus generating both vibration and acoustic signals. 
These signals propagate for long distances both inside the water column and pipe 
shell.

3. Water flow at leak position: At a leak position, the water pressure and flow 
rate changes. These changes result in water hitting the internal pipe wall with 
different pressures resulting into a number of vibro-acoustic signals.

In addition to these, there are several other sources of vibro-acoustic signals in a water 
distribution pipe network. Some of these are water flowing inside the pipe, pipe network 
discontinuities such as bends and access points such as gate valves and hydrants. These 
signals are not actual leak signals, however they may interfere with leak signals and are 
sometimes difficult to differentiate.

4.2 Flow of leak signals through fluid-filled pipes

For any leak in a pipe, there are theoretically infinite waves, called leak signals, traveling 
inside the pipe. However, it is usually sufficient to consider only two waves, one in the 
pipe shell and one in the water, which carries the majority of the vibro-acoustic energy 
propagating away from the leak location. This happens at wave frequencies well below 
the pipe ring frequency\(^1\). At these low frequencies, pipe vibrations are similar to that 
of a beam of deformable cross-section which can move not only in flexure but also

\(^1\)This is the frequency below which the propagating wave travels and transfers most of the leak 
ergy. The term ‘ring’ refers to the circumferential mode shapes for \(n=0\) and \(n=1\). Above this 
frequency, the waves with higher order \(n=2\) dominates and their mode shapes is much different as can 
be seen in Figure 4.1, in comparison to the ring shaped for \(n=0\) and \(n=1\).
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axially and in radius. These leak signals propagate in buried water distribution pipes in a similar manner to waves propagating in fluid filled circular cylindrical shells. This problem has been covered extensively in the literature such as Fuller (1981, 1983); Fuller & Fahy (1982); Muggleton & Brennan (2002, 2004, 2005); Muggleton et al. (2004) and Pinnigton & Briscoe (1994).

Each wave has a specific mode index number \((n, s)\) and a wavenumber \(k_{ns}\). The circumferential modeshapes corresponding to orders, \(n=0,1,2,3\) are shown in Figure 4.1. The deformation of the circumferential mode for the order \(n=0\) is called normal or breathing mode and for the order \(n=1\) a flexural mode. The wavenumber \((k_{ns})\) can be real, imaginary or complex representing a propagating, evanescent or quasi-propagating waves respectively. Propagating waves travel above a certain ‘cut-on’ frequency which depends on the pipe and fluid properties. However, evanescent and quasi-propagating waves decay exponentially with distance along the pipeline and are mostly generated by the pipe discontinuities such as bends and access points. On the contrary, the propagating waves travel longer distances and dominate the other two away from these discontinuities, which is why they are of prime interest in this chapter.

For order \(n=0\), two types of propagating waves exist named as plane waves and torsional waves and for order \(n=1\), there is only one, termed a flexural wave. The energy of plane waves largely concentrate in the water, while the energy of torsional waves are exclusively contained in the pipe wall. However, the energy of flexural waves mostly concentrates in the pipe wall, with a minute part of it being carried by the water. The higher order waves \(n > 1\) propagate only above a certain cut-on frequency, which depends on pipe characteristics and fluid parameters.

4.2.1 Waves at \(n=0\)

At \(n=0\), three axi-symmetric propagating waves occur. The first wave \((n=0, s=1)\) is a water-borne plane pressure wave with some radial motion associated with the pipe shell compliance. The second axi-symmetric wave is predominately the compressional wave in the pipe shell with some associated radial wall motion, coupled to the water motion via Poisson’s contraction. The strength of the coupling between these two motions is governed by the dimensions of pipe and its physical properties. The third axi-symmetric wave \((s=0)\) is the pipe torsion which is uncoupled from the water and does not involve
significant pipe wall radial motion. In practice, there can also be reflections in pipe due to discontinuities that can make leak signals propagation much more complicated.

4.2.2 Waves at \( n=1 \) and \( n=2 \)

At \( n=1 \) and \( n=2 \), only one propagating wave occurs. The \( n=1 \) bending wave is a beam like flexural wave associated with radial pipe wall acceleration. It consists of both an exponentially decaying near-field and dispersive propagating waves. For \( n=2 \) also, exponentially damped nearfield waves occur near discontinuities such as bends and flange plates. This means that leak signals which are measured at access points such as hydrants can be disturbed by the presence of nearfields. Therefore, it is better to measure signals directly from the pipe; however, this is not always practical, especially for buried pipes. Thus:

Well below the pipe ring frequency, four propagating waves can be considered to be responsible for the transfer of most of the leak energy along the pipeline. These are three axi-symmetric waves for mode \( n=0, s=0,1,2 \) and one for \( n=1 \).

4.3 Characteristics of leak signals in pipe

The vibro-acoustic leak signals generated by leaks in buried water distribution pipes can travel in three mediums: soil surrounding the pipe, the pipe wall itself and water contained in the pipe.

In the soil surrounding the pipe, leak signals get highly attenuated over short distances, so this medium is not of interest. Those traveling in the other two mediums can be classified into two categories: water-borne leak signals and pipe shell-borne leak signals. For both types of signals, the energy flow is similar to the vibro-acoustic energy flow in fluid-filled thin walled circular cylindrical shells.

Therefore, to derive the equations of motion of leak signals, thin-walled theory is used in this section and the pipe is considered as a thin walled circular cylindrical shell. Expressions are derived for mode \( (n=0, s=1,2) \) as waves corresponding to these are supposed to transfer most of the leak energy along the pipeline. To better understand this, consider a buried water distribution pipe of radius \( a \) and thickness \( h \) with \( a >> h \), as shown in Figure 4.2. The pipe is assumed to be surrounded by an infinite elastic
medium which exerts an external pressure on the pipe. The density of pipe material is \( \rho_s \) and the density of water inside the pipe is \( \rho_f \). \( x, \theta \) and \( r \) are the axial, circumferential and radial coordinates respectively. The axial and circumferential stress developed in the pipe are \( \sigma_x \) and \( \sigma_\theta \) respectively.

### 4.3.1 Assumptions

To derive the equations of motion of the leak signals, some of the assumptions (Fuller & Fahy, 1982) made are that:

- The thickness to radius ratio \( (h/a) \) of pipe is less than unity (thin walled theory).

This is applicable to the distribution system pipes as these are manufactured to have the thickness to radius ratio less than 0.5 (See Table 6.2 for specifications of
MDPE pipes). For example, for a 20mm diameter pipe, the thickness to radius ratio is 0.16, which is much less than unity.

- The pipe can sustain both longitudinal and shear waves and the deformation of pipe shell is negligible compared to its thickness.
- The fluid remains in contact with the shell wall, which means that the radial fluid vibrational velocity is equal to the shell radial velocity.

Figure 4.2: Co-ordinate system used for the analysis of leak signals in pipes filled with water (after Feng (1994)).

The free, simple harmonic motion of a thin walled circular cylindrical shell with a vibro-acoustic field can be most conveniently described by the simplified Flugge's shell equations (Feng, 1994; Flugge, 1973). These equations exclude the effect of rotary kinetic energy and transverse shear, and are given by:

\[
\frac{\partial^2 u}{\partial x^2} + \frac{1 - \nu}{2a^2} \frac{\partial^2}{\partial \theta^2} u + \frac{1}{a^2} \frac{\partial v}{\partial x} + \frac{\nu}{a} \frac{\partial w}{\partial x} + \frac{f_x}{\rho_s c_s^2} = \frac{1}{c_s^2} \frac{\partial^2 u}{\partial t^2} \quad (4.1)
\]

\[
\frac{1 + \nu}{2a} \frac{\partial^2 u}{\partial x \partial \theta} + \left( \frac{1 - \nu}{2} \frac{\partial^2}{\partial x^2} + \frac{1}{a^2} \frac{\partial^2}{\partial \theta^2} \right) v + \frac{1}{a^2} \frac{\partial w}{\partial \theta} + \frac{f_\theta}{\rho_s c_s^2} = \frac{1}{c_s^2} \frac{\partial^2 v}{\partial t^2} \quad (4.2)
\]

\[
\frac{\nu}{a} \frac{\partial^2}{\partial x} + \frac{1}{a^2} \frac{\partial v}{\partial \theta} + \frac{1}{a^2} w + \frac{\beta_s^2}{a^2} \left( \frac{\partial^4}{\partial x^4} + 2 \frac{\partial^4}{\partial x^2 \partial \theta^2} + \frac{1}{a^2} \frac{\partial^4}{\partial \theta^4} \right) w - \frac{(f_r + p)}{\rho_s c_s^2} = -\frac{1}{c_s^2} \frac{\partial^2 w}{\partial t^2} \quad (4.3)
\]

where \(\nu\) is the Poisson ratio, \(c_s = \sqrt{E/(1 - \nu^2)\rho_s}\), \(E\) is Young's modulus of elasticity, \(\rho_s\) is the density of pipe material, \(\beta_s^2 = h^2/12a^2\) and \(p\) is the acoustic pressure. \(w, v, u\)
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and $f_r, f_\theta, f_x$ are the displacements and external forces applied to the pipe in $r, \theta$ and $x$ directions respectively.

The solution of these equations can be given in terms of axial wavenumber $k_{ns}$, where the subscript $n$ and $s$ represents the mode $(n,s)$ (Fuller & Fahy, 1982). At a leak position, each mode has its own modal amplitudes of pipe shell displacements $U_{ns}$, $V_{ns}$, $W_{ns}$ and pressure amplitude $P_{ns}$, which are given by:

$$u(x, t) = \sum_{n=0}^{\infty} \sum_{s=0}^{\infty} U_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x + j\pi/2)$$  \hspace{1cm} (4.4)$$

$$v(x, t) = \sum_{n=0}^{\infty} \sum_{s=0}^{\infty} V_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x)$$  \hspace{1cm} (4.5)$$

$$w(x, t) = \sum_{n=0}^{\infty} \sum_{s=0}^{\infty} W_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x)$$  \hspace{1cm} (4.6)$$

In the water column inside the pipe, the acoustic pressure is not uniform both along the radial and circumferential axis of the pipe and is given by

$$p(x, r, t) = \sum_{n=0}^{\infty} \sum_{s=0}^{\infty} P_{ns} \cos(n\theta) J_n(k_s^r r) \exp(j\omega t - jk_{ns}x)$$  \hspace{1cm} (4.7)$$

where $k_{ns}$ and $k_s^r$ are the axial and radial wave numbers respectively. The Bessel function $J_n$ (Abramowitz & Stegun, 1965) in eqn 4.7 above, represents the variation of pressure in various directions. From eqn 4.7, it can be concluded that the acoustic pressure at any point, is highly dependent on the frequency and distance of the measuring position from the leak position. Therefore in the current thesis, a series of pilot study tests were conducted on the MDPE pipe to determine the dominant frequencies which transfer most of the leak energy.

4.3.2 Relationship between pressure and displacement

As discussed above, leak signals are a wave phenomenon, so each little parcel of the carrying medium (water/pip) vibrates in some fashion in the vicinity of its original position and passes on the disturbance and energy to its neighbours (Donald, 1987). These vibrations indicate motion, so assuming that the displacement of any particular parcel of the medium (pipe/water) from its undisturbed position is $\xi(x, t)$, then the corresponding velocity and acceleration is $d\xi/dt$ and $d^2\xi/dt^2$ respectively. As the leak
signals consists of compressions and rarefactions so the displacement $\xi$ differs from place to place making mass density $\rho$ (\(\rho_s\) for the pipe shell and \(\rho_f\) for water inside the pipe) proportional to the spatial derivative of $\xi$. If the mass density from the undisturbed position is $\rho_0$, then the three dimensional displacement $\xi$ is related to acoustic pressure $p$ as

$$-\nabla p = \rho_0 \frac{\partial^2 \xi}{\partial t^2} \quad (4.8)$$

To better explain this in terms of radial pipe shell displacement, it is assumed that the fluid remains in contact with the shell wall, which means that the radial fluid vibrational velocity is equal to the shell radial velocity, i.e.

$$v_r |_{r=a} = v_{sr} \quad (4.9)$$

For any particular wave $(n, s)$, the associated radial displacement is given by

$$\xi_r(r, t)|_{(n,s)} = \frac{1}{\omega^2 \rho_f} \frac{\partial p}{\partial r} = \frac{P_{ns}}{\omega^2 \rho_f} \cos(n\theta) J_n'(k_s^r r) k_s^r \exp(j\omega t - jk_{ns}x) \quad (4.10)$$

The radial fluid velocity at the shell wall can be obtained by differentiating $\xi_r(r, t)$ with respect to time as

$$v_r |_{r=a} = \frac{\partial \xi_r(r, t)}{\partial t} = \frac{j k_s^r J_n'(k_s^r a)}{\rho_f \omega} P_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x) \quad (4.11)$$

where the prime denotes the differentiation with respect to $r$.

Now, the shell radial velocity is given by

$$v_{sr} = \frac{\partial \omega}{\partial t} = j\omega W_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x) \quad (4.12)$$

Substituting in eqn 4.9 to have

$$\frac{j k_s^r J_n'(k_s^r a)}{\rho_f \omega} P_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x) = j\omega W_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns}x) \quad (4.13)$$

$$\Rightarrow \quad P_{ns} = \frac{\omega^2 \rho_f W_{ns}}{k_s^r J_n'(k_s^r a)} \quad (4.14)$$

This indicates that the pressure amplitude for any particular mode $(n, s)$ is directly proportional to the shell radial displacement amplitude. For the normal mode $(n = 0)$ and small arguments, where there is less than one half of a fluid wavelength across the pipe diameter, \(J_0'(k_s^r a) \approx -\frac{k_s^r a}{2}\). Substituting above in eqn 4.14 produces:

$$P_s = -2\omega^2 \rho_f W_s / (k_s^r)^2 a \quad (4.15)$$
where \( k_r^* \) is the radial wavenumber. In eqn 4.15, \( P_s \) is inversely proportional to \( k_r^* \), which means that leak signals propagate in pipes at a speed lower than that in free space. Thus, the velocity of sound in a pipe filled with water is comparatively less than in water (1447m/s). For the normal mode, the two types of plane waves mentioned in section 4.2.1 can be numerically expressed in terms of their wavenumber \( (k_{ns}) \) as:

- **Fluid wave**: It is termed a fluid wave as its energy is predominantly contained in the fluid. The wavenumber \( k_1 \) for the fluid wave is derived in Appendix B.2 and is given by

\[
k_1^2 = k_f^2 \left( 1 + \frac{2B_f/a}{(E_h/a^2 - \omega^2(\rho_s h + M_{rad}) + j\omega R_{rad})} \right)
\]

(4.16)

where \( B_f \) is the Bulk modulus of fluid, \( 2B_f/a \) corresponds to the stiffness of contained fluid, \( E_h/a^2 \) represents the pipe wall stiffness, \( \omega^2\rho_s h \) is pipe wall mass component and \( M_{rad} \) and \( R_{rad} \) corresponds to the radiation mass and resistance of the surrounding medium respectively. For pipes with no backfill, \( R_{rad} \) and \( M_{rad} \) are too small to be ignored (Appendix B.2), which makes the value of \( k_1 \) as

\[
k_1^2 = k_f^2 \left( 1 + \frac{2B_f/a}{(E_h/a^2 - \omega^2\rho_s h)} \right)
\]

(4.17)

As mentioned in Appendix B.2, eqn 4.17 can also be expressed in terms of the normalized ring frequency \( (\Omega) \) and fluid loading term \( \beta = (2B_f a/E_h)(1 - \nu^2) \) to have

\[
k_1^2 = k_f^2 \left( \frac{1 - \Omega^2 - \nu^2 + \beta}{1 - \Omega^2 - \nu^2} \right)
\]

(4.18)

In eqn 4.18, as \( k_1 \) is directly proportional to \( \beta \) therefore the wavespeed \( (s=1) \) will decrease with increasing pipe wall stiffness so the fluid wave in pipe is slower than one in free space. As the frequency approaches the pipe ring frequency, the denominator of the above eqn 4.18 tends to zero, so the wavenumber \( k_1 \) approaches infinity. As the wavenumber is inversely proportional to wavespeed so the wavespeed approaches zero. It means that normal mode waves propagate below the pipe ring frequency.
• **Shell wave:** This is termed as a longitudinal wave or shell wave as its energy is contained in the pipe wall. As mentioned in Appendix B.2, the wavenumber $k_2$ corresponding to the shell wave ($n=0$, $s=2$) is given by

$$k_2^2 = k_I^2 \left(1 + \frac{Eh\nu^2/a^2}{(1-\nu^2)(Eh/a^2 + 2B_f/a - \omega^2(p_s h + M_{rad}) + j\omega R_{rad})}\right)$$  \hspace{1cm} (4.19)

For pipes with no backfill, $M_{rad}$ and $R_{rad}$ can be ignored to have

$$k_2^2 = k_I^2 \left(1 + \frac{Eh\nu^2/a^2}{(1-\nu^2)(Eh/a^2 + 2B_f/a - \omega^2 p_s h)}\right)$$  \hspace{1cm} (4.20)

Similarly like for $s=1$ wave, $k_2$ can be expressed in terms of $\Omega$ and $\beta$ to have,

$$k_2^2 = k_I^2 \frac{1 - \Omega^2 + \beta}{1 - \Omega^2 - \nu^2 + \beta}$$  \hspace{1cm} (4.21)

At low frequencies (well below the pipe ring frequency), the mass terms will be small compared to the stiffness terms and thus the $s = 2$ axisymmetric wave is slower than the compressional wave ($k_I$).

All of this means that, providing the frequency stays moderately low below the pipe ring frequency, the fluid and longitudinal waves are of sole concern for transferring leak energy for the mode $n=0$. Therefore, these two waves are the subject of the present investigation in this chapter.

### 4.4 Leak energy flow in pipes

For any leak in water distribution pipes, there will be a distribution of leak energy between the pipe shell and contained water. The degree to which this energy is concentrated in each medium depends upon the physical parameters of pipe and water properties. This section, presents the ratio of the leak energies in the pipe wall and fluid (water) for normal mode, as most of the leak energy is transferred in this mode. For practical applications such as correlating leak signals, only the energy flow through pipes in an axial direction is considered, which is the sum of the water-borne and shell-borne leak energy.
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4.4.1 Water-borne leak energy flow

The water-borne leak energy in an axial direction is calculated by integrating acoustical intensity over the cross-sectional area of the water column (de Jong et al., 1992). Acoustical intensity is defined as the time averaged product of the pressure $p$ and axial velocity $v_x$. Thus, the axial water-borne energy is given by

$$E_f = \int_0^a \int_0^{2\pi} p v_x r dr d\theta$$

(4.22)

where the axial acoustic particle velocity ($v_x$) is related to an axial pressure gradient by the Euler’s equation as:

$$v_x = -\frac{1}{j \rho f \omega} \frac{\partial p}{\partial x} = \frac{k_{ns}}{\rho f \omega} P_{ns} \cos(n\theta) J_n(k_s r) \exp(j \omega t - j k_{ns} x)$$

(4.23)

In the axial direction, acoustic intensity is given by

$$I(\theta, r, t) = \frac{1}{2} \text{Real}(p v_x^*) = \frac{P_{ns}^2}{2 \rho f \omega} \frac{k_{ns}}{2} \cos^2(n\theta) J_n^2(k_s r)$$

(4.24)

where $v_x^*$ denotes the complex conjugate of $v_x$. The total water-borne energy in an axial direction is obtained by integrating the acoustical intensity over the cross-sectional area of the water column, and is given by

$$E_f = \int_0^{2\pi} \int_0^a I(\theta, r, t) dS = \int_0^{2\pi} \int_0^a \frac{P_{ns}^2}{2 \rho f \omega} \frac{k_{ns}}{2} \cos^2(n\theta) J_n^2(k_s r) r dr d\theta$$

(4.25)

$$= \pi P_0^2 \frac{k_s}{\rho f \omega} \int_0^a J_0^2(k_s r) r dr \quad \text{for } n = 0$$

(4.26)

$$= \pi P_n^2 \frac{k_{ns}}{\rho f \omega} \int_0^a J_n^2(k_s r) r dr \quad \text{for } n > 0$$

(4.27)

4.4.2 Shell-borne leak energy flow

As discussed above, the shell borne waves carry the vibrations produced by a leak. In practise, the thickness to radius ratio of water distribution pipes is less than unity. For these thin walled water distribution pipes, the leak energy produced by vibrations is carried almost entirely by extensional and torsional stretching motions (de Jong et al.,
1992). Thus, the total shell-borne leak energy in axial direction is the sum of two individual energies,

\[ E_s = E_e + E_t \]  

(4.28)

where the subscript 'e' refers to the extensional shell motion and the subscript 't' refers to the torsional stretching motion. These can be expressed in terms of forces \( N_x \) and \( N_{x\theta} \) given by simplified Flugge's shell equations and the three dimensional displacements \( u, v, w \) of the shell as:

\[ E_e = \int_0^{2\pi} \frac{1}{2} N_x \dot{u} a d\theta \]  

(4.29)

\[ E_t = \int_0^{2\pi} \frac{1}{2} N_{x\theta} \dot{v} a d\theta \]  

(4.30)

where \( N_x \) and \( N_{x\theta} \) are the axial force and torsional shear force respectively and an overdot implies differentiation with respect to time.

Using the stress-strain relationships of the simplified Flugge’s shell theory, these forces can be written in terms of shell displacements as:

\[ N_{x\theta} = \frac{E_h}{2\alpha^2 (1 + \nu)} \left( \frac{1}{\alpha} \frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial x} \right) \]  

(4.31)

\[ N_x = \frac{E_h}{(1 - \nu^2)} \left( \frac{\partial u}{\partial x} + \frac{\nu}{\alpha} \frac{\partial v}{\partial \theta} - \frac{v}{a} \right) \]  

(4.32)

Using these expressions the total shell power flow for a particular mode \((n, s)\) in an axial direction is given by

For \( n = 0 \)

\[ E_s = \frac{\pi \omega E_h}{1 - \nu^2} \left[ (k_{0s} a) U_{0s}^2 + \nu U_{0s} W_{0s} + \frac{k_{0s} (1 - \nu)}{2\alpha} V_{0s}^2 \right] \exp(2j(\omega t - k_{0s}x)) \]  

(4.33)

For \( n > 0 \)

\[ E_s = \frac{\pi \omega E_h}{1 - \nu^2} \left[ (k_{ns} a) U_{ns}^2 + \nu U_{ns} W_{ns} + \frac{k_{ns} (1 - \nu)}{2\alpha} V_{ns}^2 \right] \exp(2j(\omega t - k_{ns}x)) \]  

(4.34)
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4.4.3 Total energy flow in pipe filled with water

In this section, a comparison of energy flow in water and pipe wall is carried out in order to determine which one dominates for leaks in MDPE pipes. As discussed before, most of the leak energy is transferred by waves propagating in normal mode. Therefore, for normal mode, the ratio of energy distribution (Fuller & Fahy, 1982) between water and pipe shell is given by

\[ E_r = \frac{E_f}{E_s} = \frac{\pi \rho_f \frac{k_s}{U_f} \int_0^a J_0^2(k_s r) r dr}{\pi \rho_h \left[ (k_{0s} a) U_{0s} + \nu U_{0s} W_{0s} + \frac{k_{0s} (1 - \nu)}{2a} \nu^2 \right] \exp(2j(\omega t - k_{0s} x))} \]  

(4.35)

To simplify this, \( P_{0s} \) can be expressed in terms of \( W_{0s} \) given by eqn 4.14, to have

\[ E_r = \frac{E_f}{E_s} = \frac{\frac{\omega^2 \rho_f k_{0s} a^2}{[k_s J_0^2(k_s a)]} \int_0^a J_0^2(k_s r) r dr}{\frac{E h}{1 - \nu^2} \left[ (k_{0s} a) R_{ar}^2 + \nu R_{ar} + \frac{k_{0s} (1 - \nu)}{2a} R_{tr}^2 \right] \exp(2j(\omega t - k_{0s} x))} \]  

(4.36)

where

\[ R_{ar} = \frac{U_{0s}}{W_{0s}} \quad \text{and} \quad R_{tr} = \frac{V_{0s}}{W_{0s}} \]  

(4.37)

are the ratio of axial and torsional to radial amplitudes of vibration. The integral in the numerator is given by

\[ \int_0^a \frac{r J_0^2(k_s r) dr}{a^2} = \frac{a^2}{2} \left\{ [J_0^2(k_s r)]^2 + J_0^2(k_s a) \right\} \]  

(4.38)

Substituting in eqn 4.36 to have

\[ E_r = \frac{\omega^2 \rho_f k_{0s} a^2}{[k_s J_0^2(k_s a)]} \frac{F_w}{F_s} \]  

(4.39)

where the factors \( F_w \) and \( F_s \) are given by

\[ F_s = (h/a) \left( (k_{0s} a^2) R_{ar}^2 + a \nu R_{ar} + \frac{k_{0s} (1 - \nu)}{2} R_{tr}^2 \right) \exp(2j(\omega t - k_{0s} x)) \]  

(4.40)

and

\[ F_w = \frac{1}{2} \left\{ [J_0^2(k_s r)]^2 + J_0^2(k_s a) \right\} \]  

(4.41)

Eqn 4.39 can be further simplified by the substitution of \( c_s^2 = E/\rho_s (1 - \nu^2) \) and \( \Omega = \omega a/c_s \) to give the final non-dimensional relationship for energy distribution,

\[ E_r = \frac{\Omega^2 k_{0s} \left[ k_s J_0^2(k_s a) \right]}{\frac{F_w}{\rho_f}} \]  

(4.42)
From eqn 4.42, it can be interpreted that at low frequencies and for the normal mode \((n=0)\), the ratio of leak energies depends upon the ratio of \(P_j/P_s\) and the thickness to radius ratio \((h/a)\). For a practical thin walled 125mm MDPE pipe \(P_j/P_s < 1\), as water is less dense than the MDPE material. This means that at low frequencies, there will be more energy in the shell wall compared to the fluid. However, at high frequencies, the energy may be distributed to a varying degree between the shell and fluid. Thus:

For a leak in a MDPE water distribution pipe, there will be more leak energy produced in the pipe wall due to vibrations compared to the leak energy produced in the water due to acoustic leak signals.

### 4.5 Experimental analysis

A test rig of 125mm diameter MDPE pipe and 14m length (Figure 4.3) was built in the hydraulics laboratory, Department of Civil and Building Engineering, Loughborough University. One end of the pipe was connected to a water supply tank using a MF2000 metal seated gate valve (British Standard (BS) 5163 type B), which provided an approximate pressure of 190kPa. The other end of the pipe was connected to a one metre pipe section (Figure 4.3(b)), using flange plate couplings (BS 4504) with full face rubber gasket in between. The other end of this pipe section was connected to a FH2 fire hydrant (DN80, PN16 pressure rating and BS 750 type 2) using flange fittings with a 100mm full face rubber gasket in between. MDPE couplings were connected to the pipe using electro-fusion welding. The test rig was built in a cul-de-sac shape on the firm floor because of space restrictions.

Vibrations produced by leaks were measured using Monitran DF10 accelerometers (sensitivity 10V/g and frequency response 0.1Hz to 5kHz). For measuring acoustic leak signals, hydrophones (sensitivity 30\(\mu\)V/Pa and frequency response 0.1Hz to 100kHz) were used. The pipe was marked at intervals of 1m starting from the flange fitting as shown in Figure 4.3(b). At each mark, \(1/4\"-28\)UNF screws were glued to make stud mountings for accelerometers as shown in Figure 4.4(a) and 4.4(c). Accelerometers were attached firmly to these screws with a 2mm thick steel washer in between. For better contact, a thin layer of silicone gel was applied on both sides of the washers. A magnetic mounting was used to connect the accelerometer to the hydrant (Figure 4.4(d)) and
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Valves (Figure 4.4(b)). A hydrophone was connected to the hydrant using London round thread adapter, with a thin layer of silicone gel on the internal rubber seal of the adapter to make a better contact. For these pilot study experiments backfill was not used, based on the studies of Muggleton et al. (2002), which concluded that the effect of the surrounding medium on the wavespeed in buried plastic pipes is relatively small. This test rig is designed with the aim:

- To understand the behaviour of leak signals in MDPE pipes without backfill.
- To develop the instrumentation and the signal processing techniques and design the test rig for the MDPE pipe with backfill.

4.5.1 Test procedure

Leaks with various shapes, sizes and approximate flow rates between 2 l/min and 25 l/min were simulated at the following three points on the test rig:

- Leaks at hydrant by opening the hydrant valve and removing the hydrophone.
- Leaks at flange plates by loosening the nuts, making a bad joint.
- Split leak on the one metre pipe section by making a crack in the pipe, 3cm long in the axial direction.

Sensors were connected at the hydrant top using magnetic mounting and at 6.5m and 14m (gate valve) from the hydrant using stud mountings as shown in Figure 4.4. The output of these sensors was amplified using a MJS 401D audio amplifier with the gain set to 40dB. These amplified leak signals were digitised using a 12 bit analog to digital converter (National Instrument (NI) DAQ-9221) and recorded on the hard disk of a computer using the NI data acquisition software 'VI logger'. A high sampling rate of 10kHz and a dynamic range of ±3V was chosen so that a good resolution of signal could be obtained. A sampling rate of 10kHz was chosen as it is assumed that the leak signals in MDPE pipe exists in the audio range up to 3kHz. These amplified signals were then filtered using a 5th order digital Butterworth band pass filter with the lower cut-off frequency set to 5Hz and higher cut-off frequency of 1.5kHz. Spectral analysis was then performed on the filtered signals using 1024 point FFT, averaging and a Hanning window for better frequency resolution. To avoid the circular effect of FFT, a 512 point
Figure 4.3: (a) Test rig at hydraulics laboratory and (b) Schematic diagram of the test rig.
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Figure 4.4: (a) Stud mounting for accelerometers, (b) Magnetic mounting at the gate valve, (c) Stud mounting at fitting of gate valve, (d) Sensor connected at the hydrant with magnetic mounting and a thin layer of silicon gel in between.

rectangular force window with 50% overlap was applied to the transformed data. In this test rig, there was no facility to connect a flow meter to precisely measure leak flow rate, so the leaks were classified into two categories:

<table>
<thead>
<tr>
<th>Category</th>
<th>Flow Rate (l/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>up to 10</td>
</tr>
<tr>
<td>Large</td>
<td>10 Onwards</td>
</tr>
</tbody>
</table>

A series of 28 leaks were simulated at hydrant, flange plate and split leak, with different flow rate and shapes. Initially, the leak signals were monitored for a length of 5 minutes, however later on leak signals of a length of approximately 110 seconds were recorded for post processing. The results obtained are discussed below in section 4.5.2.
4.5.2 Leaks at hydrant

Initially, a small scale leak (Table 4.1) was simulated at the hydrant as shown in Figure 4.5. It was later changed to a large scale leak using the hydrant valve.

![Figure 4.5: A typical small scale leak at the hydrant](image)

4.5.2.1 Small scale leaks at hydrant

For a typical small scale leak shown in Figure 4.5, the frequency spectrum of signals measured is shown in Figure 4.6 and are explained below:

- **At the hydrant:** The frequency spectrum of signals measured at hydrant were found to be different from those obtained at other locations. It showed some high frequency signals between 500Hz and 1.2kHz (Figure 4.6(a)). These signals represents locally generated evanescent, quasi-propagating and standing waves at hydrant, which may be due to the:

  - Variation in size, shape and material of the propagation medium at hydrant. Some of the sources of these variations are fitting bends and internal structure of the hydrant (Figure 4.4(d)).
  
  - Reflection of signals from the hydrant top cover and fitting bends.

These signals were found to be highly attenuated with distance along the pipeline and were evident only up to short distances from the hydrant. This matches with the theory that the evanescent and quasi-propagating waves decay exponentially with distance along the pipeline.
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• At 6.5m from the hydrant: The frequency spectrum of signals obtained from the sensor located at 6.5m from the hydrant is shown in Figure 4.6(b). The observations made are as follows:

  - Most significant signals exists in the band 10Hz to 500Hz approximately.
  - The signals between approximately 60Hz to 150Hz were found to be of higher amplitude compared to those measured at hydrant (Figure 4.6(a)). This may be due to the locally generated waves at the pipe bend, located approximately 3m from this sensor position or because of increased distance from leak position.
  - The signals between 350 Hz and 500 Hz were found to be significantly attenuated.
  - The signals with a frequency above 550 Hz observed at the hydrant are no longer evident here, indicating that these are not the actual leak signals and that they have decayed completely over a short distance.

• At gate valve (14m from the hydrant): The frequency spectrum of the signals measured at the gate valve is shown in Figure 4.6(c). The signals were found to exist between 20Hz and 500Hz. Most of these signals were found to be attenuated (especially those above 350Hz) in comparison to those measured 6.5m from the hydrant and at the hydrant itself. Finally from Figure 4.6(c), it can also be interpreted that the effect of locally generated signals at the gate valve is less than compared to those at the hydrant and pipe bend.

4.5.2.2 Large scale leaks at the hydrant

The leak flow rate was increased by further opening the hydrant valve to make a large scale leak, but the gate valve settings were kept unchanged. Readings were taken at the gate valve and the frequency spectrum of the signals measured is shown in Figure 4.6(d). It is found to be similar to that obtained for the small scale leaks at the same sensor position (Figure 4.6(c)). However, all the signals up to approximately 350Hz were found to be amplified. This is due to the reason that increasing leak flow rate, increases the speed of water flowing through the leak aperture. This high speed flowing water exerts more pressure on the leak boundary, resulting in comparatively
higher amplitude signals. This matches with the theoretical results that for a fixed size leak increasing the flow rate increases the amplitude of leak signals.

Figure 4.6: Amplitude and frequency variation with time of signals corresponding to a small scale leak simulated at the hydrant. The signals were measured at the (a) hydrant, (b) 6.5m from the hydrant and (c) gate valve (14m from the hydrant). (d) Amplitude and frequency variation with time of signals measured at gate valve. These signals correspond to a large scale leak generated at hydrant.

4.5.3 Leaks at flange plates

A typical small scale and large scale leak simulated at the flange plate is shown in Figures 4.7(a) and 4.7(b) respectively. For these leaks, the frequency spectrum of signals measured at hydrant, 6.5m from hydrant and gate valve is shown in Figures 4.7(c), 4.7(e) & 4.7(g); and 4.7(d), 4.7(f) & 4.7(h) respectively. Comparing these results with those obtained at the same positions for leaks at hydrant (Figure 4.6), it can be interpreted that:

- For these leaks, a wide frequency spectrum was not obtained at the hydrant, as in the case of leaks at the hydrant. This means that any leak at the hydrant boosts the amplitude of locally generated signals at the hydrant.

- The frequency range of signals measured at the hydrant exist up to approximately 550Hz for all leak types. However, for small scale flange plate leaks some signals...
were found to be of comparatively smaller amplitude, which may be due to the
difference in leak characteristics such as flow rate, size and shape, and also due
to the attenuation of signals as the sensor was roughly 3m away from the leak
position. This indicates that signals up to 550Hz are related to the leak.

- The frequency spectrum of signals obtained from the sensor connected at 6.5m
  (Figure 4.7(e) & 4.7(f)) follows the same pattern as for leaks at the hydrant.
  However, the signals were found to be of comparatively higher amplitude, which
  may be due to the fact that in this case the sensor is closer to the leak position.

- At the gate valve, signals (Figure 4.7(g) & 4.7(h)) above 250Hz were found to be
  highly attenuated similar to as for the leaks at the hydrant (Figure 4.6(c)).

Comparing the results obtained for small scale flange plate leaks with large scale flange
plate leaks, it can be interpreted that:

- The frequency spectrum of signals measured for the two leak types is almost
  similar as the previous experiments with most of the signals existing upto 550Hz.

- Increasing the leak flow rate increased the amplitude of the signals (Figures 4.7(d),
  4.7(f) and 4.7(h)) especially in the frequency range 60Hz to 550Hz. This matches
  with the theory that for a fixed size leak, the amplitude of signals varies directly
  proportional with the leak flow rate.

- At 6.5m from the hydrant, some higher frequency signals between 600Hz to 750Hz
  were observed for the large scale leaks in flange plates. This may be due to the fact
  that the increase in leak flow rate increased the flow rate of water which produces
  stronger signals at the pipe bend. However, these signals were not evident at the
  hydrant and gate valve.
Figure 4.7: A typical (a) small scale leak and (b) large scale leak generated at the flange plate. Amplitude and frequency variation with time of leak signals generated by small scale flange plate leak and measured at (c) hydrant, (e) 6.5m from the hydrant and (g) gate valve. Amplitude and frequency variation with time of leak signals generated by large scale leak at flange plate and measured at (d) hydrant, (f) 6.5m from the hydrant and (h) gate valve.
4.5.4 Split leaks on one metre pipe section

The third type of leaks simulated in the test rig were split leaks made by forming a crack in the pipe. A typical split leak simulated in the test rig is shown in Figure 4.8. The gate valve was used to control the leak flow rate of split leaks. For this leak type, water pressure was approximately 160kPa. Sensors were connected at the same positions on the test rig as in previous tests and the spectrum of signals obtained is shown in Figure 4.9.

- From Figure 4.9(a), it can be interpreted that the frequency spectrum of signals measured at the hydrant is different from that obtained at the same position in earlier experiments. Some high frequency signals with high amplitude were observed near 1kHz. The signal spectrum up to 550Hz is similar to those obtained in earlier experiments. However, some signals between 40Hz and 150Hz were found to be of comparatively small amplitude. This may be due to the variation in pressure and leak characteristics.

- At 6.5m from the hydrant (Figure 4.9(b)), a big difference is observed compared to previous cases, as signals with large amplitude appear between 550Hz to 650Hz approximately. This is because the leak flow rate in this test was controlled by the gate valve. The gate valve was not fully opened, which affects the water flow at the pipe bend and gate valve, and may result in this different behaviour.

- At the gate valve (Figure 4.9(c)), a similar frequency spectrum can be seen to that obtained at the hydrant (Figure 4.9(a)). It also shows some high frequency signals around 1.0kHz. Thus, it can be concluded that if a hydrant leaks or the
gate valve is not fully opened then this may produce high frequency signals in addition to leak signals.

![Frequency spectrum graphs](image)

Figure 4.9: A typical split leak on one metre pipe section. Amplitude and frequency variation with time of leak signals measured at (a) the hydrant, (b) 6.5m from the hydrant and (c) the gate valve.

### 4.5.5 Signals measured with hydrophone

A hydrophone was connected at the hydrant outlet using a London round thread adapter in order to measure the acoustic leak signals generated by split leaks in the test pipe. The frequency spectrum of signals measured is shown in Figure 4.10. The signals were found to exist up to approximately 300 Hz. Comparing with Figure 4.9(a), it can be observed that the acoustic signals are of comparatively lower frequency, with a narrow bandwidth. This last observation confirms qualitatively the theory that for leaks in a MDPE pipe, shell-borne energy is greater than the water-borne energy. Finally, it can be concluded that the leak signals measured by hydrophones were of narrow bandwidth and exist up to 300 Hz.
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4.5.6 Reproducibility of leak signals

To determine whether leak signals can be reproduced, two tests were conducted:

- The first test used the small scale leak at the flange plate, shown in Figure 4.7(a). A sensor at position 6.5m from the hydrant was removed and reconnected again without disturbing the leak. The frequency spectrum of signals obtained is shown in Figure 4.11(a). Comparing this with Figure 4.7(e), it can be concluded that the frequency spectrum obtained is almost the same, which means that the leak signals are continuous and do not vary significantly with the time and reconnection of sensors, provided the leak characteristics and water pressure remain unchanged.

- In the second test, water supply was stopped to close the large scale leak at the flange plate. In place of this a small scale leak was made and the signals were measured at 6.5m from hydrant. The frequency spectrum of signals measured is shown in Figure 4.11(b). Comparing with Figures 4.11(a) and 4.7(e), it is found that the signal pattern is very similar. However, some signals were found to be attenuated and missing as it is not possible to simulate exactly the same leak as made in Figure 4.7(a).
Figure 4.11: (a) Amplitude and frequency variation with time of leak signals corresponding to a small scale leak generated at the flange plate. These signals were measured at 6.5m from the hydrant to determine the reproducibility of signals. (b) Spectrum of leak signals measured at 6.5m from the hydrant, when a large scale leak at flange plate was reduced to a small scale leak.

4.6 Phase of leak signals in fluid filled pipes

For any leak, the acoustic pressure varies inside the pipe (eqn 4.7). However, for the frequency range where the wavelength of the water-borne wave \((n=0, s=1)\) is much greater than the diameter of pipe, acoustic pressure can be considered to be uniform across the cross-section and its Fourier Transform is given by

\[
p(\omega, x) = P_0(\omega)e^{-jk_1x}
\]

where \(x\) is the distance between leak and sensor positions, \(P_0(\omega)\) is the amplitude of acoustic pressure at leak position \((x=0)\) and \(k_1\) is the wavenumber which is related to wavespeed \((c)\) and attenuation \((\alpha)\) of leak signals by:

\[
k_1 = \frac{\omega}{c} - j\omega\alpha
\]

(4.44)

Substituting in eqn 4.43 to get:

\[
p = P_0(\omega)e^{-\omega\alpha x}e^{-j\omega x/c}
\]

(4.45)

where phase \(\phi\) is given by

\[
\phi = -\frac{\omega x}{c}
\]

(4.46)

It is clear from eqn 4.45 that the phase of the leak signals is negative and for a constant distance and velocity, phase varies linearly with frequency. However, in practise the
phase-frequency relationship obtained was not very linear (Figure 4.12), which may be due to the fact that not all signals in the measured frequency range were leak signals. Thus, for a linear relationship it is essential to have a priori knowledge of the frequency range of leak signals. For the small scale leak at the hydrant, large scale leak at flange plate and split leak discussed previously, the phase-frequency relationships of the signals measured using the accelerometer connected at the hydrant and gate valve are shown in Figures 4.12(a) & 4.12(b); 4.12(c) & 4.12(d) and 4.12(e) & 4.12(f) respectively. The phase-frequency relationship for the hydrophone detected leak signals, generated by split leaks is shown in Figure 4.12(g). The main findings from the results obtained are as follows:

- A slightly non-linear response is observed for signals below 20Hz for all types of leaks. A similar irregular behavior can also be seen in their frequency spectrum discussed in previous section. This may be due to the reason that these signals were dominated by the ambient noise, which most probably corresponds to the resonance of the test pipe.

- From Figure 4.12, it can be interpreted that the phase-frequency relationship for signals with frequency range between 20Hz and 250Hz is nearly linear. The same is true for the frequency spectrum, where most of the signals were found in this range. However, for split leaks (Figures 4.12(e) & 4.12(f)) the phase-frequency relationship obtained in this range is not very linear, which may be due to the extra noise generated at the gate valve in comparison to other leaks. This extra noise at the gate valve is because it was not fully opened for the split leaks.

- The phase-frequency relationship for signals between 250Hz and 400Hz was not very linear as few leak signals exists in this range. However, for the large scale leak (Figures 4.12(c) & 4.12(d)), the linearity extends up to 400Hz. This is because a large number of leak signals were found to be evident in this range for large scale leaks.

- In some cases, a linear phase-frequency relationship is obtained for signals with frequency in between 400Hz to 550Hz. This is true for the frequency spectrum of leak signals as some leak signals were found to be evident in this frequency range.
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- Above 550Hz, the response is non-linear and varies considerably, probably due to the high level of ambient noise. This matches with the results obtained for the frequency spectrum where very few signals were found to exist above 550Hz.

- For the hydrophone measured signals (Figure 4.12(g)), a linear phase-frequency relationship was obtained between 20Hz and 200Hz, as acoustic leak signals were found to be of low frequency.

- In some cases, the line does not pass through origin, which is possibly due to dominant ambient noise at low frequencies.

In general, it can be concluded that for most leak types, the most significant phase information is concentrated between 20Hz to 300Hz for accelerometer measured signals. However, for hydrophone measured signals, the linear dependence exists roughly in the frequency range 20Hz to 200Hz. Therefore, the pass band of the filter was set from 10Hz to 300Hz for hydrophone measured signals and from 20Hz to 400Hz for accelerometer measured signals in later experiments in this thesis. The relative phase-frequency relationship between the leak signals measured simultaneously at two positions to perform correlation is discussed in Chapter 5.

4.7 Summary

Finally, the results obtained in all the tests presented in this chapter can be summarized below:

- The leak signals measured with an accelerometer were found to exist between 20Hz and 500Hz and are mostly concentrated below 350Hz. The frequency spectrum shift towards 500Hz and above with increase in pressure and flow rate.

- The hydrophone measured leak signals were mainly of low frequency in the range 20Hz to 300Hz.

- Access points such as a hydrant and discontinuities such as bends generate signals which decay very quickly with distance along the pipeline. The frequency and amplitude of these signals vary significantly with the water flow rate. This may
Figure 4.12: Phase-frequency relationship of signals measured at (a)(c)(e) the hydrant and (b)(d)(f) the gate valve. Signals in (a)(b) corresponds to a small scale leak at the hydrant, in (c)(d) to large scale leak at the flange plate and (e)(f) to the split leak. (g) Phase-frequency relationship of signals generated by spilt leaks and measured using a hydrophone.
be due to the change in shape, size and material of the propagating medium over a short length.

- Most of the signals with the frequency range up to approximately 400Hz are reproducible, subject to the condition that leak characteristics and fluid pressure are not significantly changed.

- The phase of the leak signals between 20Hz to 250Hz varies approximately linearly with frequency.

- Finally, the MDPE plastic pipes act as a low pass filter; however, the cut-off frequency is not limited to 120Hz as mentioned by Gao et al. (2004) and Hunaidi & Wang (2000). The frequency of leak signals varies with leak characteristics, pressure and measuring positions relative to the leak.

The effect of longer lengths of pipe, backfill and pipe dimensions is discussed in Chapters 5 and 6 of this thesis.

4.8 Conclusion

In this chapter, calculations are presented for the motion of the acoustic leak signals borne in fluid and the shell borne vibrational leak signals, assuming that the frequency of leak signals are well below the pipe ring frequency. For MDPE pipes, it is found that the acoustic leak signals ($s=1$) are strongly influenced by the pipe wall flexibility. However, the vibrational leak signals ($s=2$) are only slightly influenced by water contained in the pipe.

The ratio of energies associated with these waves is calculated and it is found that for MDPE pipes, the shell-borne energy dominates the water-borne energy. A series of pilot study tests were conducted and from the results obtained it is concluded that leaks in MDPE pipes without backfill exist between 20Hz to 350Hz, which may extend to 550Hz with change in leak characteristics, pressure and measuring position relative to leak. It is also found that for the frequency range 20Hz to 250Hz, the phase varies linearly with frequency, as expected from the theoretical results.
Chapter 5

Leak Signals in Buried MDPE Pipes

The performance of the correlation process in detecting and locating leaks depends upon the characteristics of leak signals, which further depends upon several factors such as the quality of leak signals obtained from sensors and the attenuation due to the pipe material. In Chapter 4 and Pal et al. (2006), characteristics of leak signals travelling in MDPE pipes without backfill were discussed. It was found that most of the leak signals, corresponding to the leaks simulated in MDPE pipes without backfill, lie in the frequency range 20Hz to 350Hz. It was also found that the upper limit of this frequency range increases towards 550Hz and above with an increase in flow rate. An approximately linear phase-frequency relationship was also observed for the frequency range 20Hz to 250Hz. However, in practice water distribution pipes are buried and consist of a large number of discontinuities. These discontinuities and the backfill affect the generation and characteristics of leak signals, which are not well known for buried MDPE pipes.

Therefore in this chapter, a series of pilot study tests are presented where buried MDPE pipes were fully evaluated. The results obtained are compared with leaks in MDPE pipes without backfill.

5.1 Leaks in buried MDPE pipes

A series of pilot study tests were conducted on buried MDPE pipes at the Severn Trent Lake House test site located in Anstey, Leicester. The layout of the buried
pipe network at Lake House is shown in Figure 5.1(a). The network comprised of a combination of ductile iron, asbestos cement, MDPE and PVC pipes with water supplied by a pump. Tests were conducted on a 125mm diameter MDPE pipe buried along the 'Trent Lane' shown in Figure 5.1(a). The schematic of this MDPE pipe test rig is shown in Figure 5.1(b). The 125mm diameter MDPE main pipe was 45.1m long with hydrants (H1, H2) connected to each end. A 25mm diameter MDPE service pipe approximately 3m long was connected to the main pipe at 7.8m from the hydrant H1 using electro-fused fittings and a boundary box. The other end of this service pipe was closed with a stop cap. A circular hole measuring approximately 1mm in diameter was made inside the stop cap, which acts as a known source of leakage. The boundary box valve was used to control the leak flow rate. Signals were measured from the hydrants H1 and H2, connected at 7.8m and 34.3m respectively from the boundary box. These signals measured were therefore a combination of signals produced by two sources:

1. A 1mm diameter circular hole in the stop cap connected at the end of the 25mm MDPE service pipe.

2. The boundary box and fittings used to connect the service pipe to the main pipe. Because of the change in the size of water column at the boundary box and fittings, the water flow rate changes at these discontinuities, which generates evanescent and quasi-propagating vibro-acoustic signals.

5.1.1 Test procedure

The boundary box valve was fully opened to allow water to leak through the stop cap hole. Initially, the water pressure inside the pipe network was set to 820kPa, which was later changed to 350kPa and 150kPa. Signals were measured from hydrants H1 and H2 using accelerometers. These accelerometers were connected to the access points using magnetic mountings. The output of these accelerometers was amplified using Sound and Devices MMF-1 pre-amplifier, with a gain setting of 42dB. These amplified signals were transmitted to a processing unit using two low loss coaxial cables each 40m long. The processing unit consisted of a NI DAQ 9221, which converts the input signals into digital signals at a sampling rate of 10kHz. A sampling rate of 10kHz was chosen as the frequency range of simulated leak signals was unknown. Finally for
Figure 5.1: (a) Layout of the pipe network buried at ST Lake House. (b) Schematic diagram of test rig made up of 125mm diameter MDPE main pipe and 25mm diameter MDPE service pipe, buried along the Trent Lane (after Divit (2005)).
post processing, the digital signals were recorded on to the hard disk of a PC using NI VI logger software. These recorded signals were later analysed using signal processing techniques in Matlab. Following the recording of leak signals, the simulated leak was shut down for some time to stabilise the water flow, after being disturbed by the leak. Signals were recorded again in the absence of leak and were considered to contain the background noise. This background noise was a combination of the continuous noise made by water pumps, random noise by wind, the human voice and physical movements (such as foot steps) above ground, and the low frequency pipe resonance due to flowing water. After recording both the leak signals and background noise, the same process was repeated for the pressure values of 350kPa and 150kPa.

5.2 Results and observations

5.2.1 Effect of pressure

To understand the effect of pressure, leaks were simulated at the pressure values of 150kPa, 350kPa and 820kPa. The frequency spectrum of the measured leak signals and background noise is shown in Figures 5.2 and 5.3 respectively. The observations made from the results obtained are:

- The frequency spectrum of background noise recorded for the three pressure values is nearly the same, with some signals found up to approximately 150Hz. These signals were a combination of several noises such as the noise made by wind and the low frequency pipe resonance. Some signals near 800Hz and 500Hz were observed in Figures 5.3(c)(d) and 5.3(e)(f) respectively; however, their source is not known.

- Most of the leak signals were found below 200Hz, with the high amplitude leak signals mostly concentrated in the narrow frequency range of 10Hz to 160Hz.

- A low frequency drumming sound was heard at both hydrants. It was also found to be clearly audible at longer distances in the pipe network. This sound was produced by the boundary box, which was confirmed by opening and closing the boundary box valve. When the valve was closed to shut down the simulated leak the sound was no longer audible, and on opening the valve again the sound was
again audible. This proved that the sound was produced by the boundary box. It was also noted that the amplitude of the sound decreased with a decrease in water pressure. However, at low pressures (150kPa and 350kPa), the drumming sound produced by the leak was not as clearly audible as in the case of 820kPa pressure. It is because the leak source in this test rig was small (1mm diameter hole) so the signals produced at low pressures (150kPa and 350kPa) were of comparatively lower amplitude than produced for 820kPa. The loudness of signals was found to be following the theoretical results that for a fixed dimensional leak, increasing the water pressure increases the amplitude of leak signals. This can also be observed in Figure 5.3, where the amplitude of signals is found to be increased with increase in pressure.

• At low pressures (150kPa and 350kPa), the leak signals resembles background noise and sounds like the normal pipe resonance noise but slightly louder. Their presence at low pressure was confirmed by opening and closing the valve and noticing the change in sound. It was found that the sound changes on opening and closing the valve, which indicates that leak signals exist but are highly suppressed by the background noise.

• At high pressure (820kPa), the leak signals were clearly audible and distinguishable from the background noise (Figure 5.3(c)). However, their frequency spectrum is similar to those at 150kPa and 350kPa and exists upto 200Hz. Thus, it can be concluded that for a fixed dimensional leak in a buried pipe, increasing the pressure increases the amplitude of signals without affecting the frequency of leak signals.

5.2.2 Effect of backfill

The effect of backfill is not very clear from the tests conducted in the hydraulics lab and at ST Lake House. This is because the conditions such as pressure, leak size and flow rate, under which the leaks were simulated were different for both the test rigs. Also, the relative measuring positions from the leak were different for both cases. However, some information can be gained by comparing the tests conducted on the two rigs. It was noticed that with an increase in pressure in the buried MDPE pipe,
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Figure 5.2: Background noise measured from hydrants connected to a buried 125mm diameter MDPE pipe test rig on Trent Lane at ST Lake House. Signals were recorded from the hydrant located at (a)(c)(e) 7.8m (H1) and (b)(d)(f) 37.3m (H2) from the boundary box. The pressure inside the pipe was 150kPa, 350kPa and 820kPa for (a)(b); (c)(d) and (e)(f) respectively.
Figure 5.3: Frequency spectrum of leak signals generated by a leak in the stop cap at the end of the 25mm diameter MDPE service pipe connected to a 125mm diameter MDPE main pipe lying along the Trent Lane. Amplitude and frequency variation with time of leak signals recorded from hydrants located at (a)(c)(e) 7.8m (H1) and (b)(d)(f) 37.3m (H2) from the boundary box. The pressure inside the pipe was 150kPa, 350kPa and 820kPa for (a)(b); (c)(d) and (e)(f) respectively.
the amplitude of signals was found to be increased without any significant change in frequency. However, when the pressure was increased in MDPE pipes without backfill in the hydraulics lab, the frequency range was also found to be increased. The most likely reason is that the test rig in the hydraulics lab was lying on the firm floor and water leaking from the pipe was striking the floor. With change in pressure, the speed at which the leaking water exits the pipe and strikes the floor also changed which results into signals of different frequencies. However in the case of buried pipes at Lake House, leaking water agitates the backfill soil particles which absorbs energy and does not produce new leak signals with different frequencies. A more detailed study of the effect of backfill will be presented in Chapter 8.

5.2.3 Comparison with leaks in other pipe materials

5.2.3.1 Tests at Lake House on ductile iron pipes

To understand the behaviour of metallic pipes, a test was conducted on the buried 100mm diameter ductile iron pipe test rig located in the 'SOAR Avenue' of ST Lake House pipe network (Figure 5.1(a)). The schematic of this test rig is similar to MDPE pipe test rig in Figure 5.1(b). However in this test rig, a 20mm diameter ductile iron service pipe was connected to the main pipe. The service pipe was at 22.1m from the hydrant H3 connected at one end of the 100mm diameter main pipe. Similar to the MDPE pipe test rig, a leak was simulated by making a 1mm diameter circular hole in the stop cap connected at the end of service pipe. A boundary box was also connected in between the service pipe and main pipe, and its valve was used to control the leak flow rate. The water pressure inside the pipe was set to 350kPa. For this pressure value, the frequency spectrum of measured leak signals and background noise is shown in Figure 5.4. It can be seen that the leak signals generated in ductile iron pipes were of comparatively wide bandwidth (750Hz) and frequency range up to 800Hz approximately. The background noise was also found to be of wide bandwidth with some significant signals measured up to 300Hz (Figure 5.2(b)). These results match with the theory that the wavenumber of leak signals varies with the stiffness of pipe material. Thus, it can be concluded that keeping the pipe dimensions, leak characteristics (shape and size) and water pressure fixed, a leak in less stiff MDPE pipes will generate signals of lower frequency and narrower bandwidth compared to metallic pipes.
5.2.3.2 Field tests on asbestos cement pipes

To understand leaks in non-metallic pipe materials other than MDPE, signals were recorded from a real leaking 150mm diameter asbestos cement mains at Wymswold, Leicestershire. The pipe was running at an approximate pressure of 220kPa, with its layout shown in Figure 5.5(a). The two access points (hydrants A and B) on this main were 523m apart (Figure 5.5(a)). Using DMA testing, it was first confirmed that a leak exist in this pipe. The leak location on this pipe was computed by performing correlation using a Microcorr 6 correlator. A clear correlation peak was observed indicating the position of the leak, 246m from access point ‘A’. To determine the leak signal characteristics, signals were recorded from the access points A and B, and their frequency spectrum is shown in Figures 5.5(b) to 5.5(c) respectively. It is observed that the leak signals exist up to approximately 700Hz. The signals at access point B were found to be slightly attenuated (Figure 5.5(b)), because of the comparatively longer distance from the leak location. From these results, it can be concluded that it is not only metallic pipes such as ductile iron but also non-metallic asbestos cement pipes can act as a propagation channel for wide bandwidth leak signals.

5.2.3.3 Field measurements of real leaks in MDPE pipes

To understand how the signals produced by real leaks and flowing water in real network MDPE pipes differ from the above simulated leaks, signals were recorded from a leaking 25mm diameter MDPE service pipe at Castle Donington, Leicestershire. The pressure
inside the pipe network was approximately 180kPa. The signals were recorded from a water meter (Figure 5.6(b)) connected at 10.1m and a stop tap (Figure 5.6(c)) at 17m approximately from the leak position, and their frequency response is shown in Figures 5.6(d) and 5.6(e) respectively. It was noted that

- Most of the signals exist between 50Hz to 250Hz approximately. The signals were of high amplitude (>=20dB) and dominated the low frequency pipe resonance.
- Some high frequency (600 to 850Hz) periodic transients were observed in the frequency spectrum, possibly due to the moving vehicles.
- The amplitude of signals between 225Hz to 350Hz were found to be fluctuating

Figure 5.5: (a) Layout of the 150mm diameter asbestos cement pipe at Wymswold, Leicestershire. Amplitude and frequency variation with time of leak signals recorded from (b) hydrant ‘A’ and (c) hydrant ‘B’ connected to a 150mm diameter asbestos cement pipe, running at a pressure of 220kPa.
Finally, it can be concluded that for pressures less than 250kPa, leaks in real network MDPE pipes can produce stronger signals ($\geq 20$dB) with frequency above 200Hz. This matches with the theoretical results that leak size and flow rate significantly affect the frequency and bandwidth of the generated leak signals.

### 5.2.3.4 Comparison with tests in the hydraulics lab

Both in the hydraulics lab and at ST Lake House, leak signals were found to exist in the frequency range 10Hz to 250Hz. In both cases, it was noticed that a change in pressure significantly affects the amplitude of leak signals. However, despite these similarities some of the major differences noted are:

- In the hydraulics lab, leak signals were found up to 350Hz. However, the signals at Lake House were found to exist only up to 250Hz. This difference may be due to the backfill, difference in diameter of the leaking pipe (25mm at Lake House and 125mm in the hydraulics laboratory) and the difference in leak characteristics such as size, shape and flow rate.

- In the hydraulics lab, the signals measured were of comparatively higher amplitude. It may be because of the comparatively bigger leak size and the higher flow rates. Another reason is that in the hydraulics lab, the test rig was lying on a firm concrete floor and the leaking water was striking the firm floor, which produced stronger signals. However, at ST Lake House the pipe was surrounded by soft clay and sand bedding, which absorbed energy.

- At Lake House, a leak was simulated in 25mm diameter service pipe and the signals were measured on hydrants connected to a 125mm diameter MDPE pipe. The leak energy produced in the service pipe propagated over large areas from the 25mm to the 125mm diameter MDPE pipe which may have resulted in the low amplitude signals at the hydrants.
Figure 5.6: (a) Leak signals recording kit, accelerometer sensor connected at (b) water meter and (c) stop tap. Amplitude and frequency variation with time of leak signals generated by a leak in a 25mm diameter MDPE service pipe at Castle Donington, Leicestershire. Signals in (d) were measured from the water meter located at 10.1m and (e) from the stop tap located at 17m from the leak position.
5.3 Phase of leak signals

As discussed in Chapter 4, the phase ($\phi$) of leak signals varies approximately linearly with angular frequency ($\omega$) as

$$\phi = -\frac{\omega x}{c} \quad (5.1)$$

where $c$ is the speed of leak signals and $x$ is the position of sensor relative to leak location. The phase-frequency relationship of leak signals measured from hydrants H1 and H2 at pressures 150kPa, 350kPa and 820kPa are shown in Figure 5.7.

![Figure 5.7](image)

Figure 5.7: Phase-frequency relationship of signals measured at the hydrant (a)(c)(e) H1 and (b)(d)(f) H2 connected to the 125mm diameter MDPE main pipe at ST Lake House test rig. The pressure inside the pipe was 150kPa, 350kPa and 820kPa for (a)(b); (c)(d) and (e)(f) respectively.
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The main findings from the results obtained are:

- A slightly non-linear response is observed for signals below 20Hz. A similar irregular behavior was also observed in their frequency spectrum (Figure 5.3), possibly due to the dominant low frequency pipe resonance and ambient noise.

- A linear phase-frequency relationship was obtained for signals with frequency range 20Hz to 200Hz. The same is true with the frequency spectrum in Figure 5.3, where most of the leak signals were found in this range.

- From Figure 5.7, the interesting point to note is that the leak signals measured at hydrant H1 were out of phase by 180° from the signals measured at hydrant H2.

- There is no significant effect of change in pressure on the phase frequency relationship of leak signals.

- In some cases, the line does not pass through the origin, possibly due to the dominant low frequency ambient and pipe noise.

In general, it can be concluded that for the leak signals measured at Lake House the most significant phase information is concentrated between 20Hz to 200Hz. Finally, it can be summarized that:

- Leak signals in buried MDPE pipes were of low frequency (20Hz to 250Hz) and narrow bandwidth (230Hz). The upper limit of this frequency range increases with increase in flow rate.

- At Lake House, most of the high amplitude leak signals were found in the narrow frequency range of 20Hz to 150Hz.

- For the frequency range 20Hz to 250Hz, phase of the signals was found to be linearly varying with frequency.

- Pressure was found to significantly affect the amplitude of leak signals, while the leak characteristics (size, shape and flow rate), pipe dimensions and backfill affected the frequency range of leak signals.
• The frequency range and amplitude of leak signals vary significantly with the pipe material.

5.4 Cross-correlation and coherence of leak signals

The cross-correlation function is a quantitative operation in time domain to describe the relationship between data measured at two distinct observation points. It is discussed in detail in Chapter 3. In this section, the theoretical predictions made in Chapter 3 are validated using the leak signals measured at Lake House. In the time domain, the cross-correlation function is given by eqns 3.6 and 3.7, and in the frequency domain it is expressed by eqn 3.15. The cross-spectral density can be obtained by applying the Fourier transform to the cross-correlation function in frequency domain given by eqn 3.15 as:

$$S_{x_1x_2}(f) = \int_{-\infty}^{\infty} \hat{R}_{x_1x_2}(\tau) e^{-j2\pi f \tau} d\tau$$

(5.2)

and,

$$\hat{R}_{x_1x_2}(\tau) = \int_{-\infty}^{\infty} S_{x_1x_2}(f) e^{j2\pi f \tau} df$$

(5.3)

The coherence estimate of two leak signals represents the degree to which the two signals are linearly correlated at a given frequency. It can be obtained by normalizing the cross-spectral density function (eqn 5.2) as:

$$\gamma_{x_1x_2}^2(f) = \frac{|S_{x_1x_2}(f)|^2}{S_{x_1x_1}(f).S_{x_2x_2}(f)}$$

(5.4)

where $S_{x_1x_1}(f)$ and $S_{x_2x_2}(f)$ represent the power spectral densities of two signals $x_1(t)$ and $x_2(t)$ respectively, and $S_{x_1x_2}(f)$ is their cross spectral density. This function has the limits $0 \leq \gamma_{x_1x_2}^2(f) \leq 1$, where the numerical value of $\gamma_{x_1x_2}^2(f)$ indicates the degree of similarity between the two signals at any particular frequency ($f$). In leak signal analysis, coherence is very important for assessing the linear correlation between leak signals measured at two different access points on a leaking pipe. It can be inferred from coherence estimation that the more its value is closer to unity, the higher the two leak signals are linearly correlated to each other. However in practise, leak signal measurements are contaminated with noise such as the human voices and vehicular movements,
which cause reductions in coherence. Coherence also reduces due to nonlinear relationships introduced by electronics circuitry, filters and amplifiers. Therefore, a proper selection of hardware components and linear phase of signal processing techniques is very important.

5.4.1 An example of cross-correlation and coherence using Matlab

As discussed above and described in Chapter Three, cross-correlation can be calculated using two methods: cross-correlation in the time domain and generalised cross-correlation (GCC) in the frequency domain. This section presents an example of signal correlation using Matlab. Consider the example of Figure 5.8, which shows the results of cross-correlation of two signals using various estimators. Figure 5.8(a) shows a simulated exponentially decayed sinusoidal signal of frequencies 10Hz and 20Hz. Figure 5.8(b) shows the same signal delayed by 0.125 seconds and is coupled with random noise. Figure 5.8(c) to 5.8(g) show the correlation results obtained on applying various GCC estimator functions to determine the time delay between the two simulated signals. The Matlab code for this example is presented in Appendix A.2.

To calculate correlation in the time domain, Matlab function `xcorr.m` was used and the results obtained are shown in Figure 5.8(c). The generalised cross-correlation (GCC) is obtained by taking the Fourier transform (`fft.m`) of the input signals. The cross spectral density of two signals is then calculated using the Fourier transform of the input signals. The spectral density is then multiplied by various GCC estimation coefficients and then the inverse fourier transform (`ifft.m`) of the product is taken to finally give the correlation.

From Figure 5.8, it can be deduced that correlation in time domain using `xcorr.m` gives smooth and clear peaks, while the GCC methods give noisy peaks except the GCC with no filter. However, the advantage of GCC methods with an estimator is that the main correlation peak is sharp and can be easily differentiated from smaller peaks. It was concluded from theoretical predictions in Chapter 3 that SCOT is the only suitable GCC estimator for correlating leak signals. This can be confirmed from Figure 5.8, where the ML and PHAT estimator show a lot of noisy peaks, which may be very large in practise causing difficulty in identifying the main peak. However, the delay calculated from all the methods is the same (0.125 seconds). Thus, it can be concluded that for signals with low SNR, it is advantageous to compute correlation
Figure 5.8: An example of cross-correlation of two signals using various estimators. The delay between two signals is 0.125 seconds. (a) Signal one, (b) Signal one delayed and distorted with random noise. Cross-correlation using (c) x-corr and generalised cross-correlation using (d) no filter, (e) SCOT estimator, (f) ML estimator and (g) PHAT estimator, and (h) Coherence estimate of two signals.
using GCC as it improves the sharpness of the main peak and suppresses additional peaks.

Figure 5.8(h) shows the coherence estimate of two signals. It shows that the signals with frequencies between 8Hz to 11Hz and 18Hz to 24Hz are highly related to each other, which is because as the input signal has frequencies of 10Hz and 20Hz. However, it is not showing high values particularly at 10Hz and 20Hz because of the presence of noise. Thus, coherence gives an estimate of highly related frequencies of input signals, some of which may be incorrect if a high level of noise is present.

5.4.2 Correlation of leak signals recorded at Lake House

Leak signals, recorded in tests conducted at Lake House, were filtered using a 4th order Butterworth bandpass filter with cut-off frequencies set to 10Hz and 280Hz. These filtered signals were correlated using both cross-correlation in time domain and GCC with no filter and GCC with SCOT filter in the frequency domain. In the time domain, correlation was performed on signals of length 2 and 5 seconds and the results obtained are shown in Figure 5.9. In the frequency domain, GCC was performed over 1024, 2048 and 4096 samples of leak signals and the results obtained are shown in Figures 5.10, 5.11 and 5.12 respectively. The observations made are:

- The correlation function calculated in the time domain using Matlab function `xcorr.m` and GCC calculated in the frequency domain without any filters gives smooth peaks. However, GCC using the SCOT estimator gives a sharp distinct main peak.

- It can be seen from Figures 5.9 to 5.12 that increasing the length of signals over which the correlation is performed increases the resolution of the resulting peaks and the range over which time delay can be measured. However, it also increases the number of calculations involved in computing the correlation. This range also varies inversely with the sampling frequency. Thus, large values of time delay can be measured by either decreasing the sampling frequency or increasing the length of signals recorded, at the expense of an increase in the number of calculations.

- The time delay ($t_{shift}$) obtained from the correlation results is reported in Tables 5.1 to 5.3. The velocity of leak signals in a 125mm diameter MDPE
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Pipe was chosen as 325m/s, which is the default velocity used by the Microcorr 6 correlator. The total distance between the two hydrants (H1 and H2) was 45.1m. For this value of total distance and velocity, the distance $L_1$ of leak position from hydrant H1 is reported in Tables 5.1 to 5.3. In Figures 5.9 to 5.12, the time delay calculated using the first highest peak of the correlation function was found to be fluctuating between approximately 0.069 to 0.082s and the corresponding values of distance $L_1$ calculated in between 11.25 to 9.16m. However, the actual distance of the leak position from hydrant H1 is 10.3m. The percentage error in distance is calculated and plotted in Figure 5.13.

- In Figure 5.13, the correlation (time domain) performed over leak signals measured at 820kPa, gives the maximum error. The highest peak was observed at 0.18s in Figures 5.9(e) and 5.9(f), which is an error and indicates the boundary box as the leak position. This may be because the boundary box was making louder low frequency drumming sounds at higher pressures. In Figure 5.13, a comparatively small error is obtained using GCC and an appropriate selection of filter cut-off frequencies.

- Figure 3.1 explains the principle of correlation in which the leak is assumed to be on the same pipe on which the leak signals were measured. However, in the Lake House test rig, the leak was on a service pipe and the signals were measured on the main pipe. Leak signals measured at hydrants H1 and H2 travel the common distance equal to the length of service pipe, which is not taken into account while calculating the distance using eqn 3.1. If the length of service pipe is $L$, then the distance of leak position from hydrant H1 is related to time delay ($\tau_{shift}$) by:

$$\tau_{shift} = \frac{L'_{2} - L'_{1}}{c}$$

(5.5)

where $c$ is the propagation speed of leak signals and $L'_1$ and $L'_2$ are the corresponding leak positions relative to hydrant H1 and H2. The distances $L'_1$ and $L'_2$ are related to distances $L_1$ and $L_2$ by

$$L'_1 = L_1 + L \quad \text{and} \quad L'_2 = L_2 + L$$

(5.6)
where \( L_1 \) and \( L_2 \) is the distance of boundary box from hydrants H1 and H2 respectively. Thus,

\[
L_2' - L_1' = (L_2 + L) - (L_1 + L) = L_2 - L_1
\]

(5.7)

This is the mathematical error, as the common path length \( L \) is cancelled, but leak signals have travelled this distance. Now, if the total distance \((L_1 + L_2)\) between two sensors is \( D \), then the position of the leak relative to the sensor position H1 is given by

\[
L_1 = \frac{D - c \tau_{shift}}{2}
\]

(5.8)

This is the reason for the error in the value of \( L_1 \), as the time delay \( (\tau_{shift}) \) corresponds to \( L_1' \) not \( L_1 \). Therefore, it can be concluded that the correlation method for leak location gives the domain of leak position from sensor position. This means that the distance calculated using the correlation process may refer to the leak located on any other pipe connected to the pipe on which the signals are measured.

Table 5.1: Position of leak relative to hydrant H1, with time delay calculated using correlation of leak signals in time domain (xcorr.m).

<table>
<thead>
<tr>
<th>Pressure (Sec)</th>
<th>Length of signal (Sec)</th>
<th>Time Delay ( (\tau_{shift}) )</th>
<th>( c \times \tau_{shift} )</th>
<th>( L_1 )</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2</td>
<td>0.0739</td>
<td>24.0175</td>
<td>10.49125</td>
<td>1.86</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>0.0736</td>
<td>23.92</td>
<td>10.54</td>
<td>2.33</td>
</tr>
<tr>
<td>350</td>
<td>2</td>
<td>0.0691</td>
<td>22.4575</td>
<td>11.27125</td>
<td>9.43</td>
</tr>
<tr>
<td>350</td>
<td>5</td>
<td>0.0694</td>
<td>22.555</td>
<td>11.2225</td>
<td>8.96</td>
</tr>
<tr>
<td>820</td>
<td>2</td>
<td>0.181</td>
<td>58.825</td>
<td>-6.9125</td>
<td>32.89</td>
</tr>
<tr>
<td>820</td>
<td>5</td>
<td>0.186</td>
<td>60.45</td>
<td>-7.725</td>
<td>25</td>
</tr>
</tbody>
</table>
### Table 5.2: Position of leak relative to hydrant H1, with time delay calculated using GCC (no filter).

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Length of signal (Samples)</th>
<th>Time Delay ($t_{shift}$)</th>
<th>$c \cdot t_{shift}$</th>
<th>$L_1$</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1024</td>
<td>0.0741</td>
<td>24.0825</td>
<td>10.45875</td>
<td>1.542</td>
</tr>
<tr>
<td>150</td>
<td>2048</td>
<td>0.0728</td>
<td>23.66</td>
<td>10.67</td>
<td>3.59</td>
</tr>
<tr>
<td>150</td>
<td>4096</td>
<td>0.0821</td>
<td>26.6825</td>
<td>9.15875</td>
<td>11.08</td>
</tr>
<tr>
<td>350</td>
<td>1024</td>
<td>0.0732</td>
<td>23.79</td>
<td>10.605</td>
<td>2.96</td>
</tr>
<tr>
<td>350</td>
<td>2048</td>
<td>0.07</td>
<td>22.75</td>
<td>11.125</td>
<td>8.01</td>
</tr>
<tr>
<td>350</td>
<td>4096</td>
<td>0.081</td>
<td>26.325</td>
<td>9.3375</td>
<td>9.34</td>
</tr>
<tr>
<td>820</td>
<td>1024</td>
<td>0.07</td>
<td>22.75</td>
<td>11.125</td>
<td>8.01</td>
</tr>
<tr>
<td>820</td>
<td>2048</td>
<td>0.0692</td>
<td>22.49</td>
<td>11.255</td>
<td>9.27</td>
</tr>
<tr>
<td>820</td>
<td>4096</td>
<td>0.0728</td>
<td>23.66</td>
<td>10.67</td>
<td>3.59</td>
</tr>
</tbody>
</table>

### Table 5.3: Position of leak relative to hydrant H1, with time delay calculated using GCC (SCOT).

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Length of signal (Samples)</th>
<th>Time Delay ($t_{shift}$)</th>
<th>$c \cdot t_{shift}$</th>
<th>$L_1$</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1024</td>
<td>0.075</td>
<td>24.375</td>
<td>10.3125</td>
<td>0.12</td>
</tr>
<tr>
<td>150</td>
<td>2048</td>
<td>0.0729</td>
<td>23.6925</td>
<td>10.65375</td>
<td>3.44</td>
</tr>
<tr>
<td>150</td>
<td>4096</td>
<td>0.0821</td>
<td>26.6825</td>
<td>9.15875</td>
<td>11.08</td>
</tr>
<tr>
<td>350</td>
<td>1024</td>
<td>0.0742</td>
<td>24.115</td>
<td>10.4425</td>
<td>1.38</td>
</tr>
<tr>
<td>350</td>
<td>2048</td>
<td>0.0718</td>
<td>23.335</td>
<td>10.8325</td>
<td>5.17</td>
</tr>
<tr>
<td>350</td>
<td>4096</td>
<td>0.078</td>
<td>25.35</td>
<td>9.825</td>
<td>4.61</td>
</tr>
<tr>
<td>820</td>
<td>1024</td>
<td>0.0716</td>
<td>23.27</td>
<td>10.865</td>
<td>5.48</td>
</tr>
<tr>
<td>820</td>
<td>2048</td>
<td>0.0685</td>
<td>22.2625</td>
<td>11.36875</td>
<td>10.37</td>
</tr>
<tr>
<td>820</td>
<td>4096</td>
<td>0.074</td>
<td>24.05</td>
<td>10.475</td>
<td>1.70</td>
</tr>
</tbody>
</table>
Figure 5.9: Correlation in the time domain, of leak signals measured at hydrants H1 and H2 connected to a 125mm diameter MDPE pipe at ST Lake House. The pressure inside the pipe was 150kPa, 350kPa and 820kPa for (a)(b); (c)(d) and (e)(f) respectively. The length of signals correlated in (a)(c)(e) is 2s and in (b)(d)(f) is 5s.
Figure 5.10: GCC of leak signals measured at hydrants H1 and H2 connected to a 125mm diameter MDPE pipe at lake house. The pressure inside the pipe was 150kPa. The length of signals correlated in (a)(b), (c)(d) and (e)(f) is 1024, 2048 and 4096 samples respectively.
Figure 5.11: GCC of leak signals measured at hydrants H1 and H2 connected to a 125mm diameter MDPE pipe at lake house. The pressure inside the pipe was 350kPa. The length of signals correlated in (a)(b), (c)(d) and (e)(f) is 1024, 2048 and 4096 samples respectively.
Figure 5.12: GCC of leak signals measured at hydrants H1 and H2 connected to a 125mm diameter MDPE pipe at lake house. The pressure inside the pipe was 820kPa. The length of signals correlated in (a)(b), (c)(d) and (e)(f) is 1024, 2048 and 4096 samples respectively.
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Figure 5.13: Percentage error in leak location computed by calculating time delay using (a) correlation in the time domain, (b) GCC with no filter and (c) GCC with SCOT filter.
5.4.3 Coherence estimate of leak signals

As explained before, coherence represents the degree to which the two leak signals are linearly correlated at a given frequency. Figure 5.14 gives the coherence estimate of 1024 samples of signals measured from hydrants H1 and H2 connected to the 125mm diameter MDPE pipe at Lake House running at pressures of 150kPa, 350kPa and 820kPa. It can be observed that most of the signals between 20Hz to 200Hz are related to each other with most of the values above 0.4. The same is true for the frequency spectrum where most of the leak signals were found in the frequency range 10Hz to 250Hz. However, the coherence function obtained for the three pressure values of 150kPa, 350kPa and 820kPa is dissimilar, which may be due to the reason that the amplitude of the leak signals varies with the pressure and not all signals in this range were leak signals. From Figure 5.14, it can also be interpreted that the coherence estimate acts as a filter and gives the selection of frequency range of leak signals over which correlation should be performed.

5.4.4 Cross-spectral density and relative phase of leak signals

As discussed in Chapter 4, for the normal mode \( n=0 \), the acoustic pressure at any position \( x \) relative to leak position can be expressed as

\[
p(\omega, x) = P_0(\omega) \exp(-jkx)
\]

where \( P_0(\omega) \) is the acoustic pressure at leak position \( x=0 \) and \( k \) is the wavenumber which is related to speed \( c \) and attenuation \( \alpha \) by \( k = \omega/c - j\omega\alpha \). Substituting in eqn 5.2 to have

\[
S_{x_1x_2}(\omega) = \frac{1}{T} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (P_0(\omega))^2 e^{-\omega\alpha(L_1+L_2)} e^{j\omega(L_1-L_2)/c} df d\tau = S_{ll}(\omega) \Psi(\omega) e^{j\omega(L_1-L_2)/c}
\]

where \( L_1 \) and \( L_2 \) is the corresponding positions of sensor 1 and 2 from the leak position, \( S_{ll}(\omega) \) is the auto-spectral density of leak signal and

\[
\Psi(\omega) = e^{-\omega\alpha(L_1+L_2)}
\]

The argument of the cross-spectral function (eqn 5.10) gives the related phase between the two signals \( x_1(t) \) and \( x_2(t) \) by

\[
\phi_{x_1x_2}(\omega) = \text{Arg} \{ S_{x_1x_2}(\omega) \} = \omega(L_1 - L_2)/c
\]
Figure 5.14: Coherence estimate of leak signals measured from hydrants H1 and H2 connected to a 125mm diameter MDPE pipe at Lake House running at the pressure of (a) 150kPa, (b) 350kPa and (c) 820kPa.
Chapter 5: Leak Signals in Buried MDPE Pipes

From eqn 5.10, it can be inferred that the cross-spectral density is an exponentially decaying function. It depends upon the frequency, attenuation with distance and the distance between sensors. Thus, it will be more difficult to estimate the delay using the correlation function if the pipe is heavily damped and/or the measurement positions where the sensor is attached are far from the leak. The cross spectral density of leak signals measured in tests conducted at ST Lake House at 150kPa, 350kPa and 820kPa are shown in Figure 5.15. It is observed from the results obtained that:

- The cross-spectral density decreases with increase in frequency which matches with the theoretical results given by eqn 5.10. The same is true for the coherence estimate where the signals at higher frequencies are less related to each other.

- The cross-spectral density was found to increase with increase in pressure in Figure 5.15. This is because the cross-spectral density is directly proportional to the magnitude of the leak signals, which increases with increasing pressure.

- The effect of attenuation and distance cannot be determined because of the fixed measurement positions.

- The relative phase of two leak signals was found to be approximately linearly varying with frequency in the range 10Hz to 200Hz. However, at higher frequencies above 200Hz, it is non-linear which may be due to the low values of coherence and cross-spectral density at these positions.

- At low frequencies below 10Hz, the phase frequency is non-linear and in some instances the line does not pass through the origin. This may be because of dominant low frequency ambient and pipe resonance noise.

Finally, the results obtained in previous experiments can be summarized as:

- Most of the leak signals in buried MDPE pipes were found to be of low frequency (20Hz to 250Hz) and narrow bandwidth (230Hz), with the upper limit of frequency range increasing with increase in flow rate.

- For the frequency range 20Hz to 250Hz, individual phase of leak signals was found to be linearly varying with frequency.
Figure 5.15: Cross-spectral density and relative phase of 1024 samples of leak signals measured from hydrant H1 and H2 connected to a 125mm diameter MDPE test rig running at pressures of (a)(b) 150kPa, (c)(d) 350kPa and (e)(f) 820kPa.
• The frequency range of leak signals found in various types of pipe is summarized in Table 5.4. At Lake House, the leak signals in buried MDPE pipes were found up to 250Hz. However, in MDPE pipes without backfill, the leak signals were found to exist up to 550Hz depending upon the leak size and flow rate. The signals measured from a non-metallic asbestos cement pipe at Wymswold and ductile iron pipe at Lake House were of wide bandwidth of 750Hz and exist up to 800Hz. Leak signals with frequency range 20Hz to 200Hz were found for all the pipe types.

• Pressure was found to significantly affect the amplitude of leak signals, while the leak characteristics (size, shape and flow rate), pipe dimensions and backfill affected the frequency range of leak signals. However, the pipe material affected both the frequency range and amplitude of the leak signals.

• The correlation function calculated in time domain using Matlab function \( \text{xcorr.m} \) and GCC calculated in frequency domain without any filters give smooth peaks. However, GCC using the SCOT estimator gives a sharp distinct main peak.

• Large values of time delay between leak signals can be measured by either decreasing the sampling frequency or increasing the length of signals recorded, at the expense of increasing the number of calculations.

• At Lake House, most of the leak signals between 20Hz to 200Hz were found to be related to each other with a coherence estimate above 0.4.

• The cross-spectral density decreases with an increase in frequency of leak signals. The same is true for the coherence estimate where the signals at higher frequencies are less related to each other. However, for a particular frequency, the cross-spectral density was found to be increased with an increase in pressure.

• At Lake House, the relative phase of leak signals was found to be linearly varying with frequency in the range (10Hz to 200Hz).

• At low frequencies, below 10Hz, the relative phase frequency was non-linear and in some instances the line did not pass through the origin. This may be because of the dominant low frequency ambient and pipe resonance noise.
• The effect of backfill is not very clear from the tests conducted in the hydraulics lab and at ST Lake House. It was noticed that with an increase in pressure in the buried MDPE pipe at Lake House, the amplitude of signals was found to be increased without any significant change in frequency. For MDPE pipes without backfill in the hydraulics lab, the frequency of leak signals was also found to be changing with pressure.

Table 5.4: Summary of the frequency spectrum of leak signals obtained from the various leaking pipes.

<table>
<thead>
<tr>
<th>Pipe material</th>
<th>Leaking pipe diameter (mm)</th>
<th>Measuring pipe diameter (mm)</th>
<th>Pressure (kPa)</th>
<th>Leak size</th>
<th>Frequency range (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDPE</td>
<td>25</td>
<td>125</td>
<td>150, 350, 820</td>
<td>1mm diameter hole</td>
<td>10 to 250</td>
</tr>
<tr>
<td>MDPE without backfill</td>
<td>125</td>
<td>125</td>
<td>180</td>
<td>2l/min to 25l/min</td>
<td>10 to 550</td>
</tr>
<tr>
<td>Ductile iron</td>
<td>20</td>
<td>100</td>
<td>350</td>
<td>1mm diameter hole</td>
<td>10 to 800</td>
</tr>
<tr>
<td>Asbestos cement</td>
<td>150</td>
<td>150</td>
<td>220</td>
<td>--</td>
<td>10 to 750</td>
</tr>
</tbody>
</table>

5.5 Conclusion

In this chapter, the characteristics of leak signals in buried MDPE pipes are discussed. It is found from the experimental results that most of the leak signals in buried MDPE pipes exist in the frequency range 20Hz to 250Hz. The upper limit of this frequency range varies with change in leak characteristics, pipe dimensions, flow rate and backfill. For this frequency range, both the individual and related phase of leak signals were found to be linearly varying with frequency. These signals were correlated and it is found that correlation in time domain and GCC with no filter gives smooth peaks. GCC with SCOT estimator improves the sharpness of correlation peaks. It is found that large values of time delay can be calculated by either increasing the length of
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signals or decreasing the sampling frequency. Cross-spectral density of the signals is also calculated and is found to be decreasing with increase in frequency.

The effect of the backfill on generation of leak signals is not clearly understood as the leak signals were not measured for one leak with and without backfill. Therefore, a further series of controlled experiments is reported in Chapter 8 to investigate a common frequency range, which exists within all the leak signals (i.e. with and without backfill) but not in background noise.
Chapter 6

Speed and Wave Propagation Theory

The correlation method for leak location in pipes depends upon three variables: the distance (D) between sensors, the time delay ($\tau_{shift}$) between two measured leak signals and the propagation speed (c) of leak signals. Distance (D) between sensors positions can be measured quite accurately using various methods such as measuring wheel/tape. The estimation of time delay depends upon the sharpness of the correlation peak, type and positioning of sensors and the processing of signals obtained. Time delay estimation is discussed in detail in Chapters 3 and 4, where it is found to be affected by several factors such as the type of sensors. However, it can be estimated with the proper choice of sensors, hardware and signal processing. The third variable, propagation speed (c) of leak signals depends upon the dimensions and material properties of pipe section between the two sensor positions. In practice, the water distribution network has many discontinuities in dimensions and material properties of pipe, which makes it cumbersome to determine the propagation speed using existing theoretical and experimental approaches such as the time of flight and correlation method. These methods are difficult to use as they require a priori knowledge of the dimensions and material properties of pipe, each time the velocity is calculated using these methods. This information is not always easy to gather; therefore in this chapter, a new method to calculate the speed of leak signals in water filled MDPE pipes is proposed and experimentally verified. This method is based on the linear phase-frequency relationship of leak signals.
6.1 Calculation of propagation speed

The traditional correlators use pre-defined values of velocity stored in a database. These values are calculated using various theoretical and experimental methods mentioned below:

- Analytical method.
- Time-of-flight method.
- Correlation method.
- Three sensor method.

Selection of the value of velocity depends upon user defined information on the dimensions and material properties of pipe. However in practise, these are not always easy to obtain because of the incomplete record of discontinuities such as a change of pipe material (for example, due to repair work) between the two measuring positions.

6.2 Analytical method

This method uses the theoretical relationship between the physical properties (dimensions and material) of pipe and the speed of leak signals (Gao et al., 2004). It is based on the assumption that there is no variation in pipe physical properties between the two sensor positions and the leak is on the same pipe on which the signals will be measured. It requires a prior knowledge of the dimensions and material properties of pipe section under survey.

The theoretical relationship between the speed of leak signals and physical properties of pipe can be obtained using the wavenumber of leak signals (Gao et al., 2004). As discussed in Chapter 3, wavenumber for the fluid borne waves at frequencies well below the pipe ring frequency is given by

\[ k^2 = k_f^2 \left( 1 + \frac{2Bfa}{(Eh + j\eta Eh)} \right) \]

(6.1)

where \( \eta \) is the pipe loss factor. Rearranging eqn 6.1 to have

\[ k^2 = k_f^2 \left( 1 + \frac{2Bfa}{Eh(1 - \eta^2)} - j \frac{2Bf a \eta}{Eh(1 - \eta^2)} \right) \]

(6.2)
The pipe loss factor ($\eta$) is typically much less than unity, e.g. 0.00478 for a 125mm MDPE pipe, thus the term $\eta^2$ can be neglected to finally give

$$k^2 = k_f^2 \left( 1 + \frac{2B_f a}{E_h} - j\frac{2B_f a \eta}{E_h} \right) = Q + jS \quad (6.3)$$

where,

$$Q = k_f^2 \left( 1 + \frac{2B_f a}{E_h} \right) \quad \text{and} \quad S = k_f^2 \left( -\frac{2B_f a \eta}{E_h} \right) \quad (6.4)$$

The wavenumber $k$ is complex and assuming that $k = k_R + jk_I$, then eqn 6.3 becomes

$$Q + jS = (k_R + jk_I)^2 = k_R^2 - k_I^2 + 2jk_Rk_I \quad (6.5)$$

where $k_R$ and $k_I$ represent the real and imaginary components of the wavenumber $k$. Comparing the real and imaginary parts in eqn 6.5, and rearranging to have

$$4k_R^4 - 4k_R^2Q - S^2 = 0 \quad (6.6)$$

The solution of the above equation is given by

$$k_R^2 = \frac{Q \pm \sqrt{(Q^2 + S^2)}}{2} \quad (6.7)$$

As $k_R$ and $k_I$ are real numbers, considering only positive terms in eqn 6.7, will give:

$$k_R = \sqrt{\frac{Q + \sqrt{(Q^2 + S^2)}}{2}} \quad \text{and} \quad k_I = \frac{S}{\sqrt{2(Q + \sqrt{(Q^2 + S^2)})}} \quad (6.8)$$

Substituting the value of $Q$ and $S$, and neglecting the higher order terms of $\eta$ to give

$$k_R = k_f \sqrt{\left( 1 + \frac{2B_f a}{E_h} \right)} \quad (6.9)$$

and

$$k_I = \frac{k_f \left( -\frac{2B_f a \eta}{E_h} \right)}{2 \sqrt{\left( 1 + \frac{2B_f a}{E_h} \right)}} \quad (6.10)$$

The wavenumber ($k$) is related to the speed ($c$) and attenuation ($\alpha$) of leak signals by

$$k = \frac{\omega}{c} - j\alpha \omega \quad (6.11)$$
Chapter 6: Speed and Wave Propagation Theory

Equating the real and imaginary parts in eqns 6.9, 6.10 and 6.11 to give the wavespeed as

\[ c = \frac{\omega}{Re(k)} = \frac{\omega}{k} \left( \frac{1 + \frac{2Bf\alpha}{Eh}}{1 + \frac{2Bf\alpha}{Eh}} \right)^{-1/2} \] (6.12)

and the attenuation is given by

\[ \alpha = -\frac{Im \{k\}}{\omega} = \frac{k_f \left( \frac{Bf\alpha}{Eh} \right)}{\omega \left( 1 + \frac{2Bf\alpha}{Eh} \right)} = \frac{1}{c_f \sqrt{\left( 1 + \frac{2Bf\alpha}{Eh} \right)}} \] (6.13)

where \( c_f \) is the fluid wavespeed. It can be inferred from eqn 6.12 that the propagation wavespeed is independent of frequency but is dependent on the dimensions and Young's modulus of pipe. Therefore, the speed of leak signals in MDPE pipes will be less compared to metallic pipes as MDPE pipes have comparatively higher flexibility and less stiffness than metallic pipes. In eqn 6.13, the attenuation of leak signals depends upon the stiffness of pipe material. MDPE pipes have more flexibility, less stiffness and are more effective energy radiators; therefore, they have higher attenuation than metallic ones.

Table 6.1: Material properties of PE80 MDPE pipe (after WAVIN (2001)).

<table>
<thead>
<tr>
<th>Property</th>
<th>Density (kg/m³)</th>
<th>Poisson Ratio</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (MPa)</th>
<th>Coefficient of Linear Expansion (°C⁻¹)</th>
<th>Thermal Conductivity (W/M°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td></td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PE80</td>
<td>Blue 944</td>
<td>0.4</td>
<td>18</td>
<td>700</td>
<td>1.5 * 10⁻⁴</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Black 949</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The material properties and pipe dimensions of MDPE pipe with standard dimensional ratio¹ (SDR) 11, are mentioned in Tables 6.1 and 6.2 respectively. The MDPE pipe considered here is of BS 6730:1986 and WIS 4-32-17 standard. For this pipe and the bulk modulus of water taken as \( 2.2 \times 10^9 \) Pa, the values of velocity calculated using eqn 6.12 and attenuation using eqn 6.13 are reported in Table 6.2. It can be seen that the velocity values obtained are not constant and vary in between 225m/s

¹SDR is the ratio of the minimum outside diameter to the minimum wall thickness of the pipe.
to 260 m/s with the dimension of the pipe. This can also be confirmed from eqn 6.12, where the velocity of leak signals is found to be significantly influenced by the radius to thickness ratio \((a/h)\) of pipe. The variation of velocity and attenuation with the radius to thickness ratio is shown in Figures 6.1(a) and 6.1(b). It can be seen from Figure 6.1(a) that for a particular radius \((a)\) of MDPE pipe, increasing the thickness \((h)\) increases the velocity \((c)\) of leak signals. Or in other words, increasing the radius for a constant thickness causes the leak signals to slow down. The radius and thickness of the MDPE pipe is not always constant because of manufacturing defects. Therefore, for a single pipe, the velocity may vary between a certain minimum and maximum value, so it is preferable to take the mean velocity for the correlation method.

![Figure 6.1(a): Variation in velocity with the radius to thickness ratio of MDPE pipe.](image)

![Figure 6.1(b): Variation in attenuation with the radius to thickness ratio of MDPE pipe.](image)

Figure 6.1: Variation in (a) velocity and (b) attenuation of leak signals with the radius to thickness ratio of MDPE pipe.
### Table 6.2: Velocity and attenuation of leak signals in MDPE pipes (after WAVIN (2001))

<table>
<thead>
<tr>
<th>Outer Diameter (mm)</th>
<th>Mean Diameter (mm)</th>
<th>Max. Thickness (mm)</th>
<th>Min. Thickness (mm)</th>
<th>Mean Radius (mm)</th>
<th>Standard Dimensional Ratio</th>
<th>Mean Bore Diameter (mm)</th>
<th>Max. Velocity (m/sec)</th>
<th>Min. Velocity (m/sec)</th>
<th>Mean Velocity (m/sec)</th>
<th>Attenuation Factor ((10^{-5}))</th>
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<td>246.15</td>
<td>246.25</td>
<td>1.851</td>
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</tbody>
</table>
6.2.1 Time-of-flight method

Time-of-flight is the most commonly used practical method to calculate propagation speed of leak signals in water distribution pipes. In the time-of-flight method, propagation speed is calculated based on the difference in arrival times of transient signals at known locations (Hunaidi et al., 1999). Velocity is calculated based on the theoretical formula, as the distance travelled divided by the difference in arrival times. In practice, the transient signals can be generated in the pipe by abruptly opening and closing valves. The position of a source such as a valve, can be in-bracket or out-of-bracket relative to measuring locations. In the out-of-bracket source method, the source of transient signals lie outside the two measuring points while for the in-bracket source method, the source lies within the two measuring points. For example, at the Lake House test rig, an in-bracket transient source was made by opening and closing the boundary box valve. The signals were measured at hydrants H1 and H2 using accelerometers. The hydrants H1 and H2 were at 7.8m and 37.3m respectively from the boundary box, with a total distance between the hydrants of 45.1m. The time of flight calculated for the hydrants H1 and H2 was 0.022 seconds and 0.107 seconds respectively and the corresponding values of calculated velocity were 354.5m/s and 348.5m/s. These values are comparatively higher than those calculated using the numerical method.

6.2.2 Correlation method

The correlation method is similar to the time-of-flight method. In the correlation method, the propagation velocity is estimated based on the time lag between coherent continuous signals measured at two points, a known distance apart (Gao et al., 2004; Hunaidi & Chu, 1999). Signals can be generated using an in-bracket or out-of-bracket source such as a simulated leak at a known location. The velocity is calculated by dividing the net distance travelled by measured signals with the time delay between measured signals (eqn 5.8). For example, the time differences between signals measured at hydrants H1 and H2 in tests conducted in Chapter 5 are reported in Table 6.3. These signals were generated by a leak simulated in the 25mm diameter MDPE service pipe in the ST Lake House test rig. The time difference is calculated using both correlation in time domain and frequency domain. The distance between hydrants H1 and H2 was
45.1m. The velocity of leak signals is calculated using eqn 5.8 and the results obtained are tabulated in Table 6.3. As the leak was simulated on the service pipe, so the distance \( L'_1 \) is taken instead of \( L_1 \). To illustrate the difference, velocity is calculated using both \( L'_1 \) and \( L_1 \), and the results obtained are plotted in Figure 6.2. It can be seen that the incorrect value of distance \( L_1 \) gives higher values of velocity in comparison to 325m/s used in section 5.4.2. The velocity calculated using \( L'_1 \) is in between 330 to 350m/s. The interesting point noted here is that the time difference calculated using correlation in the time domain of leak signals measured at 820kPa gives a velocity of 135m/s. This is due to the error in selecting an incorrect peak as mentioned in section 5.4.2. Thus, the accuracy of the correlation method in calculating velocity depends upon the sharpness and clarity of the correlation peak.

Thus, the cross-correlation method is also a very effective practical method similar to the time of flight method. However, in the correlation method the effect of signal source is more important than for the time-of-flight method. This is because the cross-correlation method is based on the similarity between measured signals, which is affected by dispersion and frequency-dependent attenuation along the pipeline. Therefore, the shorter the net distance between measurement points, the more similar are the signals and hence the more relevant their cross-correlation. However, for shorter distances the time lag is very small and may lead to an error. Thus, the efficiency and accuracy of both methods significantly depends upon the accuracy with which the time delay between leak signals and transient events is measured.
Chapter 6: Speed and Wave Propagation Theory

Table 6.3: Velocity of leak signals in 125mm diameter MDPE pipe at Lake House calculated using correlation method.

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Length of signal (sec)</th>
<th>Time Delay (sec)</th>
<th>Velocity (m/sec) using $L_1$</th>
<th>Velocity (m/sec) using $L_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2</td>
<td>0.0739</td>
<td>331.529</td>
<td>399.188</td>
</tr>
<tr>
<td>350</td>
<td>2</td>
<td>0.0691</td>
<td>354.558</td>
<td>426.92</td>
</tr>
<tr>
<td>820</td>
<td>2</td>
<td>0.181</td>
<td>135.359</td>
<td>162.983</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Length of signal (Samples)</th>
<th>Time Delay (sec)</th>
<th>Velocity (m/sec) using $L_1$</th>
<th>Velocity (m/sec) using $L_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
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<td>0.0741</td>
<td>330.634</td>
<td>398.11</td>
</tr>
<tr>
<td>350</td>
<td>1024</td>
<td>0.0732</td>
<td>334.699</td>
<td>403.01</td>
</tr>
<tr>
<td>820</td>
<td>1024</td>
<td>0.07</td>
<td>350</td>
<td>421.428</td>
</tr>
</tbody>
</table>

Correlation in frequency domain using GCC (No filter)

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Length of signal (Samples)</th>
<th>Time Delay (sec)</th>
<th>Velocity (m/sec) using $L_1$</th>
<th>Velocity (m/sec) using $L_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
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<td>820</td>
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<td>0.0716</td>
<td>342.178</td>
<td>412.012</td>
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</tbody>
</table>
6.2.3 Three sensor method

The three sensor method (Prek, 2007) measures the speed and attenuation of leak signals in water filled MDPE pipes using the transfer function between the pressure measurements at three locations. To determine the transfer function, consider a water filled MDPE pipe of arbitrary length \( l \) with a simulated leak (Figure 6.3), which generates leak signals with acoustic pressure \( P_0(\omega) \) at the leak position. For higher accuracy, this method requires that the sensors should have similar characteristics and mounted equally spaced distances relative to the leak position. Thus in Figure 6.3, the distance \( \Delta x_1 = \Delta x_2 = \Delta x \), with respect to \( x_2 = 0 \) as the reference point for the transfer function.

The acoustic pressures \( p_1(\omega, x_1), p_2(\omega, x_2) \) and \( p_3(\omega, x_3) \) at positions \( x_1, x_2 \) and \( x_3 \) along the pipeline are given by

\[
p_1(\omega, x_1) = P_0(\omega)e^{j(\omega t - kx_1)} \quad (6.14)
\]

\[
p_2(\omega, x_2) = P_0(\omega)e^{j(\omega t - kx_2)} \quad (6.15)
\]
Therefore,

\[ \frac{1}{2} (H_{12} + H_{32}) = \frac{p_1(\omega, x_1) + p_3(\omega, x_3)}{2p_2(\omega, x_2)} = \frac{P_0(\omega)e^{i(\omega t - kx_1)} + P_0(\omega)e^{i(\omega t - kx_3)}}{2P_0(\omega)e^{i(\omega t - kx_2)}} \]

\[ = \frac{1}{2} \left( e^{-jk(x_1 - x_2)} + e^{-jk(x_3 - x_2)} \right) = \frac{1}{2} \left( e^{j(\Delta x)} + e^{-j(\Delta x)} \right) \]

\[ = \cos(k\Delta x) \]

(6.17)

where \( H_{12} \) is the transfer function between sensor positions 1 and 2, defined as \( p_1(\omega, x_1)/p_2(\omega, x_2) \) and \( H_{32} \) is between sensor positions 3 and 2 given by \( p_3(\omega, x_3)/p_2(\omega, x_2) \).

Thus, the wavenumber \( k \) is related to the three pressures as

\[ k = \frac{1}{\Delta x} \arccos \left( \frac{H_{12} + H_{32}}{2} \right) = \frac{1}{\Delta x} \arccos \left( \frac{p_1(\omega, x_1) + p_3(\omega, x_3)}{2p_2(\omega, x_2)} \right) \]

(6.18)

Substituting the value of \( k = \omega/c - j\alpha \omega \), the transfer function in general can be expressed as:

\[ H(\omega, \Delta x) = e^{-j\omega\Delta x/c}e^{-\alpha\Delta x} \]

(6.19)

With this expression for the transfer function, eqn 6.18 could be rewritten as

\[ \frac{1}{2} (H_{12} + H_{32}) = \cos(\omega\Delta x/c) \cosh(\alpha\Delta x) + j \sin(\omega\Delta x/c) \sinh(\alpha\Delta x) \]

(6.20)

The transfer functions \( H_{12} \) and \( H_{32} \) are calculated from the three pressure measurements. The wave number and speed is calculated from the real part of measured
transfer functions, while the attenuation coefficient is calculated from the imaginary part of measured transfer functions using eqns 6.18 and 6.20. At Lake House, there was no facility to connect three sensors at three equidistant positions so this method was not used to measure the velocity. However, this method was evaluated by Prek (2007) and he found it quite efficient and accurate in calculating velocity of leak signals. The velocity of leak signals in a 25.4mm diameter polyethylene pipe calculated by Prek (2007) was 340m/s.

Finally, from all the methods discussed above, it can be concluded that the velocity of leak signals varies significantly with the dimensions and material properties of the water supply network pipe sections under survey. In practise, it is not possible to keep a record of dimensions, material properties and discontinuities of each section (say 100m long) of the water distribution network. Therefore, these methods fail to give accurate results in most instances. This makes it important to propose a new method, which calculates speed using the linear phase-frequency relationship of leak signals.

### 6.3 Phase-frequency method for calculation of speed

The four methods discussed above, either require a priori knowledge of the physical (dimension and material) properties of the pipe under inspection or a known simulated leak/transient event source. Among all the methods discussed above, correlation is probably the easiest method to measure velocity of leak signals. However to calculate velocity, it requires a known source of leak signals for each pipe section. A partial solution to this problem can be obtained using the three point correlation method, but it increases the cost of equipment and also the time of operation. For other methods, a priori knowledge of the pipe's physical properties and a source is required which is not always easy to obtain in practise. Therefore, a new method based on the linear phase-frequency relationship of leak signals is proposed in this section. It was found in Chapters 4 and 5, that both the individual and relative phase of leak signals vary linearly with frequency and the velocity can be calculated from the slope of this linear phase-frequency relationship.

The schematic of measuring velocity using linear phase-frequency relationship method is shown in Figure 6.4. To calculate the speed of leak signals, the Fourier
Transform of two leak signals are multiplied and averaged over a theoretically infinite observation interval \((T)\) to have

\[
S_{x_1 x_2}^m(\omega) = \lim_{T \to \infty} \frac{1}{T} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (P_0(\omega))^2 e^{-\omega L_1 + L_2} e^{-j\omega L_1 + L_2}/c d\omega dT
\]

\[
= S_{II}(\omega)\Psi(\omega)e^{-j\omega(L_1 + L_2)/c}
\]

(6.21)

where \(L_1\) and \(L_2\) are the respective positions of sensor 1 and 2 from leak position, \(S_{II}(\omega)\) is the auto-spectral density of leak signals and

\[
\Psi(\omega) = e^{-\omega L_1 + L_2} = e^{-\omega D}
\]

(6.22)

where \(D\) is the total distance between two sensor positions. The argument of eqn 6.21 gives the phase as

\[
\phi_{x_1 x_2}^m(\omega) = \text{Arg} \{S_{x_1 x_2}^m(\omega)\} = -\omega(L_1 + L_2)/c = -\omega D/c
\]

(6.23)

From eqn 6.23, it can be inferred that the phase of the product of Fourier Transform of leak signals measured at two locations varies linearly with frequency \(\omega\). The velocity \((c)\) can be calculated from the slope of this linear relationship between \(\phi_{x_1 x_2}^m\) and frequency \(\omega\), provided the distance \(D\) is known, which can be measured quite accurately using various methods such as measuring wheel/tape. The benefit of this method is that there is no need to specifically simulate a leak for measuring velocity. This method requires the total distance \((D)\) between the two sensor positions so any leak on the pipe can be considered. The main important aspect of this method is the coherence between signals. The higher the coherence, the better will be the results, so the signal measurements on shorter sensor spacings is preferred.

![Figure 6.4: Schematic diagram of calculating velocity using linear phase-frequency relationship of leak signals.](image-url)
6.3.1 Validation of the method

The effectiveness of the proposed method is assessed from the tests conducted at ST Lake House test rig. The phase frequency relationship of the product of Fourier Transform of leak signals measured in tests conducted at ST Lake House at 150kPa, 350kPa and 820kPa pressure is shown in Figure 6.5. The results obtained are 'unwrapped' as more than half a wavelength is observed between the two accelerometer positions. This is done as follows:

\[
\hat{\phi}_{x_1,x_2}(\omega) = (n_a + 1)m_p\pi - \phi^m_{x_1,x_2}(\omega) \quad \text{if } n_a \text{ is odd}
\]

\[
\hat{\phi}_{x_1,x_2}(\omega) = (n_a)m_p\pi + \phi^m_{x_1,x_2}(\omega) \quad \text{if } n_a \text{ is even}
\]

where \(\hat{\phi}_{x_1,x_2}(\omega)\) is the unwrap phase, \(\phi^m_{x_1,x_2}(\omega)\) is the measured phase, \(n\) is the number of half wavelengths between adjacent accelerometers and \(m_p\) is the multiplying factor which depends upon the total distance \(D\) between the sensors positions. The wavespeed \((c)\) is calculated using the eqn 6.23 and the results obtained are shown in Figure 6.5. It can be observed from Figure 6.5 that:

- The phase of the product of Fourier Transform of leak signals measured at two access points H1 and H2 varies linearly with frequency in the range 20Hz to 300Hz. It is non-linear at higher frequencies above 300Hz, as the filter cut-off frequencies are set for 10Hz to 300Hz based on the results obtained from the frequency spectrum of leak signals in Chapters 4 and 5.

- At low frequencies below 20Hz, the phase-frequency relationship is non-linear and in some instances the line does not pass through origin. It may be because of dominant low frequency ambient and pipe resonance noise.

A least square linear regression line is drawn in Figure 6.5 and the slope of the line is multiplied by the distance \((D)\) and a factor of \(2\pi\) to give the velocity of leak signals. The results obtained are shown in Figures 6.5(b), 6.5(d) and 6.5(f). The speed is found to be nearly linear in the frequency range 40Hz to 300Hz. Using the least-squares linear regression in this range, the obtained speed of signals measured at 150kPa, 350kPa and 820kPa are 0.0155 + 325.707, 0.0073 + 318.7782 and -0.00032 + 321.560 respectively, where \(f\) denotes the frequency in Hz and the speed in m/s. It can be seen from the results that the slope is very small so the velocity can be considered as
constant to be 325m/s, 319m/s and 322m/s. These results match those obtained from the correlation method, the time-of-flight method and the standard value of 325m/s used in section 5.4.2. However, it can be seen from Figures 6.5(b), 6.5(d) and 6.5(f) that the value of the velocity obtained for different frequencies are not same. These are found to be varying in between approximately 240m/s to 430m/s. This may be due to the reason that all of these signals may not be the leak signals. Therefore, it is preferred to choose the correct and narrow frequency range of filters, so that most of the signals in the selected range corresponds to leak.

Figure 6.5: (a)(c)(e) Phase-frequency relationship of the product of leak signals measured at hydrants H1 and H2 of the Lake House test rig. (b)(d)(f) Velocity of leak signals calculated from the slope of phase frequency relationship. The leak signals in (a)(b); (c)(d) and (e)(f) were measured from hydrant H1 and H2 connected to 125mm diameter MDPE test rig running at the pressure of 150kPa, 350kPa and 820kPa respectively.
6.4 Attenuation of leak signals

The measurement of loss factor ($\alpha$) is based on the attenuation of leak signals with distance along the length of pipe. There are two basic mechanisms by which a wave is attenuated: geometric attenuation and material attenuation. Geometric attenuation is the phenomenon by which the amplitude of a wave decreases as the wavefront spreads out over a wider area. Material attenuation can be classified as either intrinsic (absorption) or extrinsic (scattering). Absorption losses are a result of internal friction due to the inner surface of a pipe. Since these effects are coupled, attenuation measurements include the influence of all effects and it is often impossible to separate them. Therefore, a negative imaginary part is introduced in the wavenumber which quantifies the frequency dependant wave attenuation. The sign is negative because the attenuation refers to the decrease in amplitude of the propagating wave with distance along the pipeline. The attenuation is given in dB/m, and in the longitudinal direction it can be calculated using eqn 6.13. The results obtained from eqn 6.13 are expressed in Table 6.2 for the mean value of radius and thickness. It can be seen from eqn 6.13 that attenuation is inversely proportional to the fluid wavespeed and is dependent upon the dimensions (radius ($a$) and wall thickness ($h$)) and material properties (Young's Modulus ($E$) and material loss factor ($\eta$)) of pipe. In practice, it is difficult to determine the dimensions of buried pipe, material loss factor ($\eta$) and the number of discontinuities between two measuring positions, so it is not possible to accurately calculate attenuation of leak signals using eqn 6.13. Therefore, a new method is proposed in this section for the estimation of attenuation of leak signals with distance (dB/m) along the pipeline.

Implementation of the proposed method assumes that the attenuation can be calculated from the transfer function of the pressure measurements taken at two positions along the pipeline. For any leak, the transfer function of the pressure measured between the sensor location ($x_1$) and leak location is given by eqn 6.19. The attenuation of leak signals can be expressed in terms of the ratio of transfer functions at two locations as:

$$H(\omega, D) = \frac{e^{(-j\omega D_1/c)} e^{(-\omega a x_1)}}{e^{(-j\omega D_2/c)} e^{(-\omega a x_2)}} = e^{(-j\omega D/c)} e^{(-\omega a D)}$$

(6.25)

where $D$ is the distance between two sensors. Taking the magnitude and log to
finally get the attenuation in dB/m as:

\[
\text{Attenuation (dB/m)} = \frac{-20 \ln |H(\omega, D)|}{D \ln(10)}
\]  
(6.26)

To validate the proposed method, the attenuation is plotted with frequency in Figure 6.6. The signals taken in Figure 6.6 were measured from the 125mm diameter MDPE pipe of ST Lake House test rig running at 150kPa, 350kPa and 820kPa pressures. In Figure 6.6, the attenuation is found to be linearly varying with frequency in the range 10Hz to 300Hz.

Using the least squares linear regression, the attenuation for the three measurements is related to the frequency \((f)\) by 

\[-0.000308f - 0.0945, -0.000289f - 0.1133 \text{ and } -0.000172f -0.29211.\]

To find the attenuation factor \((\alpha)\), consider eqn 6.11 in which the attenuation with distance is related to the imaginary part of the wavenumber as:

\[
\text{Attenuation (dB/m)} = \frac{-20 \text{Im}\{k\}}{\ln(10)} = 8.67\alpha \omega
\]  
(6.27)

Equating the eqns 6.26 and 6.27 to have

\[
\alpha = \frac{\ln |H(\omega, D)|}{\omega D}
\]  
(6.28)

Thus attenuation factor \((\alpha)\) can be calculated from the slope of the attenuation vs frequency relationship. For the distance \((D)\) between the two sensors of 45.1m at the ST Lake House test rig, the value of attenuation factor for the signals measured at 150kPa, 350kPa and 820kPa are \(5.65 \times 10^{-6}\) s/m, \(5.308 \times 10^{-6}\) s/m and \(3.159 \times 10^{-6}\) s/m respectively. This matches with the results obtained from the theoretical calculations in Table 6.2. The attenuation factors calculated using the proposed method are slightly higher because of the additional attenuation due to the discontinuities, such as boundary box, in the test rig. However, these discontinuities were not taken into consideration while doing the theoretical computations. This is why in practise the signals measured is weaker than expected using theoretical computations.

Thus, finally it can be summarised that the proposed methods for both the velocity and attenuation gives more precise results than the theoretical computations. These are based on the real leak signals and can be used easily using the existing leaks, without any need of prior knowledge of physical properties of pipe and the requirement of a simulated source of leak signals or transient events as other methods have.
Figure 6.6: Attenuation of the leak signals measured at hydrants H1 and H2 connected to the 125mm diameter MDPE pipe running at the pressure of (a) 150kPa, (b) 350kPa and (c) 820kPa at ST Lake House.
6.5 Conclusion

Velocity and attenuation of leak signals with distance play an important role in determining leak position using the correlation method. Velocity can be approximated using the time-of-flight, correlation and three sensors methods. However, these methods require a prior knowledge of the pipe physical properties and a known leak signal/transient event source, which are not always easy to obtain in practise. The analytical method can also be used to calculate velocity and attenuation; however, it is not preferred in real network, as it does not consider the presence of discontinuities in the pipe network. Therefore, a new method based on the linear phase frequency relationship of leak signals is proposed and experimentally validated in this chapter. The velocity and attenuation of axisymmetric waves propagating in a finite length pipe is determined from the pressure measurements made at two locations along the length of pipe. The velocity is obtained from the linear phase frequency relationship of the product of Fourier Transform of the leak signals measured at two locations, using the least squares linear regression. The attenuation is calculated by comparing the transfer functions at the two leak signal measurement positions. The effectiveness of the proposed method is assessed for the MDPE pipes at ST Lake House. The simulated leak signals were found to be highly attenuated because of noise; however, the proposed method was found to be less sensitive to excessive noise. Even in these circumstances the proposed method enables the determination of the acoustical properties (velocity and attenuation) of water-filled MDPE pipes within the frequency range 10Hz to 300Hz. The measured results using the proposed method were found to exhibit less fluctuation in comparison with the results using the theoretical and other experimental methods.
The accuracy with which the correlation process detect and locate leaks in water distribution pipes, especially MDPE, depends upon the type of sensors, their positioning and the processing of signals obtained. Hydrophones and accelerometers are the two most commonly used transducers for this purpose. In MDPE pipes, leak signals were found to be of low frequencies and narrow bandwidth with poor signal to noise ratio compared to ductile iron and asbestos cement pipes. Therefore, it becomes very difficult to measure leak signals in MDPE pipes using existing transducers. The signal to noise ratio can be improved by increasing the water pressure, which increases the amplitude of leak signals provided the dimensions of leak remains fixed. However, practically this can't be implemented everywhere in water distribution systems. Therefore, the only way is to use high sensitivity sensors and appropriate signal processing techniques to improve the quality of signals obtained.

Therefore in this chapter, various types of sensors, their parameters and the associated signal processing techniques are discussed with the aim to obtain a sharp correlation peak and a higher value of coherence.

7.1 Introduction

In Chapters 4 and 5, a series of tests were performed on MDPE pipes without backfill at the hydraulic laboratory, Loughborough University and buried MDPE pipes at
Severn Trent Lake House. It was found from the results obtained that:

- Leak signals in MDPE pipes exist between 20Hz to 350Hz, with most of the high amplitude leak signals concentrated below 150Hz. Therefore, the frequency range of interest for leaks in practical water distribution MDPE pipes is 20Hz to 350Hz.

- Phase of the leak signals in MDPE pipes was found to be linearly varying with frequency in the range 20Hz to 250Hz.

- Increase in water pressure increases the amplitude of leak signals provided the dimensions of leak remains fixed.

Based on these results, the correlation process including sensors, hardware and signal processing techniques is re-designed as shown in Figure 7.1. The various steps involved are explained below in section 7.2.

### 7.2 Selection of sensors

The first step is to make a selection of sensors, which can measure leak signals from the leaking water distribution pipes, especially MDPE. Leak signals are vibro-acoustic in nature, so they can be measured using various sensors such as hydrophones and accelerometers. The measured signals are a combination of attenuated leak signals and noise, which can be quantified in terms of signal to noise ratio (SNR). SNR depends upon the type of sensor and their position relative to leak location. For better correlation a higher SNR is required, which can be obtained by either increasing the fluid pressure or optimising the choice of sensors, their parameters and noise floor. Increasing fluid pressure increases the amplitude of leak signals and thus SNR. However, this practise is not possible to implement everywhere in water distribution systems. Thus, the only way is to use sensors with high sensitivity and proper frequency range. However, high sensitivity sensors may record more noise from surroundings and the pipe itself. Therefore, these should be used in conjunction with appropriate signal processing techniques, which can filter or attenuate the unwanted noise.

To make a proper choice of sensors, consider the theoretical relationship between the acoustic pressure and radial wall displacement established in Chapter 4, which is
Figure 7.1: (a) Leak signal acquisition and transmission, (b) Analog to digital conversion of received signals and (c) signal processing techniques involved.
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reformulated here for low frequencies, well below the pipe ring frequency as:

\[ W = \frac{Pa^2}{Eh} \]  

(7.1)

where \( W \) is the amplitude of radial wall motion given by eqn 4.6, \( P \) is the acoustic pressure amplitude given by eqn 4.7, \( E \) is the Young's modulus, \( a \) is the mean pipe radius and \( h \) is the pipe wall thickness.

From eqns 7.1, 4.6 and 4.7, it can be interpreted that there are four parameters: acoustic pressure \( (P) \), radial wall motion \( (w) \), velocity \( (\frac{dw}{dt}) \) and acceleration \( (\frac{d^2w}{dt^2}) \), which can be used to quantify leak signals. Based on these parameters there are four sensors: hydrophones, accelerometers, velocity and displacement sensors to choose from. The displacement and velocity sensors are not suitable for measuring leak signals as these are extremely difficult to connect to the buried water distribution pipes. These are mostly used in situations where the signals are of known frequency such as monitoring the health status of a mechanical machine. Therefore, these are not further discussed and only the hydrophones and accelerometers will be investigated in this chapter.

7.2.1 A selection of hydrophone vs accelerometer sensor

In this section, an analytical model is presented to investigate the potential of hydrophone and accelerometer to measure leak signals in MDPE pipes. Using eqn 4.7, the frequency response function \( (H_h(w, x)) \) of the hydrophone measured signals, at the sensor location and leak location is given by

\[ H_h(w, x) = e^{-j\omega x/c}e^{-\omega ax} \]

(7.2)

where \( x \) is the distance between leak location and sensor position, and \( \alpha \) is a measure of loss within the pipe wall. Using eqns 7.1 and 4.6, the frequency response function \( (H_a(w, x)) \) for the accelerometer measured signals is given by

\[ H_a(w, x) = -\frac{a^2\omega^2}{Eh}e^{-j\omega x/c}e^{-\omega ax} = -\frac{a^2\omega^2}{Eh}H_h(w, x) \]

(7.3)

The variation of transfer functions \( H_h(w, x) \) and \( H_a(w, x) \) with frequency \( (\omega) \) is shown in Figure 7.2(a). It can be seen that \( H_h(w, x) \) acts as a low-pass filter and decreases exponentially with increasing frequency. The higher frequencies attenuate at
a faster rate than the lower frequencies. In contrast, \( H_a(\omega, x) \) behave as a band-pass filter with a comparatively wide bandwidth and lower amplitude. The wide bandwidth means that an accelerometer will pass more frequency information and thus is more susceptible to noise.

To understand the effect of sensors on the correlation of leak signals, consider the cross spectral densities of the hydrophone and accelerometer measured signals, given by:

\[
S_{x_1x_2}^{h}(\omega) = S_{ll}(\omega)e^{-\omega D e^{j\omega(L_1-L_2)/c}}
\]

(7.4)

\[
S_{x_1x_2}^{a}(\omega) = \frac{(a\omega)^4}{(Eh)^2} S_{ll}(\omega)e^{-\omega D e^{j\omega(L_1-L_2)/c}}
\]

(7.5)

where \( S_{ll}(\omega) \) is the auto spectral density of leak signal \((l_s(t))\), \( S_{x_1x_2}^{h}(\omega) \) and \( S_{x_1x_2}^{a}(\omega) \) denotes the cross-spectral density of the hydrophone and accelerometer measured signals respectively. From eqn 7.4 and 7.5, it can be interpreted that the phase spectrum is independent of the choice of acoustic/vibration sensors and is given by:

\[
\phi_{x_1x_2}^{cs}(\omega) = \arg\{S_{x_1x_2}^{cs}(\omega)\} = \omega(L_1 - L_2)/c
\]

(7.6)

where ‘cs’ represents ‘a’ or ‘h’ for the accelerometer or hydrophone sensors. Using eqns 7.4 and 7.5, the normalised cross-correlation function of the hydrophone and accelerometer measured signals is given by

\[
\rho_{x_1x_2}^{h}(\tau) = \frac{R_{x_1x_2}^{h}(\tau)}{\sqrt{R_{x_1x_1}^{h}(0)R_{x_2x_2}^{h}(0)}} = \frac{2\sqrt{L_1/L_2}}{(1 + L_1/L_2)\left[1 + (\tau/(\alpha D) + (L_1 - L_2)/c\alpha D)^2\right]^2}
\]

(7.7)

\[
\rho_{x_1x_2}^{a}(\tau) = \left(\frac{2\sqrt{L_1/L_2}}{1 + L_1/L_2}\right)^5 \left(\frac{1}{1 + (\tau/(\alpha D) + (L_1 - L_2)/c\alpha D)^2}\right)^3 \left\{1 - \frac{12}{1 + (\alpha D/(\tau + (L_1 - L_2)/c))^2} + \frac{16}{\left[1 + (\alpha D/(\tau + (L_1 - L_2)/c))^2\right]^2}\right\}
\]

(7.8)

The response of eqns 7.7 and 7.8 is plotted in Figures 7.2(b) and 7.2(c) respectively. It can be seen from Figures 7.2(b) and 7.2(c) that when the sensors are equidistant \((L_1 = L_2)\) from leak position, the correlation between accelerometer measured signals...
Figure 7.2: (a) Frequency response function of the hydrophone (−) and accelerometer (⋯) measured signals. Cross-correlation of the hydrophone (−) and accelerometer (⋯) measured signals when (b) $L_1 = L_2$ and (c) $L_1/L_2 = 1/3$. 
provides a more sharp peak than hydrophone measured signals. However, the magnitude of correlation peaks for both sensors is unity, as the sensors are equidistant relative to leak position. In Figure 7.2(c), the ratio of $L_1/L_2$ is changed to 1/3, which shifts the correlation peak from zero axis. It can be seen in Figure 7.2(c) that the hydrophone measured signals give a higher peak than the accelerometer measured signals. However, the accelerometer measured signals gives a sharp correlation peak. Therefore, it can be concluded that hydrophones are more effective for measuring leak signals with small signal-to-noise ratio (SNR), as they give comparatively higher correlation peaks than accelerometers. But a sharp correlation peak can be achieved at the expense of a comparatively lower peak value of the correlation coefficient, if accelerometers are used.

A more clear choice between the hydrophone and accelerometer sensors, can be made by considering their principle, design and installation in practice. This is explained below in section 7.2.2.

### 7.2.2 Hydrophones

The principle of operation of a hydrophone (also called a pressure sensor) is shown in Figure 7.3. A hydrophone measures the applied pressure by noticing the effect of pressure against its diaphragm. The diaphragm is connected to a strain gauge using a mechanical transmitter or transmission fluid (oil). When the fluid pushes the diaphragm, the strain gauge gets deflected and reflects this as a change in its electrical resistance. The strain gauge is arranged in a whetstone bridge circuit, which identifies the resulting change in electrical resistance as a change in applied pressure to the sensor. From the principle and layout of a hydrophone shown in Figure 7.3, it can be interpreted that for measuring leak signals, a hydrophone needs to be in physical contact with the water flowing in the distribution pipes. This is not preferred practically, because of the following reasons:

- Contamination of water due to the possible entry of foreign elements (Health and Safety reasons).
- Non-availability of suitable access points, where hydrophones can be safely connected in live water distribution pipes, especially those operating at high pressures.
Therefore, hydrophones are not preferred even though they give better response in situations of low SNR.

### 7.2.3 Accelerometer for measuring leak signals

From the above discussion it can be concluded that accelerometer is the only choice to measure leak signals. This section explains the specifications of an optimum accelerometer, for measuring low frequency leak signals in water distribution pipes especially MDPE. The specifications are designed using the characteristics of leak signals measured in Chapters 4 and 5. A ceramic based piezoelectric accelerometer is decided to use, as a high sensitivity is required to measure leak signals. The specifications set for the optimum accelerometer is reported in Table 7.1 and are explained below in section 7.2.3.1. Based on these specifications, an accelerometer called DF10, is manufactured by Montiran Ltd\(^1\), UK. DF10 is a piezo-electric accelerometer with a ceramic crystal, three-wire voltage output and isolated base. Its internal layout is shown in Figure 7.4. A mass (called as seismic mass) is attached to the piezo-electric ceramic crystal. When the accelerometer is connected to a leaking pipe, the vibrations produced by leaking water vibrates the mass. The mass wants to stay still due to inertia, but these vibrations force it to compress and stretch the crystal, which converts

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\(^1\)www.monitran.com
these mechanical movements into electrical charge. As per the Newton's law \((F=ma)\) this force is proportional to the accelerations produced by vibrational leak signals. Thus, the generated charge gives the measure of vibrational leak signal. This charge is converted into a usable alternating voltage by applying a constant current \((150\text{mA})\) power supply of \(\pm 15\text{VDC}\). This alternating voltage gives the measure of the vibrations produced in a leaking pipe.

Figure 7.4: Layout of the DF10 accelerometer designed for measuring leak signals in water distribution pipes \((\text{Monitran, 2008})\).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Useable frequency range</td>
<td>5Hz to 5kHz</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>10kHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>10V/g</td>
</tr>
<tr>
<td>Cross sensitivity</td>
<td>1%</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>(\pm g)</td>
</tr>
<tr>
<td>Supply</td>
<td>(\pm 15\text{V})</td>
</tr>
<tr>
<td>Mounting</td>
<td>Magnetic mounting</td>
</tr>
<tr>
<td>Isolation</td>
<td>Isolated base compression</td>
</tr>
</tbody>
</table>
7.2.3.1 Specifications of an optimum accelerometer

The specifications of an optimum accelerometer mentioned in Table 7.1 are explained below:

- **Useable frequency range:** This is the frequency range of an accelerometer over which its frequency response is flat i.e. the output is directly proportional to the acceleration it is measuring. Leak signals in MDPE pipes were found to be in the frequency range 20Hz to 350Hz and in metallic pipes between 20Hz to 750Hz approximately. To measure these signals, an accelerometer should have a flat frequency response in the range 20Hz to 750Hz. As it is difficult to maintain the sensitivity of sensor around DC; therefore, the lower 3dB frequency is set to 5Hz and the higher 3dB frequency of the optimum accelerometer is set to 5kHz. A higher value of 5kHz instead of 750Hz is chosen because the useable frequency range is affected by several factors such as mountings, when the accelerometer is operated.

- **Natural frequency:** The natural frequency of an accelerometer is the frequency where the ratio of output to input is highest. This ratio becomes non-linear from a frequency roughly 1/3 to 1/2 of the natural frequency. Therefore, the higher the natural frequency of an accelerometer, the higher the useful frequency range i.e. where the output to input is flat. The natural frequency $f_N$ is given by:

$$f_N = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \quad (7.9)$$

where $K$ and $M$ represents the stiffness and mass respectively. To increase the natural frequency, the mass ($M$) needs to be as small as possible and the stiffness needs to be as high as possible. A small mass usually means a lower sensitivity, but for leak signals a higher sensitivity is required. Therefore, the natural frequency is set to 10kHz, assuming that the maximum useful frequency (5kHz) is 1/2 of the natural frequency.

- **Sensitivity:** The ratio of change between an accelerometer's output and input is known as its sensitivity. The sensitivity of an accelerometer is determined from the difference of maximum to minimum acceleration\(^1\) it is measuring. In practise,

\(^1\)Acceleration produced by vibrations is expressed in terms of acceleration due to gravity (g).
it is extremely difficult to predict how much accelerations will be produced by leaks in a water distribution pipe. For example, in tests conducted at Severn Trent Lake House test rig and at hydraulics lab (See Chapters 4 and 5 for details), a maximum acceleration of 0.01g was found at the pressure of 8.2kPa. Therefore, it was decided to choose a sensitivity of 10V/g and the accelerometer maximum output of 10V, which gives the dynamic range ±g. The existing correlator's accelerometer have a maximum sensitivity of 1V/g, which is considerably less so these are not able to detect weak leak signals in MDPE and plastic pipes (Hunaidi et al., 2000).

- **Cross sensitivity or transverse sensitivity:** An accelerometer produces a small charge when it is vibrated in the axis 90 degrees to the main axis of measurement. This charge is indistinguishable from acceleration in the main axis. The sensitivity of the accelerometer to a transverse vibration is known as the transverse sensitivity. When leak signals are measured from the water distribution pipes, there can be a significant amount of vibrations produced in the transverse axis by several factors such as human and vehicular movements. These unwanted signals may lie in the frequency range of leak signals. Therefore, the transverse sensitivity of an optimum accelerometer should be zero or as low as possible. This is the reason for using an isolated base (Figure 7.4) in DF10 accelerometer, which helps to reduce the transverse sensitivity to 1% on calibration.

- **Dynamic range:** Dynamic range describes the minimum to maximum accelerations that the accelerometer can detect. The smallest acceleration is dictated by the noise floor of amplifying electronics and the highest acceleration depends on the power supply used. The noise floor can be minimised by using a bipolar power supply, which cancels the noise produced by the internal electronics. The another advantage of the bipolar supply is that its total effective power is doubled the unipolar power supply, which helps in measuring large accelerations. This is the reason for using three-wire output in the DF10 accelerometer. A bipolar power supply (±15V) is applied using these wires, which not only provides a total high voltage of 30V but also the bipolarity cancels the noise produced by the internal electronics and thus provides a low noise floor. Dynamic range is inversely proportional to the sensitivity of the accelerometer, which means the higher sensitivity
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leads to a lower dynamic range. The dynamic range of the DF10 accelerometer is $\pm g$ for the sensitivity of $10V/g$ and maximum output of $10V$.

- **Mountings**: Mountings significantly affect the stiffness with which the accelerometer can be connected to a surface (such as a pipe). It also affects the natural frequency of an accelerometer. The higher the stiffness of the mounting, the higher is the natural frequency. Magnetic mounting is the least stiff mounting, while a high tensile screw tightened to correct torque gives the highest stiffness. Other mounting methods come in between these two extremes. For measuring leak signals, magnetic mounting is preferred as the accelerometer needs to be temporarily connected to the access points. The magnetic mounting is the least stiff mounting; therefore, the natural frequency was chosen as $10kHz$. This is because of the reason that if the natural frequency range decreases by 50% due to magnetic mounting, there is still significant flat response left to measure leak signals. The stiffness of magnetic mounting can be improved by using a slight smear of Silicone grease between the mounting base and access points.

- **Ground isolation**: In water distribution systems, ground looping is a significant problem. Ground loops occur when the pipe access points and the ground surface above the access points have different electrical grounds. These grounds may only differ by a few millivolts or less. However, if set up in the sensor cable, they may interfere with the low level voltage signals coming from the sensors. There are several ways to prevent this, however as the accelerometer needs to have a temporary connection with the access points, so it is better to isolate its internal electronics from the base to prevent ground loops. For example, an electrically isolated mounting base (Figure 7.4) was used in the DF10 accelerometer, which isolates the accelerometer internals from the outer case. However, this reduces the stiffness and natural frequency of the optimum accelerometer. This is the another reason why a high natural frequency of $10kHz$ was chosen.

- **Connector**: As the accelerometer needs to have a temporary connection with the access points in the water distribution pipes, so a connector is preferred instead of direct cable connection. The connector makes it easy to disconnect and remove the sensor. However, this makes the sensor less waterproof and less resistant to the environmental moisture.
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- **DF10 accelerometer:** Finally for the specifications listed above, the DF10 accelerometer was manufactured and calibrated by Monitran, for a sensitivity of 9.8V/g @ 80Hz and frequency range 1Hz to 10kHz.

After measuring leak signals using an accelerometer, the next step is to remove unwanted frequencies. Before discussing this, it is important to determine the sampling frequency of leak signals, which is required for designing the digital filters. Ideally, as per the Nyquist theory (Taub & Schilling, 2002), the sampling frequency should be twice the highest frequency of the measured signals. However, in practice, to avoid the under-sampling, a sampling frequency greater than twice the highest signal frequency is used. In Chapters 4 and 5, the highest frequency of leak signals obtained in MDPE pipes and metallic (ductile iron) pipes is 350Hz and 750Hz respectively. Therefore, a sampling frequency of 2.5kHz is taken using the highest frequency of leak signals in metallic pipes. The sampling frequency is not chosen separately for both MDPE and ductile iron pipes as was done by Hunaidi & Wang (2000) and Hunaidi & Chu (1999). This is because in real pipe networks, the pipe under survey can be a combination of various pipe materials. Therefore, it is not sensible to choose the sampling frequency for each pipe material.

### 7.3 Filtering of leak signals

Filtering simply means to remove the undesired frequencies from the measured signals leaving frequencies of interest for further analysis. For example, an accelerometer while measuring leak signals also records the undesired ambient noise such as vehicular and human movements, which needs filtering in order to have a high signal to noise ratio.

In leak signal analysis, it is decided to perform the filtering operations two times. Firstly, on the signals obtained from the sensor and secondly on the recorded digital leak signals. To understand the effect of a filter on measured leak signals, consider an ideal band pass filter (Figure 7.5) given by:

\[
G(\omega) = \begin{cases} 
1 & \omega_0 \leq |\omega| < \omega_1; \\
0 & \text{elsewhere}
\end{cases}
\] (7.10)

where \(\omega_0\) and \(\omega_1\) are the lower and upper cut-off frequencies of the band-pass filter, \(G(\omega)\) is the frequency response of filter and \(\Delta\omega = \omega_1 - \omega_0\) is the bandwidth of band-pass filter.
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Figure 7.5: An ideal bandpass filter.

filter. The signals measured by the accelerometer are filtered using this bandpass filter and the cross-correlation coefficient of the filtered signals is given by:

\[
R_{x_1x_2}^F(\tau) = \frac{a^2 S_{II}(\omega)e^{-\omega_0 aD}}{\pi \theta h} \left\{ \begin{array}{l}
\frac{\omega_1^2 e^{-\Delta \omega aD} (\cos (\omega_1 (\tau + T_f) + \theta)) - \omega_0^2 (\cos (\omega_0 (\tau + T_f) + \theta))}{[(\alpha D)^2 + (\tau + T_f)^2]^{1/2}} \\
+ \frac{2a^2 S_{II}(\omega)e^{-\omega_0 aD}}{\pi \theta h} \left\{ \begin{array}{l}
\frac{\omega_1 e^{-\Delta \omega aD} (\cos (\omega_1 (\tau + T_f) + 2\theta)) - \omega_0 (\cos (\omega_0 (\tau + T_f) + 2\theta))}{[(\alpha D)^2 + (\tau + T_f)^2]^{3/2}} \\
+ \frac{2a^2 S_{II}(\omega)e^{-\omega_0 aD}}{\pi \theta h} \left\{ \begin{array}{l}
\frac{e^{-\Delta \omega aD} (\cos (\omega_1 (\tau + T_f) + 3\theta)) - (\cos (\omega_0 (\tau + T_f) + 3\theta))}{[(\alpha D)^2 + (\tau + T_f)^2]^{5/2}}
\end{array} \right\}
\end{array} \right\}
\right\}
\]

(7.11)

Similarly, the cross-correlation coefficient of the filtered hydrophone measured signals is given by:

\[
R_{x_1x_2}^{HF}(\tau) = \frac{S_{II}(\omega)e^{-\omega_0 aD}}{\pi \sqrt{(\alpha D)^2 + (\tau + T_f)^2}} \left\{ \cos[\omega_0(\tau + T_f) + \theta] - e^{-\Delta \omega aD} \cos[\omega_1(\tau + T_f) + \theta] \right\}
\]

(7.12)

where \( \theta = \tan^{-1}\left( \frac{T_f}{\alpha D} \right) \) and the time factor \( T_f = (L_1 - L_2)/c. \) If the frequency bandwidth satisfies the condition \( e^{-\Delta \omega aD} < < 1, \) eqn 7.12 can be approximated by

\[
R_{x_1x_2}^{HF}(\tau) \approx \frac{S_{II}(\omega)e^{-\omega_0 aD}}{\pi \sqrt{(\alpha D)^2 + (\tau + T_f)^2}} \left\{ \cos[\omega_0(\tau + T_f) + \theta] \right\}
\]

(7.13)

In eqn 7.11, the cross-correlation coefficient of the filtered accelerometer measured signals depends on the bandwidth (\( \Delta \omega \)), lower cut-off frequency (\( \omega_0 \)) and higher cut-off frequency (\( \omega_1 \)) of the filter. However, in eqn 7.13 the cross-correlation coefficient of the filtered hydrophone measured signals depend upon the bandwidth and lower cut-off frequency. Because eqn 7.11, contains the terms \( \omega_1^2 \) and \( \omega_1 \), so even if \( e^{-\Delta \omega aD} < < 1, \) the
product of these cannot be neglected. Therefore, provided that the bandwidth of filter is relatively broad, the cross-correlation function of the hydrophone measured signals is mainly dominated by the lower cut-off frequency and those of the accelerometer measured signals by the lower and upper cut-off frequency. Thus, it is important to choose all the signal processing techniques and electronics which do not disturb the lower and higher frequencies of the accelerometer measured signals.

7.3.1 Pre-filtering of analog leak signals

The analog signals obtained from the DF10 accelerometers are pre-filtered using a low pass filter so that the lower frequencies of leak signals are not disturbed. At this stage, filter cut-off frequency is selected based on the maximum frequency of leak signals noticed irrespective of the material and dimensions of pipe. Therefore, the 3dB frequency of the low pass filter is set to 760Hz using the highest frequency of 750Hz corresponding to leak signals in metallic pipes. A linear low pass filter is preferred so that the phase of leak signals is not disturbed.

These pre-filtered signals are amplified and then transmitted to a processing unit. The processing unit converts these into digital signals at a sampling frequency of 2.5kHz. The preamplifier, transceiver and processing unit are discussed in section 7.6.

7.3.2 Filtering of recorded leak signals using digital filters

In the second stage of filtering operation, the recorded digital leak signals are filtered using digital filters. At this stage, filter’s highest cut-off frequency is set according to the type of pipe, e.g. 360Hz for MDPE pipe. The choice of digital filters highly depends on the phase frequency relationship of the filter transfer function. This is because the phase of leak signals varies linearly with frequency and this phase information is used to determine the velocity of leak signals. Therefore, linear time-invariant digital filters are preferred which can be described as:

\[
y_F = \sum_{i=0}^{q} b_i x_{F-i} - \sum_{i=1}^{m} a_i y_{F-i}
\]  

(7.14)

where \(a_0=1\), \(x_F\) is the unfiltered input data, \(y_F\) is the filtered data and the coefficients \(a_i\) and \(b_i\) characterize the digital filter. The transfer function corresponding to eqn 7.14
is given by

\[ H_F(\omega) = \frac{Y(\omega)}{X(\omega)} = \frac{\sum_{i=0}^{q} b_i(j\omega)^i}{1 + \sum_{i=1}^{m} a_i(j\omega)^i} \]  (7.15)

Digital filters can be further divided into two categories: recursive and non-recursive filters, as explained below:

1. Recursive digital filters are also known as Infinite Impulse Response (IIR) filters. This is because the IIR filter contains not only the terms involving input values \((x_F, x_{F-1}, x_{F-2}, \ldots)\), but also the previous output values \((y_F, y_{F-1}, y_{F-2}, \ldots)\). Butterworth IIR digital filter can be considered suitable for filtering digital leak signals.

2. Non-recursive filters are also known as Finite Impulse Response (FIR) filters. In these filters, the output values depend only on the input values (the coefficients \(a_i, i=1,2,\ldots\) are all zero), thus eqns 7.14 and 7.15 simplifies to have,

\[ y_F = \sum_{i=0}^{q} b_i x_{F-i} \]  (7.16)

\[ H(\omega) = \sum_{i=0}^{q} b_i(j\omega)^i \]  (7.17)

Eqn 7.16 is also called as digital convolution. Based on the linear phase frequency requirement for filtering leak signals, Bessel FIR filter can be used to filter digital leak signals. These are discussed below in section 7.3.4.

### 7.3.3 Butterworth filter

Butterworth filter is also called ‘maximally flat magnitude filter’ as it is designed to have a frequency response that is as flat as mathematically possible in the passband (Taub & Schilling, 2002). The frequency response of the Butterworth filter has no ripples in the passband and rolls off towards zero in the stopband.

The gain \(G(\omega)\) of the \(n^{th}\) order Butterworth low pass filter in terms of the transfer function \(H(\omega)\) is given as:

\[ G^2(\omega) = |H_F(j\omega)|^2 = \frac{G_0^2}{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}} \]  (7.18)

where \(n\) is the order of filter, \(\omega_c\) is the cut-off frequency and \(G_0\) is the DC gain. It can be seen from eqn 7.18 that the higher the value of \(n\), the higher is the sharpness of cut-off frequency.
7.3.4 Bessel Filter

Bessel filter is a type of linear filter with a maximally flat group delay and linear phase response. It preserves the wave shape of filtered signals in the passband. A low-pass Bessel filter is characterized by its transfer function as:

\[ H_F(s) = \frac{\theta_n(0)}{\theta_n(s/\omega_c)} \]  

(7.19)

where \( \theta_n(s) \) is the reverse Bessel polynomial and \( \omega_c \) is the cut-off frequency. Lowpass Bessel filters have a monotonically decreasing magnitude response, as do lowpass Butterworth filters. However, they have more slower roll-off than Butterworth filters and require a higher order to meet an attenuation specification.

7.3.5 Digital filters in Matlab

Butterworth and Bessel filters discussed above can be designed in Matlab using the functions butter.m and besself.m respectively. Figure 7.6 shows the characteristics of a 4th order Butterworth and Bessel bandpass filter with cut-off frequencies set to 15Hz and 50Hz. Two simple scripts my.butter.m and my.bessel.m (See Appendix A.3 for the Matlab code) call these functions and compute the filter coefficients \( a_i \) and \( b_i \). The function filtfilt.m then filters the input data using these filter coefficients \( a_i \) and \( b_i \).

Compared with the same order Butterworth filter in Figure 7.6, the Bessel filter has a slower roll-off around the cut-off frequencies, thus it requires a higher order to implement the stopband specification. However, it has a more linear phase response in the passband than the Butterworth filters.

Figure 7.7 shows a simulated signal consisting of five frequency components at 10, 20, 35, 40 and 60Hz. This signal is passed through 4th order Butterworth and Bessel bandpass filters with cut-off frequencies set to 15Hz and 50Hz. It is observed that the Butterworth rolls off slowly around 50Hz, causing the 60Hz frequency component to be attenuated but not completely suppressed.

For a 4th order Bessel bandpass filter (Figure 7.7), high pass response is very good and the 10Hz frequency component is completely filtered. However, its low pass response is not very good. It rolls-off slower than the Butterworth around the higher cut frequency (50Hz) and attenuates the passband signals near the higher cut-off frequency.
Similar to Butterworth, it is not able to completely filter frequencies around the cut-off frequency of 50Hz.

To overcome these unwanted attenuation of frequency components near the filter cut-off frequencies, it is preferable to employ different order high and low pass filters. Figures 7.8 and 7.9 shows the response of 4th to 9th order low and high pass Bessel and Butterworth filters. These are designed for filtering leak signals in MDPE pipes with cut-off frequencies set to 15Hz and 360Hz respectively and the sampling frequency of 2.5kHz. For these frequency settings, the transfer function of the Bessel and Butterworth filter obtained in Figures 7.8 and 7.9 is discussed below:

- **Low pass filter**: From Figures 7.8(a)(b) and 7.9(a)(b), it can be seen that increasing the order of Bessel and Butterworth low pass filter, increases the roll-off factor around the cut-off frequency. However, for order \( n > 8 \), the non-linearity in the phase-frequency relationship of the Butterworth low pass filter increases. For Bessel filter, a higher order \( (n=9) \) is preferred as it gives the higher roll-off around the cut-off frequency. Therefore, for a sampling frequency of 2.5kHz and cut-off frequency of 360Hz, 9th order Bessel low pass filter and 8th order Butterworth low pass filter are preferred.

- **High pass filter**: From Figures 7.8(c)(d) and 7.9(c)(d), it can be observed that Bessel high pass filter response is not as good as Butterworth high pass filter. For Butterworth filter, the response starts distorting and the non-linearity in the phase-frequency relationship increases above 7th order. Therefore, a 9th order Bessel and 7th order Butterworth high pass filter is preferred for the cut-off frequency of 15Hz and sampling frequency 2.5kHz.

Bessel filter gives a more linear phase; therefore, it is preferred to Butterworth filter for leak signal analysis. However, it has a slower roll-off around the cut-off frequencies. Therefore, a choice of 9th order Bessel low pass filter and 8th order high pass filter would be suitable for filtering leak signals measured from MDPE pipes. From the above discussion, it can also be concluded that order significantly effects the high pass response in comparison to the low pass response. Therefore, filter order may be different for filtering leak signals measured from ductile iron or other pipe materials.
Figure 7.6: Bode plot showing the (a) Amplitude-frequency response, (b) Phase-frequency response of the 4\textsuperscript{th} order Bessel and Butterworth bandpass filter with cut-off frequencies set to 15Hz and 50Hz.
Figure 7.7: A simulated unfiltered signal in (a) time domain, (b) frequency domain, (c)(d) response of the 4th order Butterworth bandpass filter and (e)(f) Bessel bandpass filter to the input signals with cut-off frequencies set to 15Hz and 50Hz.
Figure 7.8: Bode plot showing the response of 4th to 9th order Bessel (a)(b) low pass filter and (c),(d) high pass filter. The lower cut-off frequency is 15Hz and higher cut-off frequency is 360Hz with the sampling frequency of 2.5kHz.
Figure 7.9: Bode plot showing the response of $4^{th}$ to $9^{th}$ order Butterworth (a)(b) low pass filter and (c)(d) high pass filter. The lower cut-off frequency is 15Hz and higher cut-off frequency is 360Hz with the sampling frequency of 2.5kHz.
7.4 Windowing

To perform the frequency domain analysis, digital leak signals have to be windowed. In signal processing, *window* is a function that is zero-valued outside of some chosen interval. In windowing, when a signal is multiplied by a window function, the product is zero-valued outside the window interval, with the "view" through the window remaining. Windows are characterised by their resolution ability.

For leak signals, it is advantageous to use better resolution windows as leak signals are highly affected by ambient noise. The three types of windows suitable for leak signals are:

- **Rectangular window**

  \[ H_w(n) = 1 \]  

  \hspace{1cm} (7.20)

- **Hamming window**

  \[ H_w(n) = 0.53836 - 0.46164 \cos \left( \frac{2\pi n}{N - 1} \right) \]  

  \hspace{1cm} (7.21)

- **Hanning window**

  \[ H_w(n) = 0.5 \left( 1 - \cos \left( \frac{2\pi n}{N - 1} \right) \right) \]  

  \hspace{1cm} (7.22)

where,

- \( N \) is an integer power-of-2 and represents the width, in samples, of a discrete-time window function. For leak signal analysis, the value of \( N \) is chosen to be 1024.

- \( n \) is an integer, with values \( 0 \leq n \leq N - 1 \).

### 7.4.1 Windows in Matlab

In Matlab, the rectangular window is made using the function `rectwin.m`, while the Hanning and Hamming windows are made using functions `hanning.m` and `hamming.m` respectively (See Appendix A.4 for the Matlab code). A window length of 1024 samples is chosen and window characteristics are shown in Figure 7.10. Figure 7.11 shows the power spectra of input signal with Hanning, Hamming and rectangle windows of length 1024 samples. The input signal is a sinusoidal signal coupled with random noise with frequency components at 10, 20, 35, 40 and 60Hz. When selecting a window function
for an application, the most important parameter is usually the stopband attenuation close to the main lobe. The rectangular window does not force any attenuation to the signal. It can be seen in Figure 7.11, that the spectra of input signal with rectangle window is the same as with 'No windowing', thus rectangle window is preferable for transient leak signals.

Hanning and Hamming windows, have the shape of one cycle of a cosine wave and when applied to an input time signal (Figures 7.11), they force the ends of the signal to zero regardless of what the input signal is doing. In Hanning window '1' is added to a cycle of cosine wave (eqn 7.22) making it always positive, which does not increase noise in negative domain of the signal as done by Hamming windows (Figures 7.11).

While the Hanning window does a good job of forcing the ends to zero, it also adds distortion to the waveform being analyzed in the form of amplitude modulation.
This amplitude modulation results in sidebands or side lobes in waveform spectra, which reduce the frequency resolution of the analyzer by 50%. In contrast, Hamming window increases noise in the passband, thus Hanning is preferred over Hamming for leak signals.

Therefore, Hanning window is suitable for continuous leak signals. However, it is not suitable for transient leak signals, as it will distort the shape of the transient, and the frequency and phase content of a transient is intimately connected with its shape.

![Power Spectra using Window Functions](image)

Figure 7.11: Power spectra of input signal with Hanning, Hamming and rectangle windows of length 1024 samples. (a)(b) The input signal has frequency components at 10, 20, 35, 40 and 60Hz and is coupled with random noise, (c)(d) response of the Hanning window, (e)(f) Hamming window, (g)(h) rectangle window.

In a Hanning weighted signal, one half of the signal is usually removed by the windowing. Thus, if a small change occurs in the signal near the beginning or end of the time record, it will either be analysed at a much lower level than its true level,
or it may be missed altogether. For this reason, a 50% overlap of Hanning windows is chosen for processing leak signals. These windowed signals are then analysed in frequency domain by taking the Fast Fourier Transform. If the measured signals are evident in the frequency range (20Hz to 350Hz), then this indicates a possibility of a leak. In practise, the amplitude of leak signals is found to be fluctuating; therefore, averaging is done to obtain a smooth frequency spectrum for better analysis.

7.5 Averaging

In signal processing, averaging is done to make the spectrum of a signal stable. This helps to reduce the fluctuations in the amplitude of signals when analysed in frequency domain. There are two types of averaging modes suitable for leak signals:

1. **Root mean square (RMS) averaging:** RMS averaging is used to stabilize amplitude variations of signals having a constant frequency and linear phase. The RMS average of \( b \) windowed signals is given by

\[
x_{\text{rms}} = \sqrt{\frac{1}{b} \sum_{i=1}^{b} x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_b^2}{b}}
\]  

(7.23)

The effect of RMS averaging to reduce amplitude fluctuations of real signals is shown in Figure 7.12. It can be seen that an average of 10 windowed leak signals has significantly reduced the amplitude fluctuations making the leak signals clearly visible.

2. **Peak hold averaging:** In peak hold averaging, the maximum value of a windowed signal is chosen, held and displayed in the power spectra. In the next window again peak is determined, held and displayed and it goes on. This is used when there is a lot of amplitude variations in the power spectra and it becomes difficult to analyse signals in frequency domain. Peak hold averaging is preferred for analysing correlation peaks. This is because each time correlation is performed it will choose and display the highest correlation peak, which makes it easier to isolate the main peak from the spurious peaks.

Therefore, RMS averaging over 10 to 25 (depending upon the fluctuations) windowed leak signals is preferred for leak signal analysis in frequency domain, while peak hold averaging is preferred for analysing correlation peaks.
7.6 Pre-amplifier, trans-receiver and A/D convertor

In the pilot study tests conducted at hydraulics laboratory and ST Lake House (See Chapters 4 and 5 for details), the magnitude of signals measured by accelerometer sensors (sensitivity 1V/g) was found to be of few millivolts, depending upon the leak characteristics. This is very small; therefore, the measured signals needs pre-amplification before being digitised or transmitted to a distant processor using cables or wireless trans-receiver system. A minimum gain of 20dB is required so that the leak signals can be amplified enough to be converted into digital signals. From these experiments, it was also found that leak signals in water distribution pipes exist in the frequency range 10Hz to 750Hz, depending upon the pipe characteristics. A linear phase frequency relationship is also obtained for MDPE pipes in the frequency range 20Hz to 250Hz. Therefore, the hardware (pre-amplifier, trans-receiver and A/D convertor) selected should work in the frequency range 10Hz to 750Hz and give a linear phase-frequency relationship. Based upon the above requirements, Sound Devices MM-1 preamplifier, Sennheiser EW 122-P G2 trans-receiver system and National Instruments 9221 DAQ is selected for the purpose of pre-amplification, signal transmission and analog to digital conversion respectively. The specifications of these devices is detailed below:

- **Preamplifier**: Sound Devices MM-1 is a single-channel, portable microphone preamplifier with a headphone monitoring function used to listen to leak signals. It incorporates a transformer balanced input and output to produce low-noise, low-distortion adjustable gain between 0dB to 66dB maximum. It works in the
10Hz to 50kHz audio bandwidth and provides a wide dynamic range exceeding 120dB. It has a balanced input, which is used to feed the sensor outputs.

- **Transreceiver:** The Sennheiser EW 122-P G2 system is used for transmitting leak signals. The system includes a portable transmitter and receiver. It features 1440 tunable UHF frequencies in the license free band 830 - 866 MHz. It has the frequency response of 10Hz to 18kHz with signal-to-noise ratio > 110 dB and a HDX compander to reduce the noise interference. It comes with an XLR to 3.5mm cable which is used to connect it to the pre-amplifier.

- **A/D convertor:** NI 9221 is a USB2 based data acquisition module featuring integrated signal conditioning. This module has eight single-ended analog input channels with an input range of ±60V for direct connection to sensors. It provides a maximum single channel sampling rate of 800 kS/s with the resolution of 12 bits/sample and features simultaneous acquiring of signals, as required for performing correlation. Its dynamic range is set to ±3V as the input leak signals were found to be in the range ±2V after amplification. This can be changed depending upon the amplitude of leak signals.

### 7.7 Conclusion

In this Chapter, an analytical model is presented to evaluate the effectiveness of different sensors in measuring leak signals from MDPE pipes. Their effect on the correlation of measured signals is also studied. It is found that hydrophones lead to a higher correlation peak than accelerometers. Therefore, a measure of pressure responses using hydrophones would be most suitable for locating leaks having small SNR. However, hydrophones are found to be difficult to use in practise and do not comply with Health and Safety rules, which makes accelerometers preferable for leak signal analysis.

From the analytical model, it is found that the use of acceleration signals results in the sharpest correlation peak. It also exhibits the least spreading of the envelope, which makes accelerometers particularly suitable in multi-leak and coherent noise situations.

A discussion on choice of filters, sampling frequency, averaging and hardware systems is also reported. Bessel filters have a linear phase, which makes them suitable for filtering leak signals. It is found that it is advantageous to use a combination of higher
order low and high pass filter rather than a bandpass filter for the narrow bandwidth leak signals. RMS averaging is preferred for the frequency domain analysis while peak hold averaging can be used for obtaining a clear identifiable correlation peak.
Chapter 8

System Evaluation

The objective of this chapter is to evaluate the monitoring procedure, sensor and the signal processing techniques specified in Chapter 7. A test rig of MDPE pipes was built at the hydraulics laboratory, Loughborough University. Several types of leaks were simulated and the leak signals were measured using the sensors and acquisition systems reported in Chapter 7. Finally, the specified signal processing techniques were applied and the complete system is evaluated to detect and locate leaks. The effect of backfill on the generation of leak signals is also discussed and the difference between the signals measured from access points and directly from the pipe is determined.

8.1 Test set up

A test rig was built in the hydraulics laboratory of the Department of Civil and Building Engineering, Loughborough University. The schematic diagram of the buried MDPE pipe test rig is shown in Figure 8.1. The test rig was made of 125mm diameter MDPE pipe approximately 32m in length. A FH2 underground fire hydrant (DN80, PN16 pressure rating and BS 750 type 2) was connected to one end of the pipe using flange fittings and 100mm full face rubber gasket, while the other end was connected to the water tank using MF2000 metal seated gate valve (BS 5163 type B). A 25mm diameter MDPE service pipe was connected to the 125mm diameter main pipe at 2.25m from the hydrant using an electro-fused fittings. The service pipe was 2.0m
long with a boundary box (Figure 8.2(c)) and stop tap (Figure 8.2(b)) in between. The other end of the service pipe was closed by using an end cap fitting (Figure 8.1(c)). A crack was made in the plug (Figure 8.2(d)) of this end cap fitting, to make a simulated leak.

Due to the space restrictions, only a portion of the test rig was buried to study the effect of backfill on the generation of leak signals. An existing pit of 3.5m length and 4m width was used for this purpose, in which a wooden rectangular box of 3m length, 2.5m width and 1.2m height was made using 18mm plywood, supported with wooden posts. Initially, there was clay rich soil covering the base of the pit, so an approximately 50mm thick soil layer was added and compacted to provide a firm planar base. Its top level was approximately 150mm below the lower edge of the 125mm MDPE pipe. After compacting the soil, sand was added to form a layer up to 150mm above the pipe's top surface. Sand was well compacted to make an approximately 150mm layer surrounding the pipe. Finally, an approximately 400mm high layer of rounded gravel was added on top of the sand to provide the overburden stress. This combination of sand and gravel provides the backfill for the MDPE pipes. In practice, lime dust and industrial waste are used as backfill (Divit, 2005); however, as the experiments need to be repeated several times, with backfill removed each time, so for ease of excavation, gravel and sand were used.

8.1.1 Mountings for the sensors

Vibrations produced by leaks were measured using DF10 accelerometers (sensitivity 10V/g and frequency response 0.1Hz to 5kHz) specified in Chapter 7. For measuring acoustic leak signals, hydrophones (sensitivity 30µV/Pa and frequency response 0.1Hz to 100kHz) were used. In this test rig, there were 90° and 45° bends (Figure 8.1), which may change the leak signals, therefore signals were measured at five positions (access points) along the test rig. These access points were made at 3m, 13m, 20m, 27m and 32m from the hydrant, by connecting the 1/4”-28UNF screw to the pipe using steel clamps which provide stud mounting for the accelerometers. Accelerometers were attached firmly to these screws with a thick steel washer in between to increase the area of contact. To improve the stiffness of the contact, a thin layer of silicone gel was applied to both sides of the washers. A magnetic mounting (2 pole magnet of 35mm diameter) was used to connect the accelerometers to the hydrant and valves. A
hydrophone was also connected to the hydrant using a London round thread adapter, with a thin layer of silicone gel on the internal rubber seal of the adapter. A flow meter was connected in the boundary box to measure flow rate, while a pressure gauge was connected to the hydrant for measuring the fluid pressure. The unconfined section of the test rig pipe was located roughly 150mm above ground level using concrete blocks to minimise transmission of noise from the ground.

Figure 8.1: (a) Schematic diagram of the buried 125mm MDPE pipe test rig at hydraulics laboratory, (b) test rig showing wooden posts and (c) the wooden rectangular box with pipes buried under the sand. It is showing the black boundary box, pipe with stop tap and black end cap of the 25mm service pipe with outer cover which prevents it from collapsing due to freezing.
Figure 8.2: (a) Outer covering of service pipe to keep it safe from freezing, (b) stop tap connected to the 25mm service pipe, (c) inner view of the boundary box, (d) stop cap with a split for simulating leaks and (e) a typical simulated leak.
8.2 Test procedure

Four leaks were simulated to evaluate the correlation system designed in Chapter 7 and to understand the effect of backfill on the generation of leak signals. Two leaks (Figures 8.3(a) & 8.4(a)) were simulated by loosening the stop cap fitting connected at the end of 25mm service pipe. The other two leaks (Figures 8.5(a) & 8.6(a)) were simulated by making a crack near the stop cap fitting. Initially, a small crack was made which was later increased to make a large leak with a typical flow rate of 16.5 l/min.

Signals were measured using accelerometers connected at access points (1 to 5) and their outputs were amplified using a portable Sound & Devices MM-1 pre-amplifier with gain set to 28dB. These amplified leak signals were transmitted to the processing unit, where these were digitised using a 12 bit analog to digital converter (NI DAQ-9221) and recorded on the hard disk of a personal computer using NI data acquisition software (VI Logger). The logger was set for a sampling rate of 2.5kHz and a dynamic range of ±3V so that a good resolution of signal could be obtained. These signals were filtered using Bessel filter specified in Chapter 7 and spectral analysis was then performed on these filtered signals using 1024 points FFT, RMS averaging and a Hanning window for better frequency resolution. In order to avoid the circular effect of FFT, a hanning window with 50% overlap was applied. The settings of the pre-amplifier, DAQ and the signal processing techniques are detailed in Table 8.1.

Table 8.1: Specifications of the hardware parameters and signal processing techniques.

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<th>Property</th>
<th>Value/Comments</th>
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<tbody>
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<tr>
<td>Window type</td>
<td>Hanning</td>
</tr>
<tr>
<td>Averaging type</td>
<td>RMS</td>
</tr>
</tbody>
</table>
8.3 Results and observations

Four leaks with a typical flow rate of $2.5 \ l/min$, $3.0 \ l/min$, $4.8 \ l/min$ and $16.5 \ l/min$ were simulated in the 25mm diameter service pipe and shown in Figures 8.3(a), 8.4(a), 8.5(a) & 8.6(a) respectively. For each leak, three types of signals were recorded simultaneously from two access points to perform correlation. In order to record signals, one sensor (accelerometer) was connected to the hydrant and the other one was connected step by step to each access point. The three recorded signals are:

1. **Background noise**: Background noise was recorded in the absence of a leak to measure the level of ambient noise and pipe resonance noise. However, the pipe was full of water at 170kPa pressure. The frequency spectrums of the background noise recorded from the hydrant and gate valve are shown in Figures 8.3(b), 8.4(b), 8.5(b) & 8.6(b) and Figures 8.3(c), 8.4(c), 8.5(c) & 8.6(c) respectively. For the frequency domain analysis of background noise, the averaging and filtering operations were not performed as these operations may attenuate or filter the random noise. For these tests, the background noise at the gate valve was found to be up to approximately 200Hz. However at the hydrant, the frequency spectrum of background noise was found to exist up to approximately 100Hz. The reason for this difference was found by listening to the noise. It was found that the gate valve was lying on the concrete floor so it was picking up the noise and vibrations from the floor, produced by nearby construction work. However, the hydrant was not in direct contact with concrete floor and was far away from the construction site. In addition to these noises, random noise such as human and traffic movements were also noticed. However, these noises were less problematic as these were not continuous and only in a few instances, were these picked up simultaneously by both sensors.

2. **Leak signals produced by leaks without backfill**: In the second step, a section of service pipe was excavated and a leak was simulated. Signals were recorded, which gives a combination of background noise and the signals produced by leaking water. The leak flow rate was controlled by the boundary box valve and measured using the water flow meter connected in the boundary box. The frequency spectrum of leak signals recorded for the four simulated leaks without
backfill are shown in Figures 8.3(d)(e), 8.4(d)(e), 8.5(d)(e) and 8.6(d)(e). It is observed that at the gate valve, the frequency range of measured signals exists up to 250Hz with most of the higher amplitude signals up to 200Hz. However, at the hydrant, leak signals were found to exist up to approximately 150Hz with most of the higher amplitude signals up to approximately 90Hz. Also, the signals at the hydrant were found to be of lower amplitude in comparison to the signals at gate valve. This difference in frequency and amplitude is due to the presence of high background noise at the gate valve and the noise made by water running through the gate valve.

3. Leak signals produced by leaks with backfill: Finally, the pipe section with leak was covered with the backfill soil without disturbing the flow rate and pressure in the main pipe. After placing the backfill, leak signals were again recorded after some time so as to allow the leaking water to make any changes to soil surrounding the leak location, which might affect the leak signals. The frequency spectrum of the recorded leak signals is shown in Figures 8.3(f)(g), 8.4(f)(g), 8.5(f)(g) and 8.6(f)(g). Compared with the results obtained above for leaks in service pipe without backfill, no significant change is observed in the frequency response of signals after leaking pipe was covered with backfill. However, some signals were found to be attenuated in Figures 8.5(f)(g) and 8.6(f)(g). On listening, the signals obtained for leaks with backfill sound similar to those obtained for leaks in service pipe without backfill. Therefore, it can be concluded that there is no significant effect of the backfill (sand and gravel) used on the frequency range and amplitude of the leak signals investigated. However, in practice, clay rich soil is also used as backfill, which has more stiffness than sand and may affect the characteristics of leak signals. But the clay is not presently used in the water distribution systems and because of difficulty in removing, its effect is not investigated in this thesis.

8.3.1 Effect of bends and access points

To understand the effect of bends and access points on the propagation of leak signals along the pipe, leak signals were measured using the accelerometer connected at the hydrant and five other access points (Figure 8.1) on the test rig. A hydrophone was also
used to measure the water-borne leak signals. The frequency spectrums of the signals obtained are shown in Figure 8.7. In Chapter 4, it was found from the theoretical predictions that discontinuities such as bends generate exponentially decaying signals which may interfere with the leak signals. A similar effect is also observed in Figure 8.7, where a lot of signals (especially above 200Hz) were observed in the frequency spectrum of signals measured near pipe bends. However at the hydrant, the frequency spectrum of accelerometer measured signals was found to be similar to the frequency spectrum of the hydrophone measured signals (Figure 8.7). Therefore, it can be concluded that the hydrant itself did not produce significant locally generated signals or the actual leaks signals were not disturbed. However, at the gate valve, the frequency response is slightly different which may be due to the high background noise, locally generated signals and the sound produced by running water. At other access points, the frequency spectrum was found to vary significantly due to locally generated signals. These signals may interfere with the actual leak signals; therefore, the system specified in Chapter 7, will be evaluated in this chapter using the signals measured from the hydrant and gate valve.
Figure 8.3: (a) A typical simulated leak with flow rate of 2.5 l/min. Amplitude and frequency variation with time of the (b)(c) background noise, (d)(e) leak signals corresponding to above simulated leak without backfill and (f)(g) with backfill. The signals in (b)(d)(f) were measured at the hydrant and (c)(e)(g) at the gate valve.
Figure 8.4: (a) A typical simulated leak with flow rate of 4.8 l/min. Amplitude and frequency variation with time of the (b)(c) background noise, (d)(e) leak signals corresponding to above simulated leak without backfill and (f)(g) with backfill. The signals in (b)(d)(f) were measured at the hydrant and (c)(e)(g) at the gate valve.
Figure 8.5: (a) A typical simulated leak with flow rate of 3.0 l/min. Amplitude and frequency variation with time of the (b)(c) background noise, (d)(e) leak signals corresponding to above simulated leak without backfill and (f)(g) with backfill. The signals in (b)(d)(f) were measured at the hydrant and (c)(e)(g) at the gate valve.
Figure 8.6: (a) A typical simulated leak with flow rate of 16.5 l/min. Amplitude and frequency variation with time of the (b)(c) background noise, (d)(e) leak signals corresponding to above simulated leak without backfill and (f)(g) with backfill. The signals in (b)(d)(f) were measured at the hydrant and (c)(e)(g) at the gate valve.
Figure 8.7: Amplitude and frequency variation with time of leak signals generated by a simulated split leak near the stop cap fitting connected at the end of the 25mm MDPE service pipe covered with backfill and at a flow rate of 16.5 l/min. Amplitude and frequency variation with time of leak signals recorded at (a) hydrant, (b) 3m, (c) 13m, (d) 20m, (e) 27m, (f) gate valve and (g) at the hydrant using a hydrophone.
8.4 System evaluation

In Chapter 7, the correlation system was designed with the following two aims:

1. To measure the low frequency, narrow bandwidth leak signals from the leaking MDPE pipes.

2. To process these leak signals in order to detect and locate leaks, using the cross-correlation technique.

To achieve the first aim, an accelerometer was specified in Chapter 7, which was used in section 8.2 to measure leak signals from the leaking MDPE pipe test rig at the hydraulics laboratory, Loughborough University.Leaks were simulated in the 25mm diameter service pipe with a typical flow rates of 2.5, 3.0, 4.8 & 16.5 l/min, and the fluid pressure of 170kPa. The frequency spectrum of the signals measured by the accelerometer is shown in Figures 8.3, 8.4, 8.5 and 8.6. The sensor was found to be capable of detecting low frequency signals below 80Hz and the accelerations less than 0.01g, which traditional correlator sensors are not able to measure.

To achieve the second aim, signal processing techniques were specified in Chapter 7, which were theoretically proven to be efficient for processing low frequency, narrow bandwidth leak signals produced by leaks in MDPE pipes. To evaluate the system’s (both accelerometer and signal processing techniques) performance in detecting and locating leaks, the MDPE pipe test rig at hydraulics laboratory was used. Leaks were simulated and the signals were measured by the DF10 accelerometer connected at hydrant and gate valve. These measured signals were processed by the signal processing techniques mentioned in Chapter 7. The cross-correlation techniques specified in Chapter 5 were applied to these processed signals and the results obtained are shown in Figures 8.8 and 8.9. From the results obtained, the performance of the system is evaluated as follows:

- Leak detection: In correlation method, a leak is detected if the cross-correlation function shows a distinct peak. In Figures 8.8 and 8.9, a distinct peak is obtained in the correlation function, which indicates that the system is capable of detecting leaks. However, the peak obtained is not very sharp for all the four leaks. This may be due to the reason that a high level of background noise was present at
the gate valve in the frequency range of leak signals. From Figures 8.8 and 8.9, it can be interpreted that correlation in the time domain gives more sharp and higher peaks than the correlation in the frequency domain. The SCOT filter is found to give noisy peaks; however it makes the main peak clearly identifiable. Thus, the specified system is capable of detecting leaks even at a low flow rate of 2.5 l/min and a low pressure of 170kPa.

- **Leak location:** The time delay between the signals measured at the hydrant and the gate valve is calculated by performing the correlation in time domain, generalised cross-correlation in frequency domain with no filter and SCOT filter. The results obtained are shown in Figures 8.8 and 8.9 and the time delay calculated for the four simulated leaks is reported in Table 8.2. For the velocity of leak signals in MDPE pipe as 325m/s (See Chapter 6 for details) and the total distance between the hydrant and gate valve of 32m, the position of leak relative to hydrant calculated using the cross-correlation method is reported in Table 8.2. Practically, the leak was approximately 4m from the hydrant. The error between the true distance and the calculated value is given in Table 8.2. The maximum and minimum error obtained is 0.87 and 0.0087 respectively. Theoretically, the maximum error seems to be very large; however, practically an error of ±1m is acceptable by the water industry professionals (Divit, 2005). Thus, the specified system in Chapter 7 is capable of locating leaks even in the presence of high background noise in the frequency range of leak signals.
Table 8.2: Distance of leak position from hydrant calculated using the correlation method.

<table>
<thead>
<tr>
<th>Leak flow rate l/min</th>
<th>Time Delay (sec)</th>
<th>Leak position from hydrant (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>0.077</td>
<td>3.439</td>
<td>0.562</td>
</tr>
<tr>
<td>3.0</td>
<td>0.075</td>
<td>3.796</td>
<td>0.204</td>
</tr>
<tr>
<td>4.8</td>
<td>0.076</td>
<td>3.682</td>
<td>0.317</td>
</tr>
<tr>
<td>16.5</td>
<td>0.078</td>
<td>3.227</td>
<td>0.773</td>
</tr>
</tbody>
</table>

Correlation in frequency domain using GCC (No filter)

<table>
<thead>
<tr>
<th>Leak flow rate l/min</th>
<th>Time Delay (sec)</th>
<th>Leak position from hydrant (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>0.077</td>
<td>3.472</td>
<td>0.529</td>
</tr>
<tr>
<td>3.0</td>
<td>0.078</td>
<td>3.309</td>
<td>0.692</td>
</tr>
<tr>
<td>4.8</td>
<td>0.074</td>
<td>3.992</td>
<td>0.0087</td>
</tr>
<tr>
<td>16.5</td>
<td>0.074</td>
<td>3.926</td>
<td>0.0737</td>
</tr>
</tbody>
</table>

Correlation in frequency domain using GCC (SCOT filter)

<table>
<thead>
<tr>
<th>Leak flow rate l/min</th>
<th>Time Delay (sec)</th>
<th>Leak position from hydrant (m)</th>
<th>Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>0.077</td>
<td>3.439</td>
<td>0.562</td>
</tr>
<tr>
<td>3.0</td>
<td>0.079</td>
<td>3.13</td>
<td>0.87</td>
</tr>
<tr>
<td>4.8</td>
<td>0.074</td>
<td>3.959</td>
<td>0.0412</td>
</tr>
<tr>
<td>16.5</td>
<td>0.074</td>
<td>3.943</td>
<td>0.0575</td>
</tr>
</tbody>
</table>
Figure 8.8: Cross-correlation in time domain of leak signals measured at the hydrant and the gate valve, corresponding to the simulated leak at a flow rate of (a) 2.5 l/min, (b) 3.0 l/min, (c) 4.8 l/min and (d) 16.5 l/min.
Figure 8.9: Generalised cross-correlation in frequency domain of leak signals measured at the hydrant and the gate valve, corresponding to the simulated leak at a flow rate of (a)(b) 2.5 l/min, (c)(d) 3.0 l/min, (e)(f) 4.8 l/min and (g)(h) 16.5 l/min.
8.5 Conclusion

In this Chapter, the effect of backfill on the generation of leak signals is discussed. It is found that the backfill has no significant effect on the frequency of generated leak signals. However, it may attenuate some frequencies of the leak signals.

The system proposed in Chapter 7, is evaluated for a range of leak flow rates in a service pipe using the simulated leaks in MDPE test rig at hydraulics laboratory. The system is found to be capable of detecting and locating leaks as small as 2.5 l/min at a low pressure of 170kPa. The peaks obtained in the correlation function are not very sharp, which may be due to the presence of high background noise at the gate valve. Thus, finally it can be concluded that leaks can be detected and located in MDPE pipes using the specified accelerometer and the signal processing techniques.

However, as there is a large variation in the diameter of MDPE pipes and pressure in distribution systems; therefore, the generated leak signals characteristics may vary. The current test specification may not necessarily work to quantify all leaks and some parameters such as filter cut-off frequencies may need to adjust depending upon the generated leak signals. However, the specified accelerometer and the signal processing techniques employed in the tests conducted in this thesis will work for all type of leaks in MDPE pipes, subject to some changes in parameters such as filter cut-off frequency.
Chapter 9

Conclusions and Recommendations

In this chapter, a comprehensive summary of the research work undertaken in this thesis is presented, followed by the conclusions. At the end, key recommendations for the future work are given.

9.1 Summary

This section summarises the research work done in this thesis to develop the cross-correlation technique for leak detection and location in MDPE pipes. To achieve the aim and research objectives defined in Chapter 1, the following specific tasks were reported in this thesis:

- **Objective 1:** Review existing information on distribution network pipe material properties in situ construction conditions and operational constraints.

This research objective is covered in the literature review reported in Chapter 2. The material and operational conditions of pipes used in distribution networks were reviewed and their strengths and weaknesses were compared. From the comparison, MDPE pipes were found to have numerous advantages such as low cost and high resistance to corrosion, over other pipe materials such as ductile iron. This information justifies their extensive use in water distribution systems in recent years.
Chapter 9: Conclusions and Recommendations

- **Objective 2:** *To investigate potential methods of leak detection and location such as water borne acoustic emission techniques, in use and under development.*

  In Chapter 2, a review of various leak detection and leak location techniques, both currently in use and under development is reported to compare their strengths, weaknesses and the possibility of use in MDPE pipes. From the comparison, correlator is found suitable for both leak detection and location purposes in MDPE pipes, but with several vulnerabilities. Therefore, it is necessary to optimize certain parameters such as filter cut-off frequencies to make it work effectively in MDPE pipes.

- **Objective 3:** *To develop an analytical model to predict cross-correlation of both the structure borne and fluid borne waves, for the purpose of leak detection and location in MDPE pipes.*

  To achieve this objective, an analytical model for calculating the cross-correlation function of leak signals in MDPE pipes is presented in Chapter 3. Various correlation functions for the estimation of time delay between leak signals are discussed and compared. From the model, it is noted that three parameters: distance between sensors positions, time delay between measured leak signals and the propagation speed of leak signals, directly affects the accuracy with which the correlation method locates leaks. These parameters are further investigated and found to be dependent upon several other parameters such as signal to noise ratio and the frequency range of leak signals. All these variables are listed and it is noted that these parameters requires optimisation to improve the effectiveness and accuracy of correlation process in detecting and locating leaks in MDPE pipes.

- **Objective 4:** *To produce a novel monitoring procedure, develop a test rig and conduct trials at the developed test rig and Severn Trent Lake House facilities.*

  In Chapters 4 and 5, a test rig of MDPE pipes without backfill is developed at the hydraulics laboratory, Loughborough University. The procedure of signal acquisition and analysis is designed. Various types of leaks were simulated and the leak signals were measured using both accelerometers and hydrophones. The results obtained were analysed and based on these results a further series of trials
were conducted on buried MDPE pipes at Severn Trent Lake House. The purpose of these trials was to determine the characteristics of leak signals.

- **Objective 5:** *To characterize leak signals using simulated leaks under controlled conditions and to investigate the parameters affecting signal characteristics.*

The performance of correlation process depends upon the characteristics of leak signals. Therefore, the characteristics of leak signals is investigated in Chapters 4 and 5 in two steps. In the first step, an analytical model is presented to characterise leak signals while in the second step, leak signals are characterised using the results of tests conducted on MDPE pipes with and without backfill. In these studies, most of the leak signals in MDPE pipes were found in the frequency range 20Hz to 350Hz, with an approximately linear phase-frequency relationship for the range 20Hz to 250Hz.

- **Objective 6:** *To design a monitoring system, signal acquisition sensor and signal processing techniques for locating leaks in MDPE pipes.*

To achieve this objective, a new method for calculating the velocity of leak signals in MDPE pipes is proposed and experimentally verified in Chapter 6. It is based on the linear phase-frequency relationship of leak signals and is found to give less fluctuations in the values of velocity, compared to other methods. The performance of correlation process depends upon the type of sensors, their positioning and the processing of signals obtained (See Chapter 3 for details). Therefore, an analytical model is presented in Chapter 7, to specify an optimum sensor for measuring leak signals in MDPE pipes. From the results, accelerometer was found to be suitable for measuring leak signals practically in water distribution networks. Various signal processing techniques are also discussed. A combination of Bessel low pass and high pass filter, Hanning window with 50% overlap, RMS averaging for frequency spectrum and peak averaging for cross-correlation function is found to be an appropriate choice for processing leak signals measured from leaking MDPE pipes. To optimise these variables and to do system evaluation, a final series of tests was conducted on a new test rig of buried MDPE pipes at the hydraulics laboratory, Loughborough University, where the system is proved to detect and locate leaks.
9.2 Conclusions and findings

The conclusions drawn and findings made from the research are summarised here as follows:

- In Chapter 2, various leak detection and leak location techniques were compared. Correlators were found most suitable for both leak detection and location in MDPE pipes, but with several vulnerabilities. Therefore, it is concluded that for its effective use in MDPE pipes, certain parameters such as filter cut-off frequencies and hardware components such as sensors need optimising.

- In Chapter 3, an analytical model for the calculation of cross-correlation function of leak signals in time domain and frequency domain was established. The model explained the importance of filter cut-off frequencies in correlators while performing leak detection surveys. It was found that the frequency domain analysis eliminates the requirement for selection of cut-off frequencies at the expense of low accuracy. PHAT, SCOT and ML time delay estimators were compared and found to give a sharp peak in the cross-correlation function. It was noted that PHAT estimator missed the effect of background noise, and ML estimator has the effect of overemphasising and underemphasising at certain frequencies. Therefore, SCOT is considered as the most suitable generalised cross-correlation weighting estimator for the purpose of leak detection.

- In Chapters 4 and 5, the characteristics of leak signals in MDPE pipes with and without backfill were determined using an analytical model and experimental studies. Most of the leak signals in MDPE pipes were found to exist in the frequency range 20Hz to 350Hz, with the upper limit of this frequency range found to vary with change in leak characteristics, pipe dimensions and flow rate. For the frequency range 20Hz to 250Hz, both the individual and related phase of leak signals were found to be linearly varying with frequency. From these results, it was decided to set the 3dB filter cut-off frequencies to 15Hz and 360Hz.

- In Chapter 6, a new method for the calculation of velocity and attenuation of leak signals was proposed and experimentally verified. The velocity was calculated by applying the least squares linear regression to the phase frequency relationship of
the product of the Fourier Transform of two leak signals. The attenuation was calculated by comparing the transfer functions at the two leak signal measurement positions. The proposed method was found to be less sensitive to noise and the results obtained exhibit less fluctuation compared to those obtained for the theoretical and other experimental methods.

- In Chapter 7, an analytical model was presented to evaluate the effectiveness of different sensors in measuring leak signals from the MDPE pipes. From the analytical model, it was found that the use of acceleration signals results in the sharpest correlation peak. It also exhibited the least spreading of envelope, which makes accelerometers most suitable in multi-leak and coherent noise situations. Hydrophones were found to give the largest correlation peaks so these are preferred for locating leaks with small SNR. However, hydrophones were found difficult to use, which makes accelerometers preferable for leak signal acquisition. A discussion on choice of filters, sampling frequency, averaging and hardware systems has also been presented. Bessel filter was found suitable for filtering leak signals because of their linear phase. It was found advantageous to use a combination of higher order low and high pass Bessel filter rather than a bandpass filter for the narrow bandwidth leak signals. RMS averaging is preferred for the frequency domain analysis while peak hold averaging was considered to be a best choice for obtaining a clear identifiable correlation peak.

The theoretical predictions were verified using the leak signals obtained from the tests conducted at the hydraulics laboratory, Loughborough University and ST Lake House test rig. The conclusions drawn from the experimental work are:

- The measured leak signals were found to exist in the frequency range 20Hz to 350Hz approximately.

- The phase of leak signals was found to be linearly varying with frequency in the range 20Hz to 250Hz approximately.

- The amplitude of leak signals was found to be increasing with increase in pressure while the upper limit of frequency range (20Hz to 350Hz) of leak signals changes with the leak flow rate, provided the dimensions of leak remains fixed.
Chapter 9: Conclusions and Recommendations

9.3 Contribution to Knowledge

This research contributed to knowledge in the following areas:

- The research work in this thesis is focused on the characteristics of leak signals and their variation with other parameters such as pressure and flow rate. With these results, specifications are set for an optimum sensor and signal processing techniques. With these sensors and signal processing techniques, the correlation method was found to be working effectively in MDPE pipes. This knowledge of the characteristics of leak signals in MDPE pipes can be applied to existing correlators currently used in the water industry to make them able to detect leaks in MDPE pipes, provided their sensors are capable of measuring low frequency leak signals from the MDPE pipes. In case the sensors are not capable of measuring leak signals from MDPE pipes, then the specifications of the accelerometer detailed in this thesis can be used to design a new sensor.

- The cross-correlation method is highly dependent upon the velocity of leak signals in MDPE pipes. Therefore, a new method is proposed and experimentally verified to determine the velocity of leak signals in MDPE pipes. This method is found to be giving less fluctuating results as compared to other theoretical and experimental methods and requires no prior information on the physical dimensions and material properties of pipe. This method can be used in existing correlators, without making any change in their physical design.

The results obtained in the thesis, not only help to improve the design and efficiency of correlators, but other acoustic devices can be made effective for leak detection and location purposes in MDPE pipe.

9.4 Limitations

The key limitations of the research work done and experimental setup in this thesis are:

- In both the test rigs at the hydraulics lab and ST Lake House, there was no flow of water in the absence of leaks. However in real pipe networks, there can be a flow of water inside pipes which may cause a significant level of noise. In practise,
situations such as multiple leaks, customer use and leaking access points may also exist, which will produce additional noise. To understand these situations, only one field trial has been done on MDPE pipe reported in this thesis.

- Leaks were simulated under controlled laboratory conditions. Their characteristics such as shape and size were not the same as real leaks (e.g. cracks) in water distribution pipes.

- There was no facility to conduct tests with different types of leak on longer lengths (>50m) of pipe. The lengths of test rig at the hydraulics lab and ST Lake House are 32m and 45.1m respectively, which are very short in comparison to real pipe lengths.

9.5 Recommendations for future work

This research has revealed a number of areas for further research and development in existing correlators and leak detection and leak location in water distribution pipes. The key recommendations for the future work are:

- The research work reported in this thesis is focused on detecting leaks in MDPE pipes. However, only a single leak was taken into account. Therefore, research work should be done in future studies to determine the effect of multi-leaks on frequency spectra of leak signals.

- Test results reported in this thesis showed that the correlation technique could effectively be used for time delay estimation in MDPE pipes. However, these were all conducted in laboratory conditions. Field tests could be carried out to capture real leak signals.

- The lengths of the test rigs at the hydraulics lab and ST Lake House are 32m and 45.1m respectively, which are very short in comparison to real pipe lengths. Therefore, future tests should be conducted on large diameter (>125mm) and longer lengths (>50m) of pipe to study any changes in the characteristics of leak signals and to determine the attenuation with distance of leak signals.
REFERENCES


References


Appendix A

Correlating Leak Signals

A.1 An example to correlate signals using Matlab

```matlab
% Example to illustrate the correlation of two simulated signals
%
fo=35; %Frequency (Hz) of simulated signal
fs=1000; %Sampling frequency in Hz
t=0:1/fs:1-1/fs;
% Signal One
x=sin(2*pi*fo*t).*exp(-20*t);
% Signal Two delayed
y=zeros(1,200) x(1:length(x))];
% Correlation of Signal One with Signal Two
[K,lag]=xcorr(x,y);
K(:)=K(:)/max(abs(K(:)));
lag(:)=lag(:)/fs;
% Plot Signal One
subplot(311)
plot(t,x);
xlim([0,0.5]);
grid;
text(0.8,0.8,'sin (2*pi*fo*t)*e^(-20*t)',...
    'fontsize',9,'edgecolor','red',...
    'background','white');
ylabel('x(t)');
xlabel('t (sec)');
```

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Chapter A: Correlating Leak Signals

A.2 An example to correlate signals in time domain and frequency domain

```matlab
% Example to illustrate the correlation — in time domain and frequency domain — of two simulated signals —

% Generate the signal ————
Period=1; % length of signal
Fs=1000; % sampling rate
t=0:1/Fs:Period;
a1=1; % Amplitude
a2=1.5;
```
Chapter A: Correlating Leak Signals

\[ f_1 = 10; \quad f_2 = 20; \]
\[ w_1 = 2\pi f_1; \quad w_2 = 2\pi f_2; \]
Order of Window = 1024;
\[ \text{sig}_1 = \text{zeros}(1, 1024); \quad \text{sig}_2 = \text{zeros}(1, 1024); \]
\[ g = a_1 \cos(w_1 t) \cdot \exp(-1.5 t) + a_2 \cos(w_2 t) \cdot \exp(-2 t); \]
\[ \text{N} = 1024; \quad \text{frame} = 1024; \]
\[ \text{gshift} = [\text{zeros}(1, \text{length}(g))/8] g; \]
\[ \text{noise} = \text{randn}(1, \text{length}(\text{gshift})); \]
\[ \text{noise} = \text{gshift} + \text{noise}; \]
\[ \text{fft} \quad \text{Calculations} \]
\[ \text{Z}_1 = \text{zeros}(1, 1024); \quad \text{Z}_2 = \text{zeros}(1, 1024); \]
\[ \text{Z}_1(1: \text{length}(g)) = g(1,:); \]
\[ \text{Z}_2(1: \text{length}(\text{noise})) = \text{noise}(1,:); \]
\[ \text{FF}_1 = \text{fft}(\text{Z}_1, 1024); \quad \text{FF}_2 = \text{fft}(\text{Z}_2, 1024); \]
\[ \text{Pxx} = \sqrt{\text{FF}_1 \cdot \text{conj}(\text{FF}_1)}; \]
\[ \text{Pyy} = \sqrt{\text{FF}_2 \cdot \text{conj}(\text{FF}_2)}; \]
\[ \text{Pxy} = ((\text{FF}_1 \cdot \text{conj}(\text{FF}_2))); \]
\[ \text{corr} \quad \text{Calculations} \]
\[ \text{[K, lag]} = \text{xcorr}(\text{noise}, g); \]
\[ \text{K}(:) = \text{K}(:)/\max(\text{abs(K}(:))); \]
\[ \text{resolution} = (\text{Fs} \times \text{N})/\text{frame}; \]
\[ \text{lag} = \text{lag}/\text{resolution}; \]
\[ \text{Nchn} = \text{size}(\text{Pxy}, 2); \]
\[ \text{coherence} \quad \text{Estimate} \]
\[ \text{[cxy, freq]} = \text{mscohere}(\text{g, noise}(1: \text{length}(g)), [], \text{Order of Window}/2, \text{Order of Window}, \text{Fs}); \]
\[ \text{if size(Pxx) = size(Pyy) \quad size(Pxx) = size(Pxy) \quad size(Pyy) = size(Pxy)} \]
\[ \text{error('SCOT filter: power spectra size must be the same');} \]
Chapter A: Correlating Leak Signals

```matlab
% --- case 'phat' Phase Transform (PHAT) ---
WP = ones(N,Nchn);
W_Den = abs(Pxy);
for k=1:Nchn
    nonzero = find(W_Den(:,k));
    WP(nonzero,k) = 1 ./ W_Den(nonzero,k);
end

% --- case ML-ML filter ---
if size(Pxx)<>size(Pyy) | size(Pxx)<>size(Pxy) | size(Pyy)<>size(Pxy)
    error('ML-modified: power spectra size must be the same');
end
WC = ones(N,Nchn);
factor = .75;
W_Den = (Pxx .* Pyy) .* factor;
for k=1:Nchn
    nonzero = find(W_Den(:,k));
    WC(nonzero,k) = 1 ./ W_Den(nonzero,k);
end

%---apply the filter---
R = Pxy .* W; % --- No filter ---
RS = Pxy .* WS; % --- SCOT filter ---
RP = Pxy .* WP; % --- PHAT filter ---
RC = Pxy .* WC; % --- ML filter ---
% estimate the generalized cross-correlation (GCC)
G = fftshift(real(ifft(R)),1);
GS = fftshift(real(ifft(RS)),1);
GP = fftshift(real(ifft(RP)),1);
GC = fftshift(real(ifft(RC)),1);
% % NB: the real part is extracted to avoid the small undesired imag. part
% % that sometimes compare during the inverse Fourier transform.
% normalize GCC
for k=1:Nchn
    G(:,k) = G(:,k)/max(abs(G(:,k)));
    GS(:,k) = GS(:,k)/max(abs(GS(:,k)));
    GP(:,k) = GP(:,k)/max(abs(GP(:,k)));
    GC(:,k) = GC(:,k)/max(abs(GC(:,k)));
end
% calculate time axis
resolution = (Fs*N)/(frame);
if mod(N,2)==0
    tim = [-N/2 : (N/2)-1] / resolution;
else
    tim = [- (N-1)/2 : (N-1)/2] / resolution;
end
%---Plot the signals---
```

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```matlab
xmin=-1;
xmax=1;
ylim=-5;
ymax=5;
f1=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [],...
     'YTick', [], 'Box', 'on', 'visible', 'off');
plot(t,g,'b')
ylabelCMag _Signal I','FontSize' ,14)
% xlmin = [x]...
xlim([x]...ymin ylmax]);
xlabel('Time(seconds)', 'FontSize' ,14)
grid on;

f2=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [],...
     'YTick', [], 'Box', 'on', 'visible', 'off');
plot(t,noise(1:length(t)),'r')
ylabel('Mag _Signal II' ,'FontSize' ,14);
xlabel('Time(seconds)', 'FontSize' ,14)
ylim([y]... grid on;

f3=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [],...
     'YTick', [], 'Box', 'on', 'visible', 'off');
plot(lag,K,'-k')
ylabel('Mag _xcorr' ,'FontSize' ,14);
xlim([x]...xlabel('Time(seconds)', 'FontSize' ,14)
grid on;

f4=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [],...
     'YTick', [], 'Box', 'on', 'visible', 'off');
plot(tim,G,'-k')
ylabel('Mag _GCC nofilter' ,'FontSize' ,14);
xlim([-0.5 0.5])
xlabel('Time(seconds)', 'FontSize' ,14)
grid on;

f5=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [],...
     'YTick', [], 'Box', 'on', 'visible', 'off');
plot(tim,GS,'-k')
```

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ylabel(' Mag _GCC Scot', 'FontSize', 14)
xlim([-0.5 0.5]);
xlabel('Time(seconds)', 'FontSize', 14)
grid on;

f6=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [], ...
'YTick', [], 'Box', 'on', 'visible', 'off');
plot(tim,GG,'-k')
ylabel(' Mag _GCC ML', 'FontSize', 14)
xlim([-0.5 0.5]);
xlabel('Time(seconds)', 'FontSize', 14)
grid on;

f7=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [], ...
'YTick', [], 'Box', 'on', 'visible', 'off');
stem(freq,cxy,'b*');
grid on;
xlabel('Frequency(Hz)', 'FontSize', 14);
ylabel('Mag Coherence', 'FontSize', 14);
axis([0 Fs/4 0 1]);

f8=figure;
axes('Units', 'normalized', 'Position', [0.1 0.125 0.650 .50], 'XTick', [], ...
'YTick', [], 'Box', 'on', 'visible', 'off');
plot(tim,GP,'-k')
ylabel(' Mag _GCC Phat', 'FontSize', 14)
xlim([-0.5 0.5]);
xlabel('Time(seconds)', 'FontSize', 14)
grid on;

%--Print the Figures--
print(f1, '-djpeg100');
print(f2, '-djpeg100');
print(f3, '-djpeg100');
print(f4, '-djpeg100');
print(f5, '-djpeg100');
print(f6, '-djpeg100');
print(f7, '-djpeg100');
print(f8, '-djpeg100');
A.3 Butterworth and Bessel filter in Matlab

function filter_bb

% Example to illustrate the:
% fourth order Bessel —
% —and Butterworth bandpass filter—
% Sample signal consists of—
% frequencies 10, 20, 35, 40 and 60Hz
%

% Coefficients of sample signal—
Period=1;
t=0:1/1000:Period;
a1=1; a2=1.5; a3=0.5; a4=1.75; a5=1.5;
% Frequency of sample signal—
f1=10; f2=20; f3=35; f4=40; f5=60;
w1=2*pi*f1; w2=2*pi*f2; w3=2*pi*f3; w4=2*pi*f4; w5=2*pi*f5;
% Sample signal—
g=a1*cos(w1*t)+ a2*cos(w2*t)+ a3*cos(w3*t)+ a4*cos(w4*t)+ a5*cos(w5*t);
NP=length(t);
minlimit=-3;
maxlimit=3;
f=(0:(NP-1));
fr=(0:(NP-1)/4);
% Define filter cut-off frequencies —
fh=15;fl=50;
fls=fl+2; % Filter Stop Edge Higher Frequency
fhs=fh-2; % Filter Stop Edge Lower Frequency
%
% Filter Out 10 and 50Hz
[g_1,a_1,b_1]= my_bessel(g,4,fl,fh,NP-1);
[g_2,a_2,b_2]= my_butter(g,4,fl,fh,fls,fhs,NP-1);
G=fft(my_window(g,1024),1024);
G_1=fft(my_window(g_1,1024),1024);
G_2=fft(my_window(g_2,1024),1024);
%
% Frequency Response of Filters
[H_1,f_1] = freqz(b_1,a_1,max(1024,...
nextpow2(5*max(length(b_1),length(a_1)) ) ),NP-1);
[H_2,f_2] = freqz(b_2,a_2,max(1024,...
nextpow2(5*max(length(b_2),length(a_2)) ) ),NP);
%
% Plot the results——
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```matlab
fig1=figure;
subplot(2,1,1);
l=loglog(f.1,abs(H_1),'-r',f.2,abs(H_2),b');
xlim([2 100]);
ylim([10^(-4) 10^(1)]);
xlabel('Frequency(Hz)','FontSize',10);
ylabel('Magnitude','FontSize',10);
legend('Bessel','Butter','FontSize',4,'pos','2');
hold on;
plot(ft,logspace(-5,0,200),'-k',fh,logspace(-5,0,200),'-k')
hold off;
grid on;

subplot(2,1,2);
l=semilogx(f.1,angle(H_1)*180/pi,'-.r',f.2,angle(H_2)*180/pi,'b');
xlim([2 100]);
xlabel('Frequency(Hz)','FontSize',10);
ylabel('Phase(degrees)','FontSize',10);
grid on;

print(fig1,'jpg100'); % Uncomment to save figure

fig=figure;

% Plot the filtered signal
clf;
% Input signal in time domain
subplot(4,2,1);
plot(t,g);
grid on;
set(gca,'ylim',[-6 6]);
xlabel('t(seconds)', 'FontSize',9);
ylabel('g(t)', 'FontSize',9);

% Input signal in Frequency Domain
subplot(4,2,2);
plot(f,log10(abs(G(1:NP))));
grid on;
set(gca,'ylim',[minlimit maxlimit]);
set(gca,'xlim',[0 100]);
xlabel('Frequency(Hz)', 'FontSize',9);
ylabel('|G(f)|_log10','FontSize',9)
%
% Filtered Signal with Butterworth Filter
% In Time Domain
subplot(4,2,3)
plot(t,g_2);
grid on;
```

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set(gca,'ylim',[-5 5]);
xlabel('t (seconds)', 'FontSize', 9);
ylabel('g(t) _Butter', 'FontSize', 9);
text(0.04,-7,'(c)', 'FontSize', 8);

% In Frequency Domain
subplot(4,2,4) % G:1
plot(fr,log10(abs(G_2(1:(NP/4)+1))));
grid on;
hold on
plot(f_2,abs(H_2)', r');
hold on
plot(f_1,0:0.01:1,-k', fh,0:0.01:1,-k');
hold on
plot(fh:0.5:fl,1,-k');
hold off

set(gca,'ylim',[-33]);
set(gca,'xlim',[0 100]);
xlabel('Frequency (Hz)', 'FontSize', 9);
ylabel('G(f)', 'FontSize', 9);
text(5,-4,'(d)', 'FontSize', 8);

% Filtered Signal with Bessel Filter

% In Time Domain
subplot(4,2,5)
plot(t,g_1);
grid on
set(gca,'ylim',[-55]);
xlabel('t (seconds)', 'FontSize', 9);
ylabel('g_{fBessel}', 'FontSize', 9);
text(0.04,-6.5,'(e)', 'FontSize', 8);

% In Frequency Domain
subplot(4,2,6)
plot(f,log10(abs(G_2(1:NP))));
grid on;
hold on
loglog(f_1,abs(H_1)', r');
hold on
plot(f_1,0:0.01:1,k', fh,0:0.01:1,k');
hold on
plot(fh:0.5:fl,1,-k');
hold off

set(gca,'ylim',[minlimit maxlimit]);
set(gca,'xlim',[0 100]);
xlabel('Frequency (Hz)', 'FontSize', 9);
ylabel('| G(f) | _Bessel(log10)', 'FontSize', 9);
Chapter A: Correlating Leak Signals

%---Bessel Filter---
function [y,a,b]=my_bessel(x,o,Fh,Fs)
Bpass=[Fh F] * 2* pi;
[ba,aa]=besself(o,Bpass);
[b,a]=impinvar(ba,aa,Fs);
y=filtfilt(b,a,x);

%---Butterworth Filter---
function [y,a,b]=my_butter(x,o,Fh,Fs,Fs,Fhs,Fhs,Fs)
Bpass=[Fh F] * 2/Fs;
Bstop=[Fhs Fls] * 2/Fs;
Rp=2; Rs=50;
[n,wn]=buttord(Bpass,Bstop,Rp,Rs);
[b,a]=butter(o,wn);
y=filtfilt(b,a,x);

function [z]=my_window(x,n)
y=x.*hann(length(x));
z=zeros(1,n);
z(1: length(y))=y(1:); 

A.4 Windowing in Matlab

An example of a Rectangle, Hanning and Hamming window

% Digital Filters using Windows
% Sample Signal Consists of Frequencies 10, 20, 35, 40 and 55Hz
% June 2007
% Time series
function Windowexample
Period=-L;
t=0:1/1000:Period; a1=1; a2=1.5; a3=0.5;
a4=1.75; a5=1.5; f1=10; f2=20; f3=35; f4=40; f5=60;
w1=2*pi*f1; w2=2*pi*f2; w3=2*pi*f3; w4=2*pi*f4; w5=2*pi*f5;
g=a1*cos(w1*t)+ a2*cos(w2*t)+ a3*cos(w3*t)+ a4*cos(w4*t)+ a5*cos(w5*t);
noise=randn(1,(length(g)));
g=g+noise; %--Noisy signal
NP=1024;
% Power Spectra using various Windows
z=zeros(1,NP); f=0:NP/4;
z(1:length(g))=g(1,:); %--No Window--
H=hann(length(g)); %--Hanning Window--
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\[
\text{Hn} = g^* H'; \\
\text{zhn} = \text{zeros}(1, \text{NP}); \\
\text{zhn} = \text{zeros}(1, \text{length}(	ext{Hn})) = \text{Hn}(1,:); \\
\text{Hm} = \text{hamming}(	ext{length}(g)); \quad \% - \text{Hamming Window} \\
\text{Hmm} = g^* Hm'; \\
\text{zhm} = \text{zeros}(1, \text{NP}); \\
\text{zhm} = \text{zeros}(1, \text{length}(	ext{Hmm})) = \text{Hmm}(1,:); \\
\text{R} = \text{rectwin}(	ext{length}(g)); \quad \% - \text{Rectangular Window} \\
\text{Rw} = g^* R'; \\
\text{zhr} = \text{zeros}(1, \text{NP}); \\
\text{zhr} = \text{zeros}(1, \text{length}(	ext{Rw})) = \text{Rw}(1,:); \\
\% - \text{Power Spectra} \\
\text{G} = \text{fft}(z, \text{NP}); \quad \% - \text{No Window} \\
\text{G}_1 = \text{fft}(\text{zhn}, \text{NP}); \quad \% - \text{Hanning Window} \\
\text{G}_2 = \text{fft}(\text{zhm}, \text{NP}); \quad \% - \text{Hanning Window} \\
\text{G}_3 = \text{fft}(\text{zhr}, \text{NP}); \quad \% - \text{Rectangular Window} \\
\% \\
\text{max} = 3; \\
\text{min} = -0.5; \\
\% \text{Plot the Results} \\
cf; \\
\% \text{Time Series} \\
\text{subplot}(4,2,1); \\
\text{plot}(t,g); \\
\text{grid on}; \\
\text{set}(\text{gca}, 'ylim', [-6 6]); \\
\text{ylabel}('g(t) None', 'FontSize', 9); \\
\text{str} = \text{get}(\text{gca}, 'title'); \\
\text{set}(\text{str}, 'string', 'Power Spectra using Window Functions', '...
\quad 'FontWeight', 'Bold', 'FontSize', 9, ...
\quad 'position', [1.15 0.68 1], 'Units', 'normalized'); \\
\% \\
\% \text{Signal (g) in Frequency Domain} \\
\text{subplot}(4,2,2); \\
\text{plot}(f, \log10(\text{abs}(\text{G}(1: \text{NP}/4+1)))), 'r', f, 0:0.01:max, 'g', f2, 0:0.01:max, 'g', ...
\quad f3, 0:0.01:max, 'g', f4, 0:0.01:max, -g, f5, 0:0.01:max, g); \\
\text{grid on}; \\
\text{set}(\text{gca}, 'ylim', [\text{min} \text{max}]); \\
\text{set}(\text{gca}, 'xlim', [0 100]); \\
\text{ylabel('G(f) None', 'FontSize', 9)} \\
\% \\
\% \text{Signal (g) Filtered with Hanning Window} \\
\text{subplot}(4,2,3) \% \text{Time Domain} \\
\text{plot}(t, Hn, t, H, 'r'); \\
\text{grid on};
set(gca,'ylim',[-5 5]);
ylabel('g(t) .Hann', 'FontSize', 9);

% Filtered Signal in Frequency Domain
subplot(4,2,4) 
plot(f,log10(abs(G_1(1:NP/4+1))),'r',f1,0:0.01:max,'g',f2,0:0.01:max,'g',...
    f3,0:0.01:max,'g',f4,0:0.01:max,'g',f5,0:0.01:max,'g');
grid on;
hold off
set(gca,'ylim',[min max]);
set(gca,'xlim',[0 100]);
ylabel('IG(f)1 .Hann', 'FontSize', 9);

% Signal g filtered with Hamming Filter
subplot(4,2,5) 
plot(t,Hmm,t,Hm,'r');
grid on;
set(gca,'ylim',[-5 5]);
ylabel('g(t) .Hamming', 'FontSize', 9);

% Filtered Signal in Frequency Domain
subplot(4,2,6) 
plot(f,log10(abs(G_2(1:NP/4+1))),'r',f1,0:0.01:max,'g',f2,0:0.01:max,'g',...
    f3,0:0.01:max,'g',f4,0:0.01:max,'g',f5,0:0.01:max,'g');
grid on;
hold off
set(gca,'ylim',[min max]);
set(gca,'xlim',[0 100]);
ylabel('IG(f)1 .Hamming', 'FontSize', 9);

% Signal g filtered with Rectangle Filter
subplot(4,2,7) 
plot(t,Rtw,t,R,'r');
grid on;
set(gca,'ylim',[-5 5]);
xlabel('t(seconds)', 'FontSize', 9);
ylabel('g(t) .Rectangle', 'FontSize', 9);

% Filtered Signal in Frequency Domain
subplot(4,2,8) 
plot(f,log10(abs(G_3(1:NP/4+1))),'r',f1,0:0.01:max,'g',f2,0:0.01:max,'g',...
    f3,0:0.01:max,'g',f4,0:0.01:max,'g',f5,0:0.01:max,'g');
grid on;
hold off
set(gca,'ylim',[min max]);
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A.5 Coherence estimate in Matlab

An example of a Coherence of two signals

Sample Signal Consists of Frequencies 10, 20, 35, 40 and 55Hz
% June 2007

Generate the signal

Period=1; Fs=1000; t=0:1/Fs:Period; a1=1; a2=1.5; a3=0.5;
a4=1.75; a5=1.5; f1=10; f2=20; f3=35; f4=40; f5=60;
w1=2*pi*f1; w2=2*pi*f2; w3=2*pi*f3; w4=2*pi*f4; w5=2*pi*f5;

Order of Window = 1024;
sig1=zeros(1,1024);
sig2=zeros(1,1024);
g=a1*cos(w1*t)+ a2*cos(w2*t)+ a3*cos(w3*t)+ a4*cos(w4*t)+ a5*cos(w5*t);
noise=randn(1,length(g));

noise=g+noise;

[cxy,freq]=mscohere(sig1,sig2,[],Order of Window / 2,Order of Window,Fs);

Plot the results

figure

subplot(3,1,1)
plot(t,g,'b');

subplot(3,1,2)
plot(t,noise,'r');

subplot(3,1,3)
plot(t1,noise,'r');

xlabel('Time (seconds)', 'FontSize', 9);
ylabel(' Magnitude', 'FontSize', 9);

grid on
title('COHERENCE EXAMPLE', 'FontWeight', 'Bold');

%——— Noisy Signal One———

%——— Signal One———

%——— Signals for coherence———

%——— Plot the results———
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ylabel('Magnitude', 'Fontsize', 9);
grid on;

% --- Coherence ---
subplot(3, 1, 3);
stem(freq, cxy, 'b*');
grid on;
xlabel('Frequency(\text{Hz})', 'Fontsize', 9);
ylabel('Coherence', 'Fontsize', 9);
axis([0 Fs/4 0 1]);
Appendix B

Characterising Leak Signals

This appendix reviews the characteristics of leak signals in a fluid filled pipe with and without backfill, using the low frequency vibro-acoustic behavior of fluid-filled cylindrical shells, developed by Pinnigton & Briscoe (1994).

B.1 Propagation of leak signals as sound waves in fluid-filled pipes

Leak signals are sound waves. Sound is a wave phenomenon i.e. each little parcel of carrying medium (water or pipe) vibrates in some fashion in the vicinity of its original position and passes on the disturbance and energy to its neighbors (Donald, 1987). In different locations, parcels are at different stages of vibration so the normal wave equation for a sound wave is given by

$$y - y_0 = Asin(\omega t - kx)$$  \hspace{1cm} (B.1)

where $y_0$ represents the equilibrium position, $A$ represents the amplitude and the quantity $k$ is called as wave number (spatial frequency). For leak signals in pipe or water, $y$ might represents the pressure, displacement or velocity. These vibrations indicate motion, so assuming the displacement of any particular parcel from its undisturbed position is $\xi(x, t)$ then the corresponding velocity and acceleration is $d\xi/dt$ and $d^2\xi/dt^2$ respectively.
This change in displacement of fluid elements is related to the density of the fluid. To be more precise, consider the small cube of fluid shown in Figure B.1a. Suppose for the moment, the motion is only in $x$ direction. Then the left face of the cube moves under the influence of the sound wave (leak signals) from $x$ to $x + \xi(x, t)$, while the right face moves from $x + \Delta x$ to $x + \Delta x + \xi(x + \Delta x, t)$, as indicated in Figure B.1b. Its width has increased from $\Delta x$ to $\Delta x + \xi(x + \Delta x, t) - \xi(x, t)$; so the volume has been multiplied by a factor

$$1 + \left[\xi(x + \Delta x, t) - \xi(x, t)\right]/\Delta x$$

But in the limit of small $\Delta x$ this is simply $1 + \partial \xi/\partial x$. For the three-dimensional motion, the label $x$ becomes a vector $(x, y, z)$, and the displacement $\xi$ becomes a vector $(\xi_x, \xi_y, \xi_z)$. This means the cube may have expanded by different amounts in all three directions, so that its volume is changed to

$$\Delta x \Delta y \Delta z (1 + \partial \xi_x/\partial x)(1 + \partial \xi_y/\partial y)(1 + \partial \xi_z/\partial z)$$

$$= \Delta x \Delta y \Delta z (1 + \nabla \cdot \xi)$$

As the first derivatives of $\xi$ are very small compared with unity so cross terms such as $(\partial \xi_x/\partial x)(\partial \xi_y/\partial y)$ can be dropped as these will be very small. Though its dimensions have changed, this element must still have the same mass. Therefore, its density must have decreased by exactly the same factor by which the volume has increased:

$$\rho_0 + \rho_1 = \rho_0/(1 + \nabla \cdot \xi)$$
Chapter B: Characterising Leak Signals

The quantity $\nabla \xi$ is very small compared with 1, so using the binomial expression to replace $1/(1 + \nabla \xi)$ by the approximation $1 - \nabla \xi$ to finally have

$$\rho_1(x,t) \cong -\rho_0 \nabla \xi$$

(B.5)

Using the equation of motion, $F = ma$, the fluid to the left of the cube in Figure B.1, pushes it towards the right with a pressure $p_0 + p[x + \xi_z(x + \Delta x, t), t]$. Using small amplitude approximation, the slight difference between $x$ and $x + \xi_z$ will be unimportant in evaluating the function $p$ so the net force in the $x$ direction is given by

$$F_x = \Delta y \Delta z [p(x, t) - p(x + \Delta x, t)] = \Delta y \Delta z (-\partial p/\partial x) \Delta x$$

(B.6)

A negative sign indicates that the pressure at $x + \Delta x$ is less than $x$. For the three dimensional case, similarly calculating the other two components of vector force to finally have

$$F = -\Delta x \Delta y \Delta z \nabla p$$

(B.7)

Since the mass of this piece of fluid is $\rho_0 \Delta x \Delta y \Delta z$, the final statement of Newton’s law becomes

$$-\nabla p = \rho_0 \partial^2 \xi / \partial t^2$$

(B.8)

### B.2 Leak signal flow in a fluid filled pipe

From equation B.1, the characteristics of leak signals are highly dependent on the wave number which varies considerably for fluid filled elastic shells such as MDPE pipes. The characteristics of vibro-acoustic wave propagation in pipes, in terms of wavenumbers, have been discussed by Fuller & Fahy (1982) and Muggleton et al. (2002). They found that at low frequencies (well below the pipe ring\footnote{This is the frequency below which the propagating wave travels inside the pipe and transfers most of the leak energy.} frequency), the effect of surrounding medium on the axisymmetric wavenumber is relatively small compared to the results of the fluid-filled pipe with no backfill. This section discusses an analytical model representing the behavior of leak signals in fluid-filled pipes (for both with and without backfill).

The co-ordinate system and circumferential node shapes used in the analysis of a pipe is shown above in Figure 4.2. Theoretically there are infinite waves, for a leak in a
fluid-filled pipe. However, only one generally plays a dominant role in the propagation of leak noise and transfers most of the energy through fluid/pipe (Muggleton & Brennan, 2002, 2004; Muggleton et al., 2004). Each wave has a specific value of mode \((n, s)\) and a wavenumber \(k_{ns}\). Depending upon the mode \((n, s)\) and the wavenumber \((k_{ns})\), the wave can be propagating, evanescent or quasi-propagating. Propagating waves transfer most of the energy through the fluid/pipe, however the evanescent and quasi-propagating waves exponentially decays with distance. The propagating waves travel and transfer energy below the pipe ring frequency. For both fluid and pipe, and well below this pipe ring frequency, four waves are considered to be responsible for most of the energy transfer. These are three axisymmetric waves associated with the mode \((n=0)\), and one wave related to beam bending \((n=1)\). Two of these axisymmetric waves involve both structural and fluid motions. The strength of the coupling between these motions is governed by the pipe dimensions and physical properties. The third wave is a torsional wave in the pipe shell, uncoupled from the fluid and does not have significant radial wall motion. The \(n=1\) bending wave is a beam like flexural wave and consists of a near-field and dispersive propagating waves with the cross-section of the pipe remaining largely undeformed. This section reviews the equations for axisymmetric wave motions consisting of the \(n=0\) and \(s=1,2\) waves for a fluid filled pipe.

**B.2.1 Equations of motion**

In this section expressions are derived for a fluid-filled pipe, both with and without backfill. The wave equations are solved in terms of wavenumbers, for two axisymmetric wave types \((s = 1,2)\) which correspond to a fluid dominated wave and an axial shell dominated wave respectively.

Consider the pipe in Figure 4.2, which is of mean radius \(a\) and thickness \(h\), with \(h/a \ll 1\). In case of backfill, the pipe is assumed to be surrounded by an infinite elastic medium which exerts an external pressure on the pipe. The fluid inside the pipe is of density \(\rho_f\) and \(u, v, w\) are the respective pipe shell displacements in the axial \((x)\), circumferential \((\theta)\), and radial \((r)\) directions. For the normal mode \((n=0)\), these displacements of the shell wall and the acoustic pressure, associated with an axial wavenumber \(k_{ns}\) are given by eqns 4.4, 4.5, 4.6 and 4.7. To derive the equations of motion, simplified Kennard's equations (Kennard, 1953) with shell bending neglected.
are used. The equilibrium of forces in an axial direction is given by:

$$\rho s \frac{\partial^2 u}{\partial t^2} + \frac{\partial \sigma_x}{\partial x} = 0 \quad (B.9)$$

Assuming no circumferential strain, equilibrium of forces in the radial direction gives:

$$\left( p_f(r)|_{r=a} - p_m(r)|_{r=a} \right) \left( \frac{\partial}{\partial t} \right) = \sigma_\theta + \rho_s \frac{\partial^2 w}{\partial t^2} \quad (B.10)$$

where \( p_f \) and \( p_m \) are the fluid and external medium pressure respectively, \( \sigma_x \) and \( \sigma_\theta \) are the axial and circumferential stresses, respectively and \( \rho_s \) is the density of shell material. For a pipe in air, the external medium pressure \( (p_m) \) is considered to be zero. Hooke’s law relationship for the shell are

$$\sigma_\theta = \frac{E}{1 - \nu^2} \left( \frac{w}{a} + \nu \frac{\partial u}{\partial x} \right) \quad (B.11)$$

$$\sigma_x = \frac{E}{1 - \nu^2} \left( \frac{\partial u}{\partial x} + \nu \frac{w}{a} \right) \quad (B.12)$$

where \( E \) is the Young’s modulus of elasticity, \( \nu \) is the Poisson’s ratio, \( w/a \) is the circumferential strain and \( \frac{\partial u}{\partial x} \) is the axial strain. Combining eqns B.9 and B.12 to give

$$\rho_s \frac{\partial^2 u}{\partial t^2} + \frac{E}{1 - \nu^2} \left( \frac{\partial^2 u}{\partial x^2} + \nu \frac{\partial w}{a \partial x} \right) = 0 \quad (B.13)$$

Combining eqns B.10 and B.11 to give

$$\frac{E}{1 - \nu^2} \left( \frac{w}{a} + \nu \frac{\partial u}{\partial x} \right) + \rho_s \frac{\partial^2 w}{\partial t^2} = \left( p_f(r)|_{r=a} - p_m(r)|_{r=a} \right) \left( \frac{\partial}{\partial t} \right) \quad (B.14)$$

To solve these equations for \( n=0 \) and \( s=1,2 \), the axial and radial shell displacements are given by

$$u = \sum_{s=1}^{2} U_s \exp(jr^t - jk_s x) \quad (B.15)$$

$$w = \sum_{s=1}^{2} W_s \exp(jr^t - jk_s x) \quad (B.16)$$

The internal pressure can be represented by the Bessel Function of zero order:

$$p_f = \sum_{s=1}^{2} P_f s J_0(k_f^s r) \exp(jr^t - jk_s x) \quad (B.17)$$
The pressure in the external medium can be described by the sum of two Hankel functions of zero order, one corresponding to an outgoing longitudinal wave and another one corresponding to an outgoing shear wave i.e.

\[
 p_m = \sum_{s=1}^{2} P_{ls} H_0(k_{ls}^s r) \exp(j\omega t - jk_s x) + \sum_{s=1}^{2} P_{rs} H_0(k_{rs}^s r) \exp(j\omega t - jk_s x) \quad \text{(B.18)}
\]

where \( l \) represents for longitudinal waves and \( r \) for radial (rotational) waves. Using Pythagoras theorem, the radial components of fluid, longitudinal and radial (shear) wavenumbers are given by

\[
(k_{fs}^r)^2 = (k_f^r)^2 - (k_s^r)^2, \quad (k_{ls}^r)^2 = (k_l^r)^2 - (k_s^r)^2, \quad (k_{rs}^r)^2 = (k_r^r)^2 - (k_s^r)^2
\]

(B.19)

Substituting the value of \( u \) and \( w \) for \( s = 1, 2 \) in eqn B.13 and rearranging to give

\[
\left(\Omega^2 - (\alpha_s)^2\right) U_s = j\nu\alpha_s W_s
\]

where \( \alpha_s = k_s a, \alpha_r^s = k_r^s a, \Omega = k_l a \) and \( k_l = \omega^2(\rho_s(1 - v^2))/E \).

Substituting the value of \( u, w \) and \( p \) for \( s = 1, 2 \) in eqn B.14 to give

\[
W_s(1 - \Omega^2) - j\nu a k_s U_s = \frac{(1 - \nu^2)a^2}{E h} \left( P_{fs} J_0(k_{fs}^s r) - P_{ls} H_0(k_{ls}^s r) - P_{rs} H_0(k_{rs}^s r) \right)
\]

(B.21)

At the pipe boundary, the fluid remains in contact with the shell wall. Therefore, equating the radial velocity of fluid at the shell wall (both internally and externally) to the radial velocity of the shell wall, gives independent expressions for the pressure coefficients \( P_{fs}, P_{ls} \) and \( P_{rs} \), i.e.

\[
v_r \bigg|_{r=a} = v_{sr}
\]

(B.22)

For a particular mode \((n, s)\) the radial velocity of fluid at the shell wall given by momentum equation is

\[
v_r \bigg|_{r=a} = -\left(\frac{1}{j\rho f \omega}\right) \frac{\partial p_f}{\partial r} = -\frac{k_s^r J_n'(k_s^r a)}{j\rho f \omega} P_{fns} \cos(n\theta) \exp(j\omega t - jk_{ns} x)
\]

(B.23)

where prime denotes the differentiation with respect to \( r \).

The shell radial velocity is given by

\[
v_{sr} = \frac{\partial \omega}{\partial t} = j\omega W_{ns} \cos(n\theta) \exp(j\omega t - jk_{ns} x)
\]

(B.24)
For normal mode \((n=0)\), equating \(v_{sr}\) to \(v_r\), gives the fluid pressure amplitude in terms of shell radial displacement amplitude as

\[
P_{fs} = \omega^2 \rho_f W_s / k_f^2 s J_0'(k_f s a)
\]  
\((B.25)\)

Similarly

\[
P_{rs} = \omega^2 \rho_s W_s / k_{rs}^2 H_0'(k_{rs} s a), \quad P_{ls} = \omega^2 \rho_s W_s / k_{ls}^2 H_0'(k_{ls} s a)
\]  
\((B.26)\)

where \(\rho_s\) is the density of the material of shell. This indicates that the pressure amplitude for any particular branch \((s)\) of the dispersion curves is directly proportional to the shell radial displacement amplitude.

For small arguments, where there is less than one half of a fluid wavelength across the pipe diameter, \(J_0'(k_f s a) \approx -\frac{k_f s a}{2}\). The small argument approximation for the Bessel functions may be applied to eqn B.25, which gives a general equation as

\[
P_s = -2B_f W_s / a(1 - (\alpha_s / \alpha_f)^2)
\]  
\((B.27)\)

where \(B_f = -V\Delta P / \Delta V = c^2 \rho_f = \omega^2 \rho_f / (k_f)^2\) is the bulk modulus of fluid and \(c\) is the wavespeed.

Combining eqns B.20 and B.21, and substituting the value of pressure coefficients (eqns B.25–B.26) to give

\[
(1 - k_f^2 a^2) + \nu^2 k_s^2 / (k_f^2 - k_s^2) = \left(1 - \nu^2\right) a^2 B_f k_f^2 J_0'(k_f s a) \frac{E_h k_f s}{J_0'(k_f s a)} - \left(1 - \nu^2\right) a^2 B_m k_f^2 H_0'(k_f s a) \frac{E_h k_f s}{H_0'(k_f s a)} + \left(1 - \nu^2\right) a^2 G_m k_f^2 H_0'(k_f s a) \frac{E_h k_f s}{H_0'(k_f s a)}
\]  
\((B.28)\)

where \(B_m = c_l \rho_s \omega / k_l\) and \(G_m = c_r \rho_s \omega / k_r\) are the bulk modulus and shear modulus of external medium respectively. Using the small argument approximation as above and rearranging the above equation into the impedances form of the longitudinal and shear waves in the external medium i.e. \(Z_{ls}\) and \(Z_{rs}\) to give

\[
(1 - k_f^2 a^2) + \nu^2 k_s^2 / (k_f^2 - k_s^2) = -\left(1 - \nu^2\right) a \frac{2B_f k_f^2}{(k_f^2 - k_s^2)} + j\omega Z_{ls} + j\omega Z_{rs}
\]  
\((B.29)\)

where,

\[
z_{ls} = -j\rho_s c_l k_l H_0'(k_{ls} s a) / k_{ls}^2 H_0'(k_{ls} s a) \quad \text{and} \quad z_{rs} = -j\rho_s c_r k_r H_0'(k_{rs} s a) / k_{rs}^2 H_0'(k_{rs} s a)
\]  
\((B.30)\)

and \(c_l\) and \(c_r\) is the wavespeed of the longitudinal and shear waves respectively.
B.2.2 Wavenumber for the fluid-borne wave

The wavenumber for fluid-borne wave \((n=0, s=1)\) is found by assuming that \(k_1\) is much larger than the plate compressional wavenumber \(k_i\), \((k_1^2 \gg k_i^2)\), i.e. the wavespeed of the \(s=1\) wave is much slower than the plate compressional wavespeed. Substituting in eqn B.29 and rearranging to give

\[
k_1^2 = k_f^2 \left(1 + \frac{2B_f}{a(Eh/a^2 - \omega^2 \rho_s h + j\omega(Z_{I1} + Z_{r1}))}\right) \tag{B.31}
\]

where \(Z_{I1} + Z_{r1} = R_{rad} + j\omega M_{rad}\)

\[
k_1^2 = k_f^2 \left(1 + \frac{2B_f/a}{Eh/a^2 - \omega^2 (\rho_s h + M_{rad}) + j\omega R_{rad}}\right) \tag{B.32}
\]

where \(2B_f/a\) corresponds to stiffness of the contained fluid, \(Eh/a^2\) represents the pipe wall stiffness, \(\omega^2 \rho_s h\) is pipe wall mass component and \(M_{rad}\) and \(R_{rad}\) corresponds to radiation mass and resistance of the surrounding medium respectively.

For pipes with no backfill, the density of surrounding medium (air) is very low. Thus, the radiation impedance \(R_{rad}\) and \(M_{rad}\) will be very small and thus is ignored. Under these circumstances, the value of \(k_1\) becomes

\[
k_1^2 = k_f^2 \left(1 + \frac{2B_f/a}{Eh/a^2 - \omega^2 \rho_s h}\right) \tag{B.33}
\]

This is in agreement with earlier work done by Pinnigton & Briscoe (1994) and Munjal & Thawani (1996) for the case of no surrounding medium. It can be concluded from the above equation that the fluid wave in a pipe is always slower than the fluid wave in an infinite medium and the wavespeed decreases with increasing frequency. As the frequency approaches the pipe ring frequency, the denominator of the above eqn B.33 tends to zero, so the wavenumber \(k_1\) approaches infinity and the wavespeed correspondingly approaches zero.

Expressing eqn B.33 in terms of the normalized ring frequency \((\Omega)\) and fluid loading term \(\beta = (2B_f a/Eh)(1 - \nu^2)\) to have

\[
k_1^2 = k_f^2 \left(1 - \Omega^2 - \nu^2 + \beta\right) \tag{B.34}
\]

As \(k_1\) is directly proportional to \(\beta\) therefore the wavespeed \((s=1)\) will decrease with increasing wall stiffness (as in the case of MDPE pipes) so the fluid wave in a pipe is slower than one in an infinite medium.
Chapter B: Characterising Leak Signals

At low frequencies (\( \Omega << 1 \)) the pipe wall inertia is relatively small compared with
the pipe wall stiffness term, \( \frac{Eh}{a^2} \). Therefore, eqn B.34 becomes

\[
k_1^2 = k_f^2 \left( 1 + \frac{2Ba}{Eh} \right)
\]  

(B.35)

In the case when the contained fluid is water, for the same size of pipe, the
\( s = 1 \) wavenumber is determined by the material property of the pipe wall. For a
soft MDPE pipe, the \( s = 1 \) wavenumber is much greater than the wavenumber in
an infinite medium. This indicates that the wavespeed of the fluid-borne wave for
the MDPE pipe decreases rapidly with increasing fluid loading (decreasing pipe wall
stiffness).

B.2.3 Wavenumber for the shell-borne wave

The wavenumber corresponding to the shell-borne wave (\( n = 0, s = 2 \)) can be calculated
by assuming that it is always smaller than the fluid wavenumber \( k_f \), and the wavenum-
bers in the surrounding medium. Substituting \( k^2_2 << k_f^2 \), \( k^2_2 << k^2_1 \) and \( k^2_2 << k^2_1 \) in
eqn B.29 to have

\[
k_2^2 = k_f^2 \left( 1 + \frac{Eh^2/a^2}{(1 - \nu^2)(Eh/a^2 + 2B_f/a - \omega^2 \rho_s Eh + j\omega(Z_{l2} + Z_{r2}))} \right)
\]  

(B.36)

where \( 2B_f/a \) and \( Eh/a^2 \) are defined as the stiffness components of the contained fluid
and the pipe wall respectively and \( \rho_s h \omega^2 \) is the pipe wall mass component and \( Z_{l2} \) and
\( Z_{r2} \) are the impedances of waves in surrounding medium. As the leak signal frequencies
are low so the impedances will be small as impedances are directly proportional to the
frequency, thus the above equation becomes

\[
k_2^2 = k_f^2 \left( 1 + \frac{Eh^2/a^2}{(1 - \nu^2)(Eh/a^2 + 2B_f/a - \omega^2 (\rho_s h + M_{rad}) + j\omega M_{rad})} \right)
\]  

(B.37)

where \( Z_{l2} + Z_{r2} = R_{rad} + j\omega M_{rad} \).

For pipes with no backfill, the radiation mass term will be small compared with the
pipe wall inertial term and can be ignored. In addition, the radiation resistance term
can also be considered negligible and the expression of \( k_2 \) becomes

\[
k_2^2 = k_f^2 \left( 1 + \frac{Eh^2/a^2}{(1 - \nu^2)(Eh/a^2 + 2B_f/a - \omega^2 \rho_s h)} \right)
\]  

(B.38)
This is in agreement with the work done by the Pinnigton & Briscoe (1994).

Similarly like for \( s = 1 \) wave, expressing eqn B.38 in terms of \( \Omega \) and \( \beta \) gives,

\[
k^2_2 = k^2_1 \frac{1 - \Omega^2 + \beta}{1 - \Omega^2 - \nu^2 + \beta}
\] (B.39)

At low frequencies (well below the pipe ring frequency), the mass terms will be small compared to the stiffness terms and eqn B.37 becomes

\[
k^2_2 = k^2_1 \left( 1 + \frac{Eh
u^2/a^2}{(1 - \nu^2)(Eh/a^2 + 2B_f/a - \omega^2 \rho_s h)} \right)
\] (B.40)

It is clear that well below the pipe ring frequency, the \( s = 2 \) axisymmetric wave is slower than the compressional wave \( k_1 \). Thus the wavenumber \( k_2 \) satisfies the relationship \( k^2_1 << k^2_2 << k^2_f \).

In practise, the pipe wall material itself losses signals and this loss within the pipe wall can be represented by a complex elastic modulus, \( E(1 + j\eta) \), where \( \eta \) is the material loss factor. Also in practise, for both \( s = 1, 2 \) waves discussed above, both the radiation mass and resistance terms are non-zero, which means that \( k_s \) (\( s = 1, 2 \)) are complex and both the fluid-borne wave (\( s = 1 \)) and shell borne wave (\( s = 2 \)) decay as they propagate along the pipe, radiating into the surrounding medium. Therefore eqns B.32 and B.37 becomes,

\[
k^2_1 = k^2_f \left( 1 + \frac{2B_f/a}{Eh/a^2 - \omega^2 (\rho_s h + M_{rad}) + j(\omega R_{rad} + \eta Eh/a^2)} \right)
\] (B.41)

\[
k^2_2 = k^2_1 \left( 1 + \frac{Eh
u^2(1 + j\eta)/a^2}{(1 - \nu^2)(Eh/a^2 + 2B_f/a - \omega^2 (\rho_s h + M_{rad}) + j(\omega R_{rad} + \eta Eh/a^2))} \right)
\] (B.42)

**B.2.4 Relationship between internal pressure and radial wall motions**

A relationship between the internal pressure and radial wall motions for the two wave types can be obtained by substituting eqns B.39 and B.34 into pressure amplitude eqn B.27.

For the fluid borne (\( s = 1 \)) wave, the relationship is obtained by substituting the value of \( k_1 \) in eqn B.27, i.e.

\[
P_1 = -2BW_1/a(1 - (k_1/k_f)^2)
\] (B.43)
Substituting the value of $k_1$ and $\beta$, and finally rearranging to have

$$W_1 = P_1 a^2 \left( \frac{1 - \nu^2}{E h (1 - \Omega^2 - \nu^2)} \right) \quad (B.44)$$

Similarly, for the shell-borne wave ($s = 2$) wave, the relationship is obtained by substituting the value of $k_2$ in eqn B.27, i.e.

$$P_2 = -2BW_2/a(1 - (\alpha_2/\alpha_f)^2) \quad (B.45)$$

Now for the shell wave, $k_2$ is always smaller than the fluid wave number i.e. $k_2^2 < < k_f^2$ so the above eqn B.45 becomes

$$W_2 = -\frac{P_2 a}{2B} \quad (B.46)$$

### B.3 Conclusion

In this appendix, calculations are presented for the wavenumbers for fluid-borne and shell-borne waves in the normal mode, assuming that the frequency of leak signals are well below the pipe ring frequency, for fluid-filled MDPE pipes for both with and without backfill. For MDPE pipes, it is found that the $s = 1$ axisymmetric wave is strongly influenced by pipe wall flexibility. However, the $s = 2$ wave is slightly influenced by the contained fluid.