Acoustic Noise Characterization for Leak Detection in Water Mains

by

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This thesis is dedicated to my parents

for their endless love, support and encouragement.

Abstract

Acoustic emission (AE) method is becoming popular for leak detection in municipal water mains where leaks are identified and the locations are determined through interpretation of measured acoustic signals without any excavation or disruption of services. For the interpretation of signals, several parameters such as frequency band of signals, coherence between signals, and cross-correlation between signals are employed. However, published literature lack data on applicability of the AE method under various field conditions. This research presents field investigation of leak detection using AE method, identification of leak noise source, leak noise attenuation characteristics and finite element (FE) simulation of acoustic wave propagation through fluid filled pipe. The field application of the AE method was performed through measuring acoustic noise at two points bracketing the leak along the pipe length in the City of Mount Pearl in Newfoundland and Labrador, Canada. For a better understanding of the source of leak noise, a preliminary laboratory investigation was conducted under a controlled environment. At low flow rates, it was found that water (escaping from the leak) hits surrounding obstacles and generates the leak noise. To explore the characteristics of leak noise, a new laboratory facility was developed and the attenuation characteristics of the leak noise was investigated. Leak noise attenuation was found to depend on the flow rate of the water. Finally, finite element (FE) method was used for modelling of acoustic wave propagation and attenuation characteristics. A commercially available FE software "ABAQUS" was used. FE analysis reveals that acoustic leak noise can propagate up to 150 m before attenuating to the ambient noise level in water mains.

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The acoustic emission test results were provided by the City of Mount Pearl in the Province of Newfoundland and Labrador, Canada. The support from the city is gratefully acknowledged. Dr. Rajib Dey provided data obtained from the city of Mount Pearl and valuable insights about acoustic emission tests conducted at the city.

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List of Symbols, Nomenclature or Abbreviations

$C_{xy}(f)$ = Coherence

$p_{xy}(f)$ = Cross power spectrum for x and y

$p_{xx}(f)$ = Cross power spectrum for x and x

$p_{yy}(f)$ = Cross power spectrum for y and y

d_1 = Distance of the leak from sensor1

d = Distance between two sensors

c, a = Wave propagation velocity

Δt = Time difference ('time lag')

$R_{\widehat{xy}(m)}$ = True cross-correlation sequence

$E\{.\}$ = Expectation operator

X, Y = Stationary random process

* = Conjugation

K = Bulk modulus

ρ = Fluid density

E = Modulus of elasticity

D = Pipe diameter

e = Pipe wall thickness

C = Axial restraint coefficient

μ = Poison ratio

x[] = Input signal for moving average

y[] = Output signal after applying moving average

M = The number of points for moving average

$A0$, $A1$, $A2$ = Recorded signal amplitude at reference points

α = Attenuation parameter

Chapter 1. Introduction

Water loss from leaky pipelines is a major problem for municipalities. Around 30% of the treated water get lost from leaks of water distribution pipelines (Hunaidi et al., 2004). This loss causes wastage of water resources and the energy and material resources used for abstraction, purification and transportation of the water. The escaping water also causes secondary damage to pipelines, surrounding structures and the climate. It costs a significant amount of municipal budget, causing a higher municipal tax to the city dwellers. To minimize this loss, the municipalities take proactive measures to locate leaks and take corrective actions. As the water pipelines are buried in the ground, it is difficult to locate leaks in a complicated pipeline network. Researchers have developed several methodologies for leak detection each of which has some advantages and limitations. The most important factors are that how efficiently and effectively those technologies can locate leaks and how cost effective are the operations.

Over the development of leak detection technologies, researchers have developed various equipment and methods. The common leak detection methods include monitoring of pressure, flow and temperature of fluid, acoustic emission detectors, infrared radiometric pipeline testing and fibre-optic leak detection (Zhang et al., 2013).

Leak detection using acoustic method is becoming popular in the recent years. In this technology, acoustic noise is recorded using appropriate sensors at convenient access points to the pipe (i.e. fire hydrant or curb stop). Leak location can then be traced by analyzing those sound using an appropriate computer program. The effectiveness of this method depends on correct interpretations of the acoustic signals. Misinterpretation may lead to false determinations. To the knowledge of the author, published literature does not include much information on signal processing parameters that could be used for successful determination of water main leaks. Attenuation of leak noise through water main leaks are also not studied. Understanding the propagation behaviour of acoustic wave is very important for determining the distance over which the method would be successful. In this regard, development of analytical and numerical tools (i.e. Finite element model) are required for the assessment of acoustic wave propagation.

1.1 Objectives

The objective of this thesis is to investigate acoustic wave propagation through water mains for successful leak detection under different field conditions. The specific objectives of this thesis are described below:

1) Study the acoustic noise propagation through water mains under different field conditions. Literature on the application of acoustic emission method in different field conditions are very limited. This research will investigate several field applications of acoustic emission leak detection technology in different field conditions at the city of Mount Pearl in Newfoundland and Labrador. Different parameters (e.g. coherence, cross-correlation) for acoustic signal analysis for different field conditions will be investigated.
2) Development and improvement of a new laboratory facility to study acoustic wave propagation. For the better understanding, this work will continue to investigate the acoustic parameters (i.e. coherence, cross-correlation and

attenuation) in a controlled laboratory environment. In literature, researchers have identified some factors which may lead to erroneous results in acoustic emission leak detection. Attenuation characteristics of leak noise are one of the most important factors. Attenuation characteristics will be investigated in this thesis using the new laboratory facility.

3) Finite element modeling of acoustic wave propagation. Finite element simulation can be used for the better understanding of leak noise propagation. There are very few literatures available on finite element modelling of leak noise propagation through pipelines. In this thesis, a finite element (FE) model will be developed using parameters investigated in laboratory and field conditions e.g. attenuation characteristics, velocity of sound, material parameter. A parametric study will be conducted using the FE model to find out the effective distance of the sensors for successful leak detection.

1.2 Outline of the Thesis

This thesis has been organized in seven chapters, that includes Introduction (Chapter 1), Literature review (Chapter 2), Field acoustic study for water mains (Chapter 3), Preliminary laboratory investigation (Chapter 4), Laboratory facility development and acoustic emission testing (Chapter 5), Finite element model (Chapter 6) and Conclusion (Chapter 7). A brief synopsis of each chapter is outlined as follows.

Chapter 1: This chapter introduces the thesis topic and the objectives of the research.

Chapter 2: Chapter 2 presents a brief literature review on leak detection of water mains. The Chapter includes a description of the available technologies and methodologies used for leak detection of water main. A review is presented about the methodologies used for acoustic emission leak detection. Previous studies on finite element model of acoustic wave propagation are also presented. Relevant literature review is included in more details in the following chapters.

Chapter 3: Field applications and case studies are discussed in Chapter 3. Three different case studies on the application of acoustic emission leak detection are described here. A database on leak detection parameters (e.g. coherence, cross-correlation, velocity of leak noise) are generated from the information of several field conditions. A version of this chapter has been published in the Journal of Pipeline Systems Engineering and Practice, ASCE, "Muntakim, A.H., Dhar, A.S., & Dey, R. (2017). Interpretation of acoustic field data for leak detection in ductile iron and copper water distribution pipes. Journal of Pipeline Systems Engineering and Practice, ASCE". The first author, Abu Hena Muntakim, conducted the analysis and wrote the paper. The second author, Dr. Dhar, supervised the work and reviewed the paper. The third author, Dr. Dey, provided data from the city of Mount Pearl and the insight of the tests conducted at the city.

Chapter 4: This chapter describes the preliminary laboratory setup and laboratory investigations of leak noise propagation through a test pipe. This chapter presents the results of laboratory tests conducted to develop a better understanding regarding the source of the leak noise and study the effects of surrounding obstacles on the leak noise generation in a ductile iron water main. In addition, performance of the new acoustic sensors and data acquisition and analysis system are evaluated through application to the preliminary tests conducted. A version of this chapter has been presented at CSCE Annual Conference, June 1-4, 2016, London, Ontario, Canada. The co-author, Dr. Dhar, supervised the work of the principal author, Abu Hena Muntakim, presented in this paper.

Chapter 5: A new laboratory facility is presented in this chapter to study the attenuation characteristics of leak noise propagation through buried pipe. The laboratory test facility is used to investigate leak noise attenuation through an in-air and a buried pipe. The buried pipe is backfilled with crushed stone. The laboratory study indicates that the leak noise attenuates during propagation of acoustic wave. The attenuation is higher for the high frequency waves. The attenuation also increases with the increase of flow rate through pipe.

Chapter 6: This chapter illustrates finite element modelling of leak noise propagation in a pipeline segment. A parametric study has been described to identify an appropriate attenuation parameter to simulate the test pipe of the laboratory investigation. This chapter also presents a study on how far a leak noise can propagate before attenuation below a threshold amplitude level.

Chapter 7: This chapter discusses the outcomes of the studies. Scopes of future studies are also presented.

1.3 Reference

Hunaidi, O., Wang, A., Bracken, M., Gambino, T., & Fricke, C. (2004). “Acoustic methods for locating leaks in municipal water pipe networks”. In International

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Co-authorship Statement

Based on the work presented in this thesis, one paper has been published in an ASCE Journal and one paper was presented in a Conference. Roles of co-authors in the papers are discussed below:

1. Muntakim, A.H., Dhar, A. S., and Dey, R. (2017). "Interpretation of acoustic field data for leak detection in ductile iron and copper water distribution pipes." **published** in the **Journal of Pipeline Systems Engineering and Practice, ASCE**.

I am the primary author in the paper. I carried out all analysis and prepared the first draft of the manuscripts and subsequently revised the manuscripts based on the co-authors' feedback and the peer review process. As a co-author, Dr. Ashutosh Dhar provided support in developing the idea, provided guidance and reviewed the manuscript. The third author, Dr. Dey, provided data from the city of Mount Pearl and the insight of the tests conducted at the city.

2. Muntakim, A.H., and Dhar, A. S. (2016). "Laboratory investigation of acoustic noise from leaks in ductile iron water pipe". **Presented** in the **Annual Conference of the Canadian Society for Civil Engineering**, June 1-4, 2016, London, ON, Canada and is published in the conference proceedings.

Within the capacity of the primary author, I created the framework of the study, performed laboratory investigations and drafted the initial manuscript. Dr. Ashutosh Dhar co-authored the manuscript who supported on developing the idea, provided guidance during laboratory development, testing and reviewed the manuscript.

Chapter 2. Literature Review

2.1 Overview of Leak Detection Technologies

The primary purpose of using the leak detection technology is to pinpoint the leaks. The American Petroleum Institute has classified the leak detection system into two categories as: internally and externally based systems (API RP 1130, 2007). The internally based system uses field instrumentations like flow, pressure or fluid temperature sensors. The externally based system uses external pipeline parameters like infrared radiometers or thermal cameras, vapor sensors, acoustic microphones or fiber-optic cables. These leak detection systems use different traditional methods as correlation analysis (Gao et al., 2004), statistical analysis (Zhang, 2001), ANN (Hessel et al., 1996), fuzzy system method (da Silva et al., 2005), frequency analysis (Lee et al., 2005) and wavelet analysis (Al-Shidhani et al., 2003). There are several internally based system available in the market, such as microwave back-scattering sensor, SmartBall®, Sahara system.

Microwave back-scattering sensors work on the basis of sending a microwave (frequency of 2.45 GHz) and receiving backscattered signals. The whole inner surface of the pipe is analyzed by this system. The received signals are nonhomogeneous if there are any holes or leaking water. There are no unique properties of reflected signal, which is a major disadvantage of this method. Data interpretation is a major challenge of this method. Ground penetrating radar (GPR) also has the same challenge and disadvantage. Ground penetrating radar transmits electromagnetic pulse into the ground and receives the reflection from different boundaries. It can measure any void and water content in the soil. Leakage from water pipeline is expected to create large void in the soil and the surrounding water content will be higher. Measuring these parameters, GPR can detect leak. This system however has depth constraint. It can measure up to 2 m of depth below the ground surface (Liu and Kleiner, 2013). SmartBall® technology overcomes data interpretation challenge as it conducts frequency analysis of the recorded acoustic signal to identify the presence of the leak noise. It consists of several arrays of sensors, as acoustic sensors, accelerometers, pressure sensors, temperature sensors. SmartBall® travels inside the pipeline and generates pulse every 3 seconds and measures the acoustic signal, pressure and temperature. Using these data, the SmartBall® locates the air pocket or leak location in the pipeline. Severity of the damage or leak can be measured if calibrated data is available for the field condition. Sahara system is another leak detection technology, which consists of hydrophone tethered to an umbilical cable (Costello et al., 2007). It measures the leak noise and sends the exact location to surface beacon for locating excavation location. It can detect leaks in the pipe walls, joints or welds. This system may have lighting and video sensors to enable Closed-circuit television (CCTV) feature in the potable water pipeline. The SmartBall® and Sahara systems are suitable for large diameter pipe but cannot locate leaks in small diameter (<30.48 cm diameter) lateral pipes. Pipe diameter restriction can be seized by Infrared thermography. Infrared thermography measures the energy transmission from warmer to cooler areas. Different materials respond differently based on their material parameters. Pipelines, boulders, and voids can be detected using this technology. The interpretation of infrared thermography image is sometimes misleading when temperature range is very close or objects are with erratic temperatures. This shortcomings are eliminated by other externally based system, such as vapour-sensing cable, fiber-optic leak detection system and acoustic emission detectors. In vapour-sensing cable and fiber-optic leak detection system, a tube or cable is installed along the length of the pipeline and surrounding substances are monitored to identify the presence of leak. The cost of installation and maintenance operation is very high in those systems. The acoustic emission detection system does not require permanent installation with pipelines. Sensors are placed at suitable access points to listen acoustic signals. Acoustic signals are analyzed to identify the presence of leak and leak location. The acoustic emission system has been investigated in current research and is discussed in this thesis. Since the thesis is written in manuscript format, relevant literature reviews are discussed in detail in each of the relevant chapters. A brief introduction of the acoustic emission method is provided below.

2.2 Acoustic Emission for Leak Detection

Various non-destructive testing of leak detection technologies are available in the market. Among these, acoustic emission method is one of the most popular methods used for leak detection in water mains due to its versatile usability. Acoustic emission leak detection method can be used in pressure vessel (Brunner and Barbezat, 2006) or pipelines (Miller et al., 1999). In acoustic emission leak detection technology, acoustic sensors listen sound of leak noise, cracking and active damage or deformation of stressed elements. Elastic waves from stressed elements are detected and converted into electrical signals in acoustic emission NDT (Non-destructive testing) technique. Generally, the acoustic emission sensors are piezoelectric transducers, which are placed on the surface of the structure. The electrical signals from those piezoelectric transducers are amplified through a low-noise preamplifier and then received by suitable electronic device. Acoustic emission technique is being used to assess structural integrity which gives safeguard against catastrophic failure of structure. Several standards i.e. American Society for Testing and Materials (ASTM) and American Society of Mechanical Engineers (ASME), recognize this method for locating leak in steady state pressurized system of gas and liquid (Anastasopoulos et al., 2009).

In acoustic with correlation method, two sensors are placed on opposite sides of a leak. Correlation software calculates the delay of the signal received by sensors to detect the leak location. This method however requires the contact point to the pipe. Besides, quiet leaks cannot be identified by this method. The acoustic method could be used to find leaks in all kind of water distribution system. The method could be used by inexperienced personals if the correct acoustic emission parameters could be provided in the software used to analyze the signals.

2.3 Interpretation of Acoustic Emission Results

ASME (2016) uses several definitions (i.e. indication, interpretation, evaluation) for identification and evaluation of acoustic emission (AE) test data (ASTM E1316-16a). Indication is defined as the evidence of a response of non-destructive test. Interpretation is the determination of whether the indications are relevant or false. Evaluation is the determination of significance of the relevant indications. In non-destructive AE tests, a basic indication is simply a hit. Hit is defined as a value larger than an appropriate threshold value. Different analysis methodologies are applied for indication, interpretation and evaluation of acoustic emissions from leaky pipeline. Frequency analysis is used for indication of leak noise with the recorded acoustic emission test data. Coherence analysis can determine the relevance of signal with leak noise. Cross-correlation analysis finally evaluates the location of leak noise source. The frequency analysis, coherence analysis and cross-correlation analysis are briefly introduced below. A more discussion is provided in Chapter 3.

2.3.1 **Frequency Analysis**

Time domain signal is mostly used form of signal in industrial use. However for certain cases, it is more helpful if the signal is represented in frequency domain, obtained using Fourier transform (FT) (Santos et al., 2013). Spectral analysis provides the information about the frequency content of the signal. Frequency spectrum of leak noise and non-leak noise are significantly different. Pal et al. (2010) have identified leak noise and ambient noise using frequency spectrum analysis. Frequency contents are very important in cross-correlation analysis. If the frequency band is not appropriate, the cross-correlation analysis may provide false peak position of leak noise source. Kim and Lee (2009) identified the dispersive acoustic characteristics of fluid filled steel pipe using spectral analysis of leak noise.

2.3.2 **Coherence Analysis**

Advanced signal processing based on coherence analysis has improved the leak detection efforts. Leak location detection can become difficult when leak noise become weak with respect to environmental noise (Eckert and Maresca, 1992). Coherence function gives the estimation of relatedness of two signals with or without any filtering.

This measurement is an indication of the source of noise. Researchers have used coherence analysis to identify the presence of leak noise in signals with ambient environmental noise (Hunaidi 2002, Fantozi and Fontana, 2001).

2.3.3 Cross-correlation Analysis

Cross-correlation function has been used to determine the pattern between signals. Beck et al. (2005) have used cross-correlation function to separate acoustic signal from reflected acoustic signal. Gao et al. (2002) have reported that filtered cut-off frequencies have impact on cross-correlation analysis for plastic pipes.

2.4 Modelling of Acoustic Emission

Acoustic emission signals are dispersed to surroundings when transmitted by the fluid filled pipeline. Acoustic emission test results would be more understandable and efficient if the dispersive behaviour is well-understood. To understand the dispersive behaviour, finite element modelling can be used (Millan, 2011). Despite the rapid growth of computational power, many more realistic modelling is still beyond the reach of FE modelling due to the larger model requirements for complex modelling. Mesh density is another crucial part of acoustic analysis as it has effect on dispersion behaviour and wave speed in the model (Drozdz, 2008). Pavlakovic et al. (1997) developed a new program called "DISPERSE" to model the dispersion and attenuation in different material layer. Muggleton et al. (2006) analytically solved wave propagation in water filled buried plastic pipes. The study is limited to the low frequency waves. Baik et al. (2010)

analytically modeled the dispersion behaviour and attenuation curve for liquid filled elastic tube in the vacuum. Graf et al. (2014) have simulated wave propagation in fluid filled polyethylene pipes using finite element method. They successfully evaluated the dispersion curve but to do this they needed to increase the Young's modulus of the pipe two times from manufactures given value (1.1 GPa). A FE modelling approach is developed in the current research to study the attenuation of acoustic wave through water main. The study is discussed in Chapter 6.

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Chapter 3. Field Acoustic Study for Water Main

3.1 Introduction

Leaks are the major concerns for transporting liquid and gas through pipelines. Loss of hazardous materials from pipeline leaks can affect human health, environment and the economy. Amount of water loss and the damage caused by escaping water from municipal water mains are also significant, resulting in a huge economic burden to the municipalities. Municipalities are therefore showing increased interest in the leak detection for the water and sewer pipelines for proactive maintenance of the infrastructure. A proactive maintenance program is desired in order to minimise the long-term maintenance cost and the consequence of catastrophic pipe failure. The oldest method of leak detection for municipal pipelines was to look at the surface water ponding or anomalous vegetation growth within the vicinity of the pipes. In the recent years, acoustic emission methods are becoming popular for leak detection in municipal water mains.

Acoustic method for leak detection in pipeline is not a new concept, with literatures dating back to 1930's (e.g., Smith 1933, Gilmore, 1935 and others). However, there are lack of published literature on the parameters required for successful application of the acoustic emission method for leak detection in water mains. Some historical development of acoustic methods and their applications are available in Loth et al. (2003) and Parker (1981). Listening rod or aquaphones were the early instrument for acoustic leak detection.

With the development of the technology, ground microphones and hydrophones are being used to locate the leaks.

Leak noise correlator is an acoustic emission system getting wider acceptance for leak detection in water mains. In this technology, hissing sound from leak are recorded using two or more sensors located on both sides of a suspected leak. Mathematical algorithms are then used to determine the locations of leaks. Hunaidi and Chu (1999) described many acoustic characteristics of leak noise in plastic pipeline e.g., frequency content of leak noise, effects of measurement of sound from fire hydrant versus service connections, leak type, pipe pressure, leak flow rate, season during measurement. The frequency band of the acoustic signal for leaks in PVC pipes was reported to be below 50 Hz and the propagation velocity was independent of the frequency. Researchers have investigated application of different external sensors including hydrophone and accelerometer in order to improve performance of leak detection in plastic water pipes (e.g. Hunaidi and Chu, 1999, Gao et al., 2005, Papastefanou et al., 2012 and Martini et al., 2015). Khulief et al. (2011) employed acoustic signal measurements inside the pipes using a hydrophone to complement the leak detection method using external sensors.

While the use of acoustic method is believed to be less challenging for metal pipes, only limited study is available in the literature on the application of the technology on metal pipes. Brunner and Barbezat (2006) experimentally investigated acoustic emission signals on a 50 mm diameter aluminum pipe under compressed air pressures between 400 and 800 kPa. Distinct differences in the power spectra for the pipes with and without a leak were noticed in the experiments. The study concluded that there might be a lower limit of the leak diameter for the gas pipes that can reliably be detected using the acoustic method. The gas leakage-induced acoustic waves generally propagate along multiple paths with different velocities that need to be correctly determined for leak detection and leak location, Li et al. (2014).

Anastasopoulos et al. (2009) presented several case studies of acoustic emission leak detection of liquid filled buried pipelines (water mains). In this study, a number of test pits were used for mounting of multiple acoustic sensors on the pipes at various spacing along the length ranging from less than 100 m to 125 m. Excavation of multiple test pits is no longer a preferred method of leak detection for municipal pipeline. The current practice is to mount the acoustic sensors at convenient access points to the pipe (e.g. fire hydrants) typically on either side of the leak (two point measurements). The acoustic signals are then analysed to identify the leak and determine the leak location. However, there are a number of challenges associated with the interpretation of the acoustic signals for accurate leak detection using the two point measurements. Particularly, the acoustic signals appear to depend on a number of parameters including the distance of the sensors from the leak, attenuation characteristics of pipe materials, the type of material transported through the pipes and pipe burial conditions, Anastasopoulos et al. (2009). The effects of each of these parameters on the acoustic signals are not well understood as demonstrated by the lack of documentations in the literature in this regard. As a result, the acoustic method is sometime found to be unsuccessful. For example, Hao et al. (2012) indicated limited success of the acoustic method for trunk mains (large diameter pipelines). On the other hand, Anastasopoulos et al. (2009) demonstrated that acoustic signal attenuation in small diameter pipes are higher, requiring shorter distance between the sensors for successful leak detection. Internal pressure on the pipe was also found to contribute to the successful application of the acoustic method in the case studies presented in Anastasopoulos et al. (2009). A minimum internal pressure of about 10 bar was required for their tests.

Juliano et al. (2013) experimentally investigated the acoustic emission leak detection in a 305 mm diameter steel pipeline buried in sandy soil where the method was found successful for leak rates ranging from 15.2 to 16.6 mL/s with sensor separation of 46.3 to 65.5 m. However, the method for these leak rates was unsuccessful for sensor spacing of 78 m.

Despite that the AE method for water main leak detection has been in the market for a few decades, published literature lacks information on the applicability of the method under various field conditions, including leak sizes, pipe diameters, and distances between the sensors. To this end, documented case studies would provide information on the capability and limitations of the method. This chapter presents a number of case studies with application of the AE method for leak detection in water distribution pipelines including information on pipe sizes, estimated average leak rate and sensor distances over which the method was found successful. The AE signal characteristic parameters employed in identifying and locating the leaks are also presented based on the data from different field conditions at the City of Mount Pearl in the province of Newfoundland and Labrador in Canada. With the information, the practitioners can be familiar with the parameters relevant to the AE method for leak detection in water mains and thus can effectively utilize the technology.

3.2 Acoustic Emission Method

Acoustic emission method of leak detection in pipeline employs listening of leak noise by acoustic sensors. Water exiting under pressure from pipeline through leak orifice causes turbulence which generates acoustic noises of both sonic and ultrasonic frequencies. The generated noise is propagated as waves through the pipe wall and the inside fluid (Anastasopoulos et al., 2009). The leak noises are generally concentrated at low frequencies (Gao et al., 2005) that can be detected using acoustic sensors sensitive to frequency range from 20 to 1200 kHz (Pollock, 1989). The signals received by the acoustic sensors are processed using signal processing algorithms to identify and locate the leak.

Two acoustic sensors are placed essentially on either sides of the leak to measure the acoustic signals. The method is termed herein as “two-point measurement method”. The sensors are placed at convenient access point to the pipe including fire hydrant and/or valves (e.g., curb stop valve). A key-rod is sometime used to access a point on the pipe. The method thus allows inspection of the pipe without disruption of the service. The measured signals from two access points are analysed for determination of the existence of leak. If a leak exists, the location of the leak is determined through analysis of AE signal data.

3.3 Identification of Leak

For identification of leak, the common approach is to determine the degree of relationship between two series of signals measured by the sensors located on either side of the leak. A higher degree of association (relationship) would indicate that the noise measured in two sensors is from the same source (i.e., potential leak). “Coherence” is a measure of the degree of association between two time series as a function of frequency, which is defined as:

$$C_{xy}(f) = \frac{|p_{xy}(f)|^2}{|p_{xx}(f)||p_{yy}(f)|} \tag{3-1}$$

Where, $p_{xx}(f)$ and $p_{yy}(f)$ are the power spectrum densities corresponding to x and y sound waves and $p_{xy}(f)$ are the cross power spectrum for x and y.

The magnitudes of the coherence range from 0 to 1 depending on the strength of association of two time series. A coherence magnitude of zero would mean that the time series are statistically independent whereas a magnitude of ‘1’ would mean the two time series as linearly dependent. However, the degree of relationship between time series is often more complex than the magnitude of the “coherence” only. For example, a high value of coherence not necessarily indicates a strong correlations or a very low value of the coherence does not mean that there is no relationship between the time series (McNames, 2005). The definition of the degree of relationship generally varies depending on the application.

Application of acoustic noise for leak detection in ductile iron water mains is the focus of this chapter. To the knowledge of the author, there is no published literature on the coherence value that represents a strong correlation between two acoustic noises generated from water main leak. However, a database on the values of coherence for different boundary conditions of water mains would be valuable for successful application of the acoustic emission method for leak detection. This chapter presents the coherence values obtained from a number of leak detection data from the City of Mount Pearl.

3.4 Determination of Leak Location

Once the presence of leak is determined as discussed above, the leak location is calculated with respect to the sensor positions based on known distance between the sensors, wave propagation velocity and the time difference of the leak noise propagation between the two sensors. The distance of the leak from a sensor is given in Equation (3-2):

$$d_1 = \frac{d - c\,\Delta t}{2} \tag{3-2}$$

where, 'd_1'is the distance of the leak from sensor 1 (Figure 3-1), 'd' is the distance between two sensors, 'c' is the wave propagation velocity, and Δt is the time difference ('time lag') for the waves to reach the sensors.

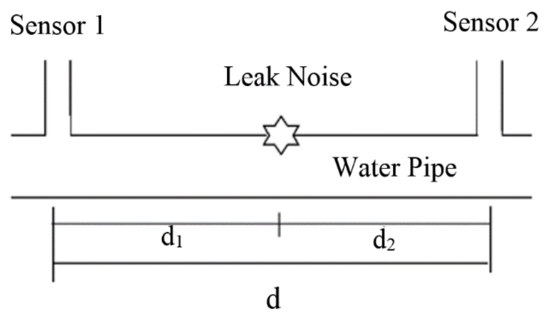


Figure 3-1 Leak location determination

In Eq. (3-2), the distance 'd' between two sensors is predetermined, the time lag 'Δt' is calculated from the signal analysis and the wave propagation velocity "c" is estimated for the pipe material and burial conditions.

3.5 Time Lag

The time lag in Eq. (3-2) is estimated based on the maximum cross-correlation between the two time series calculated using Eq. (3-3) through shifting the phase (time lag) in one of the series.

$$\widehat{R_{xy}(m)} = E\{X_{n+m}Y_n^*\} = E\{X_nY_{n-m}^*\} \tag{3-3}$$

Where X_n or Y_n are the magnitude of the series at the time instance of 'n' ($-\infty < n < \infty$), m is the lag time, $E[\cdot]$ is the expectation operator and the asterisk denotes conjugation. In Eq. (3-3) the cross-correlation is the maximum when series X or Y is shifted by lag time between the signals reaching to the two sensors.

3.6 Wave Propagation Velocity

The wave propagation velocity depends on a number of factors including bulk modulus of fluid, Young Modulus of pipe, pipe wall thickness, pipe diameter, fluid density and boundary conditions. The wave velocity for thin walled pipes is given by (Wylie and Streeter, 1993):

$$a = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1+\frac{KD}{Ee}C}} \tag{3-4}$$

Where '*K*' is the bulk modulus of fluid, 'ρ' is the fluid density, '*E*' is the modulus of elasticity, '*D*' is the Pipe diameter, '*e*' is the pipe wall thickness, 'μ' the poison ratio of pipe material and '*C*' is the coefficient depending on axial restraints. $C = 1$ for pipe with no axial restraint and $C=1-\mu^2$ for pipe with full restraint from axial movement (Wylie and Streeter 1993). Other parameters in Eq. (3-4) vary for ductile iron water mains as described in Table 3-1.

Table 3-1 Typical range parameters for ductile iron and water (After Ductile Iron Society 2015 and Finnemore and Franzini 2001)

Factors	Bulk modulus of water, *K*	Young modulus of pipe material, *E*	Poison ratio of pipe material, μ
Unit	MPa	GPa	
Range	2020-2250	162-170	0.275

Due to the variation of parameters described in Table 3-1, the estimated wave propagation velocity of acoustic wave through pipeline is expected to vary significantly. This may cause errors in leak location determination. For example, Figure 2 plots distances calculated using Eq. (3-2) for a range of propagation velocity of a 152 mm diameter ductile iron pipe. The propagation velocities were calculated using Eq. (3-4) for a range of parameters in Table 3-1. Pipe wall thickness was assumed to vary within the typical range from 6.3 to 10.9 mm. In Figure 3-2, the calculated distance varies from 81.7 m to 85.6 m for a range of wave propagation velocity one would estimate using Eq. (3-4). Thus, an error of up to 4 m may be resulted in the determination of leak location. In this regards, site specific database on the wave propagation velocity would be useful for effective application of the leak detection method. In this chapter, real time data on the wave propagation velocity through water mains in the City of Mount Pearl is provided.

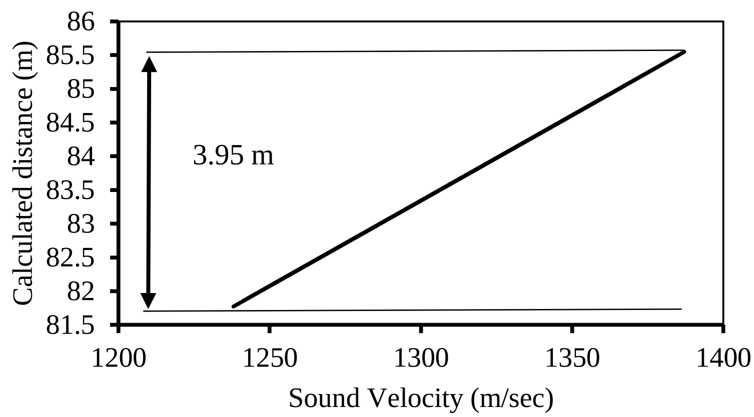


Figure 3-2 Variation of leak location with wave propagation velocity

3.7 Case Studies

A number of acoustic leak detection data was collected from the City of Mount Pearl in the Province of Newfoundland and Labrador in Canada. The City of Mount Pearl measured leak noises for the city water mains to identify and locate leaks using a commercially available leak detection system, known as LeakFinderST^{TM}. The leak detection system employs a set of two accelerometers with high-sensitivity piezoelectric sensing element and built-in amplifier to measure acoustic signals at two locations along the length of the pipe for bracketing a leak, if any. The signals are transmitted wirelessly from the sensors to a laptop computer using a transmitter and a receiver. The raw data from the laptop computer are collected for this study. The data are apparently filtered in the system using Butterworth type low-pass filter (Hunaidi and Wang, 2000). The time series data from the sensors are analysed using MATLAB built-in functions to identify leaks and determine the leak locations. The results of analysis are compared with those obtained from the commercial leak noise correlator system (LeakfinderST^{TM}). The system uses a Windows-based built-in software for signal processing for locating leak.

From the collected data, three cases are discussed in detail below. These include a case with leak on a lateral, one with leak on a water main and one without leak.

3.7.1 Case Study 1: Leak on a Lateral

In Case study 1, leak on a lateral connection between a city water main and a private house was determined using acoustic emission method. Test was conducted in the summer of 2015 (on May 22, 2015). Figure 3-3 shows the location of water main and the lateral. As seen in the figure, apparently 18 laterals are connected to the water main between the fire hydrants to supply water to the houses. The lateral with a potential leak is connected to the water main at a distance of 17.8 m from fire hydrant 1 and 83 m from fire hydrant 2 along the length of the water main (from city utility database. A schematic is shown in Figure 3-3). Information of the water main and the lateral is provided in

Table 2. Both of the water main and lateral were buried at the depth of 2.43 m to 3 m below ground surface and were backfilled with sandy crushed rock and gravels.

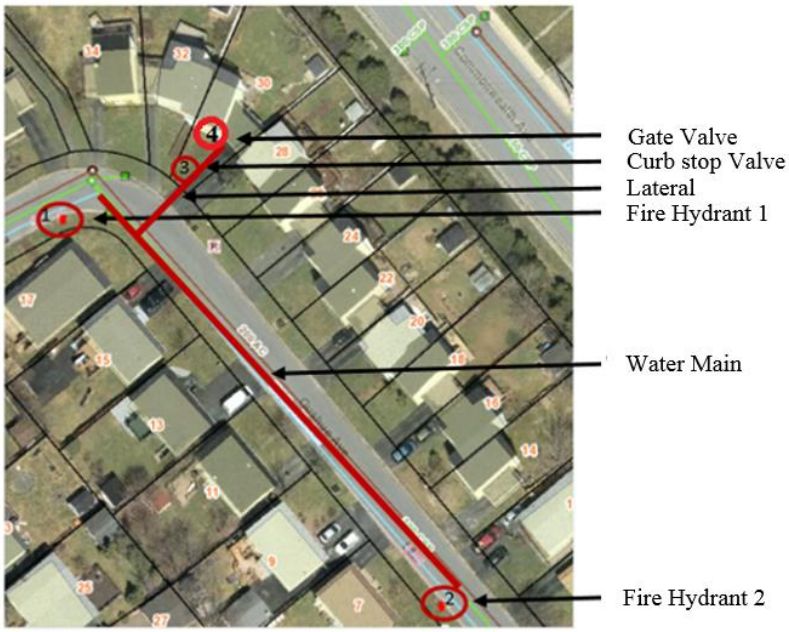


Figure 3-3 Site for leak detection on a lateral

Table 3-2 Information of water main and lateral

	Water Main	Lateral
Material	Ductile Iron	Copper
Nominal Diameter	152 mm	19 mm
Wall thickness	9.5 mm	1.65 mm

As a general practice of utilizing Acoustic Emission method, acoustic signals at two fire hydrants are first measured to identify the presence of leaks between the fire hydrants.

Figure 4 shows the installation of acoustic sensors on the fire hydrants. As mentioned earlier, acoustic sensors are connected with Wi-Fi modules to send data to a data acquisition system (DAQ) which is connected with a personal computer (laptop computer). A headphone was also connected to the module to hear the noises.

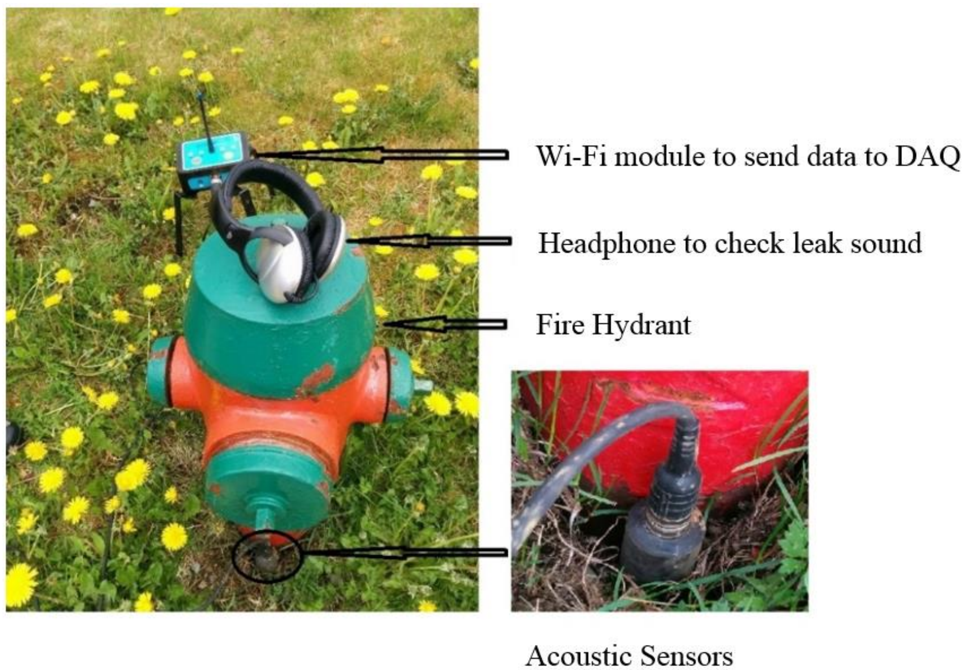


Figure 3-4 Sensors on Fire Hydrant

Acoustic signal recorded in the fire hydrant 1 (sensor 1) and 2 (sensor 2) are shown in Figure 3-5. The signals were recorded at the sampling rate of 11025 data per second. Response spectrums corresponding to the recorded signals are obtained applying Fast Fourier Transform. The resulting frequency spectrum from Fast Fourier Transform is shown in Figure 3-6. Figure 3-6(a) presents the frequency spectrum obtained from the commercial system and Figure 3-6(b) presents the results obtained from MATLAB analysis. The frequency spectrums from the MATLAB analysis and the commercial software are very similar in the figure. Peaks/spikes in the frequency spectrum are observed at almost the same frequencies in both cases (e.g., at 100 Hz, 250 Hz, 300 Hz, 400 Hz and 550 Hz for sensor 2).

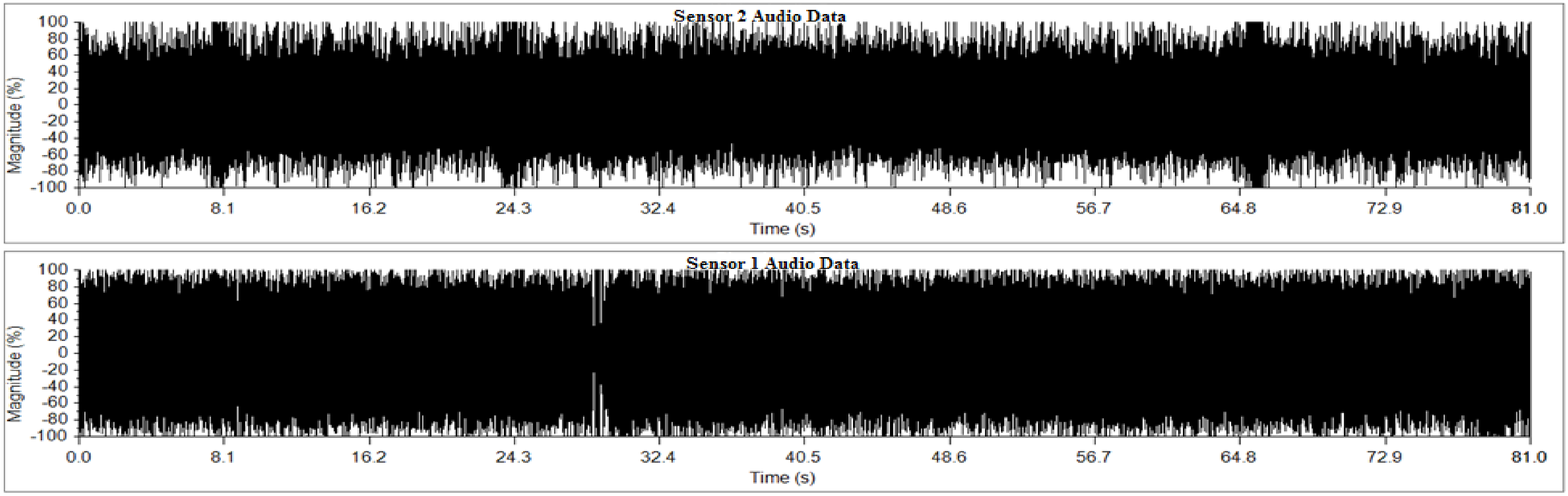
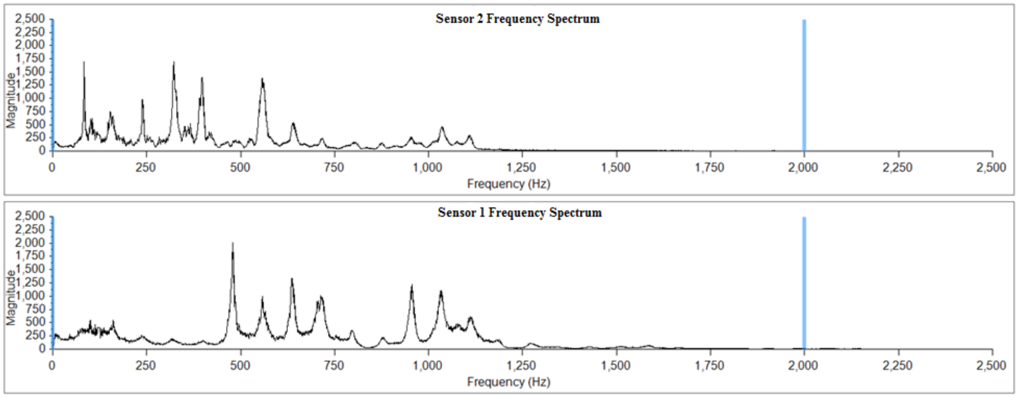
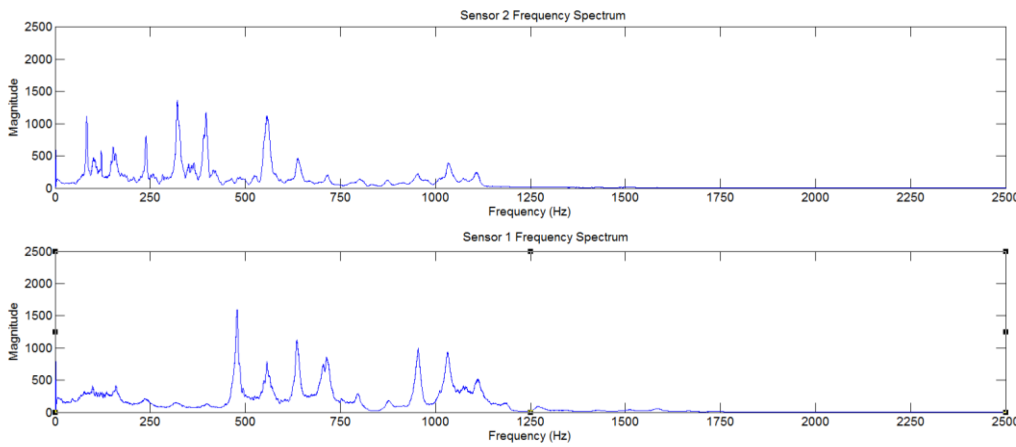


Figure 3-5 Acoustic signal from sensor 1 and sensor 2



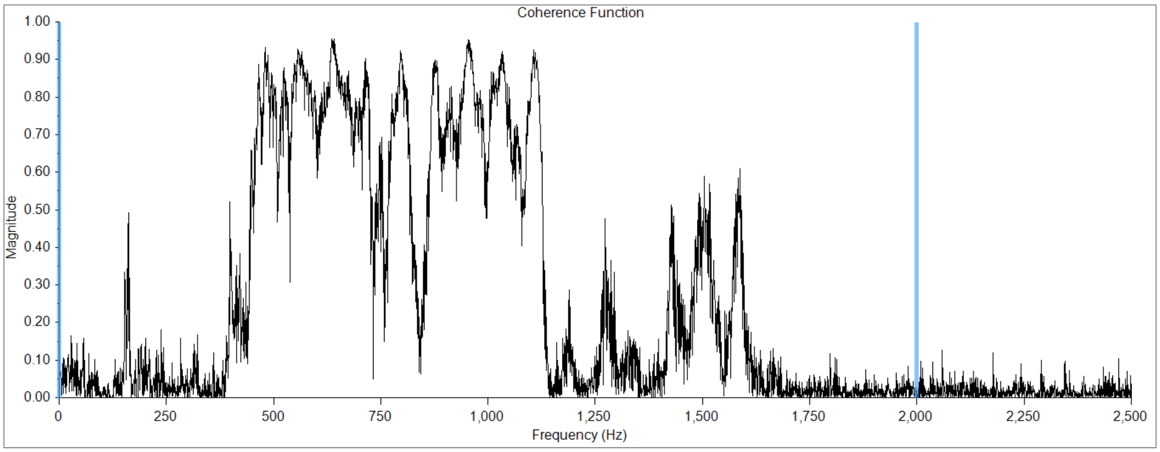
(a) *From commercial software*



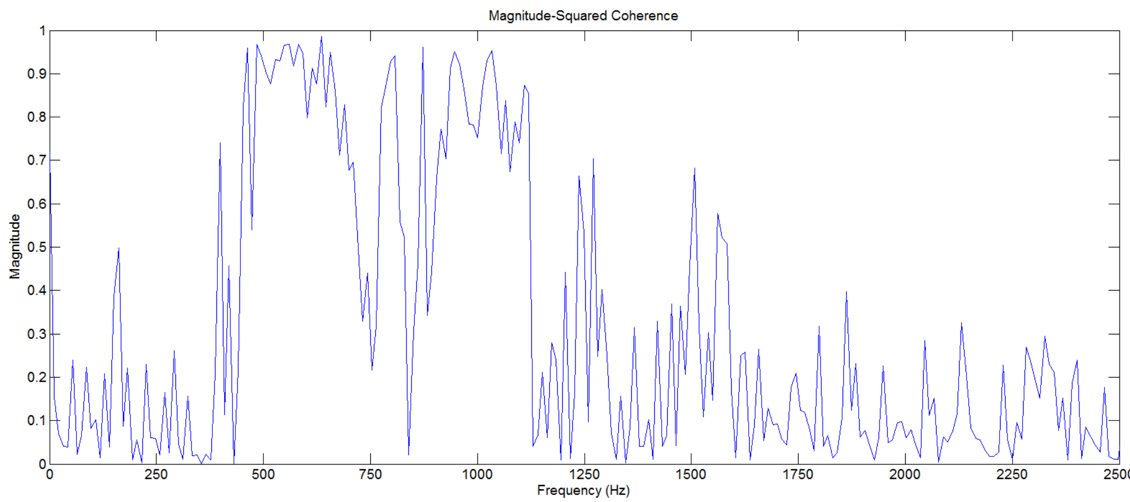
(b) *From MATLAB analysis*

Figure 3-6 Frequency spectrum of recorded signals

The magnitude-squared coherence between two signals obtained from MATLAB analysis and the coherence from the commercial leak correlator software are included in Figure 3-7. The magnitude of coherence is around 0.95 in Figure 3-7(a) and (b) within the frequency band of about 500 to 1100 Hz. This clearly indicates that the noises within the frequency band of 500 to 1150 Hz in the two sensors are from the same source, which is potentially a leak. The results obtained from MATLAB analysis are found to correspond to those given by the commercial leak correlator software.



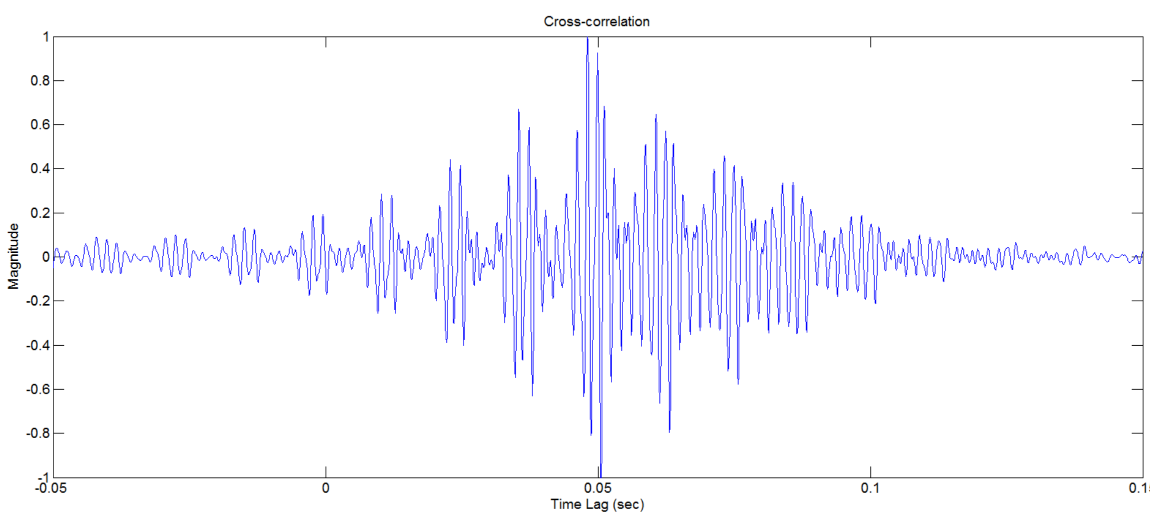
(a) From commercial software



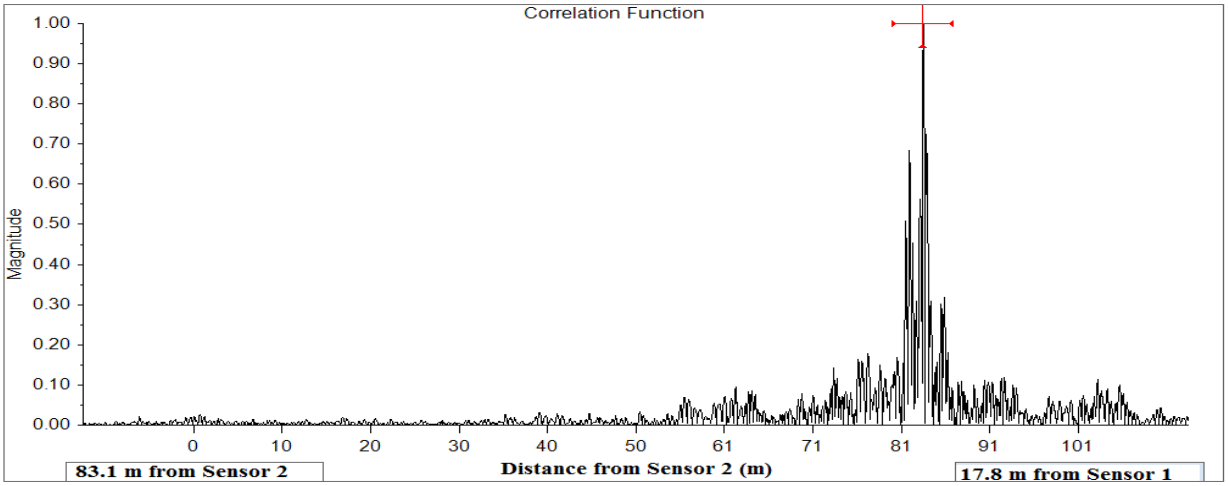
(b) From MATLAB analysis

Figure 3-7 Coherence between two recorded signals

The cross-correlation function in the commercial leak correlation system is provided directly against the distance from the sensor (s). The distance corresponding to the highest magnitude of the cross-correlation is taken as the location of the potential leak. Using MATLAB, the cross-correlation function was calculated against the time lag. The time lag corresponding to the highest magnitude of the cross-correlation is then obtained. This time lag was used to calculate the distance of the noise source from the sensors using Eq. (3-2). Figure 3-8 (a) and (b) shows the cross-correlation functions with time lag from MATLAB and with the distance from a sensor (Sensor 2) obtained for the commercial leak correlator, respectively. In Figure 3-8(a), the magnitude of cross-correlation is the maximum at the time lag of 0.0506 sec. With a wave propagation velocity of 1290 m/s (velocity used in commercial leak finder), the distance to the leak is calculated to be 17.7 m from sensor 1, which is almost the same as the distance obtained from the commercial system (i.e., 17.8 m from sensor 1 in Figure 3-8b). In Figure 3-8(b), the highest magnitude of the cross-correlation is at this distance (i.e., 17.8 m from sensor1 and 82.9 m from Sensor 2).



(a) Cross-correlation function with time lag



(b) Cross-correlation function with distance from Sensor 2

Figure 3-8 Leak location determination from correlation function

However, since a lateral is connected to the water main at this location (82.9 m from Sensor 2), there was a possibility that the noise source is located on the lateral, which might have propagated into the water main at the intersection. To investigate this further, acoustic emission testing was carried out with one of the sensors (sensor 1) on a fire hydrant (Fire Hydrant 1) and the other (sensor 2) on a curb stop valve on the lateral (see Figure 3-3). Figure 3-9 shows installation of the acoustic sensor on a key-rod connected to the curb stop valve.

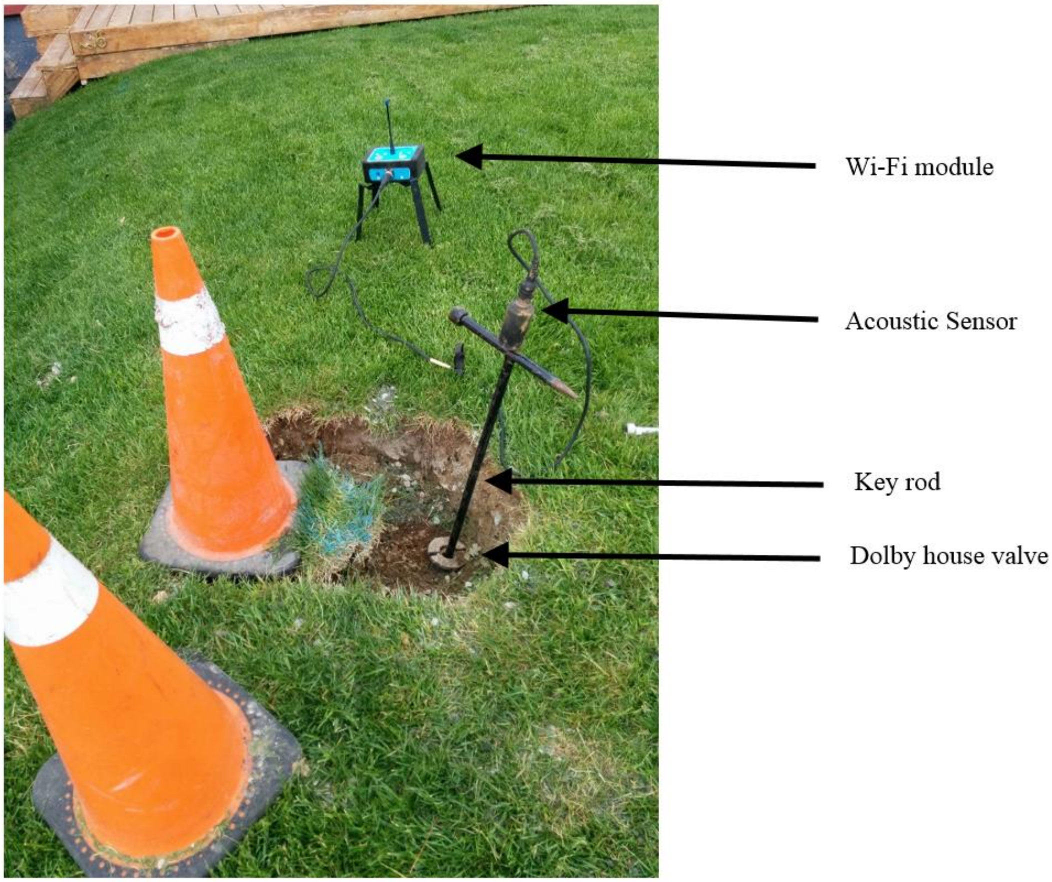


Figure 3-9 Sensor placed on the key-rod at curb stop valve box

Figures 3-10 and 3-11 show the coherence and cross-correlation of the acoustic signals for this case with one sensor on Fire Hydrant1 and the other on the curb stop valve in the private property. The MATLAB calculations are very similar to the results obtained from the commercial system in Figure 3-10. The coherence magnitudes in the figure are higher within the frequency band of 500 Hz to 1250 Hz and range from 0.5 to 0.7. These coherence magnitudes are somewhat lower than those observed over the similar frequency band (500 to 1250 Hz) when both sensors were on the water main (as discussed above). The lower coherence values in this case are attributed to the burial condition of the lateral, which is different from the water mains, as well the wave propagation through an intersection and different pipe materials.

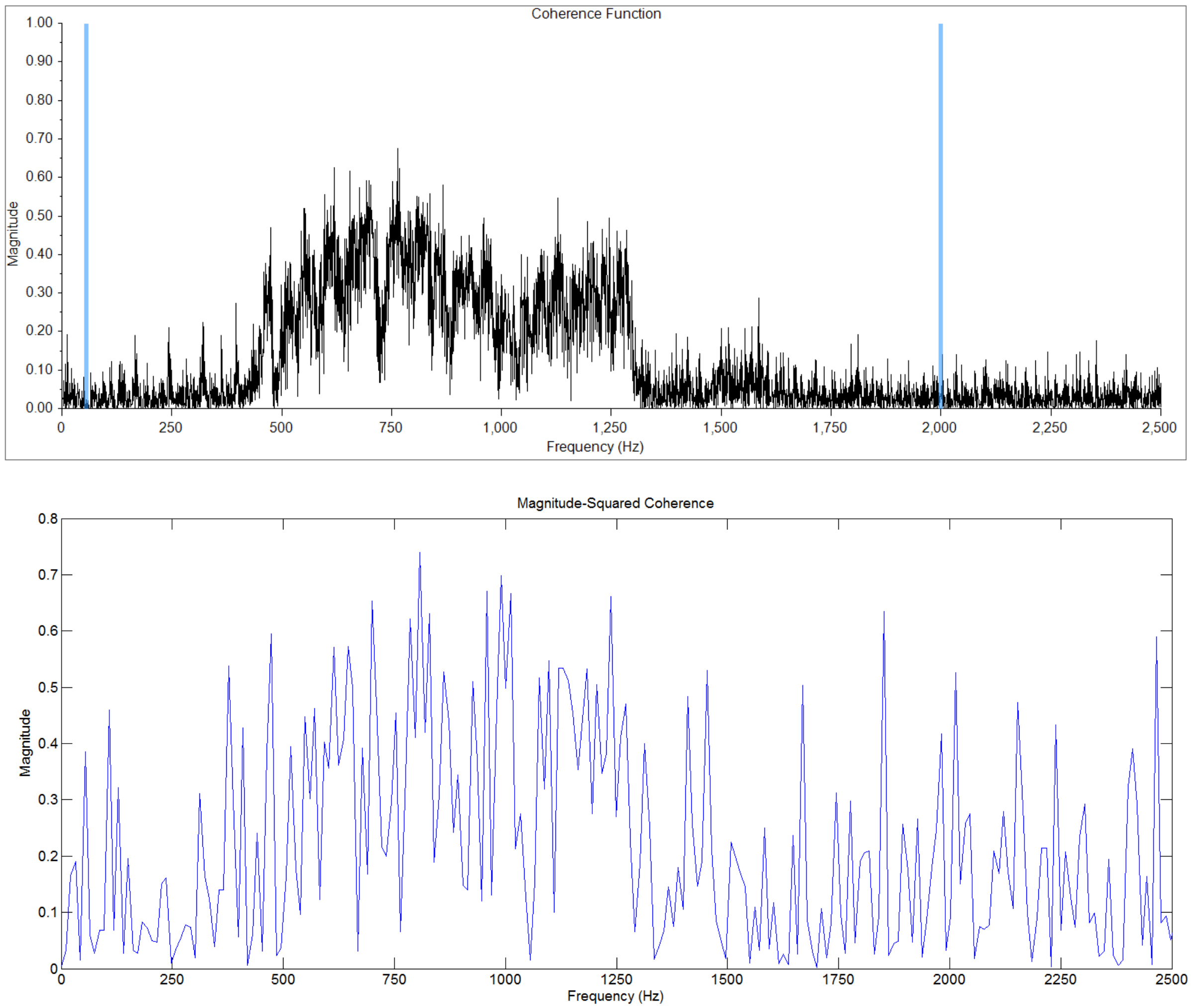


Figure 3-10 Coherence of signals with a sensor on water main and the other on lateral

However, the coherence values were much higher within the frequency band of 500 Hz to 1250 Hz than the other frequencies in Figure 3-10, indicating a common source of noise within the frequency band.

The cross-correlation in Figure 3-11 (a) shows noise source to be located right at curb stop valve (location of sensor 2). This means that the noise source is either located right at the curb stop or between the curb stop and the gate valve in the private house. Similar conclusion can be drawn from the time lag corresponding to the maximum magnitude of cross-correlation in Figure 3-11(b) where the time lag appears to be negative.

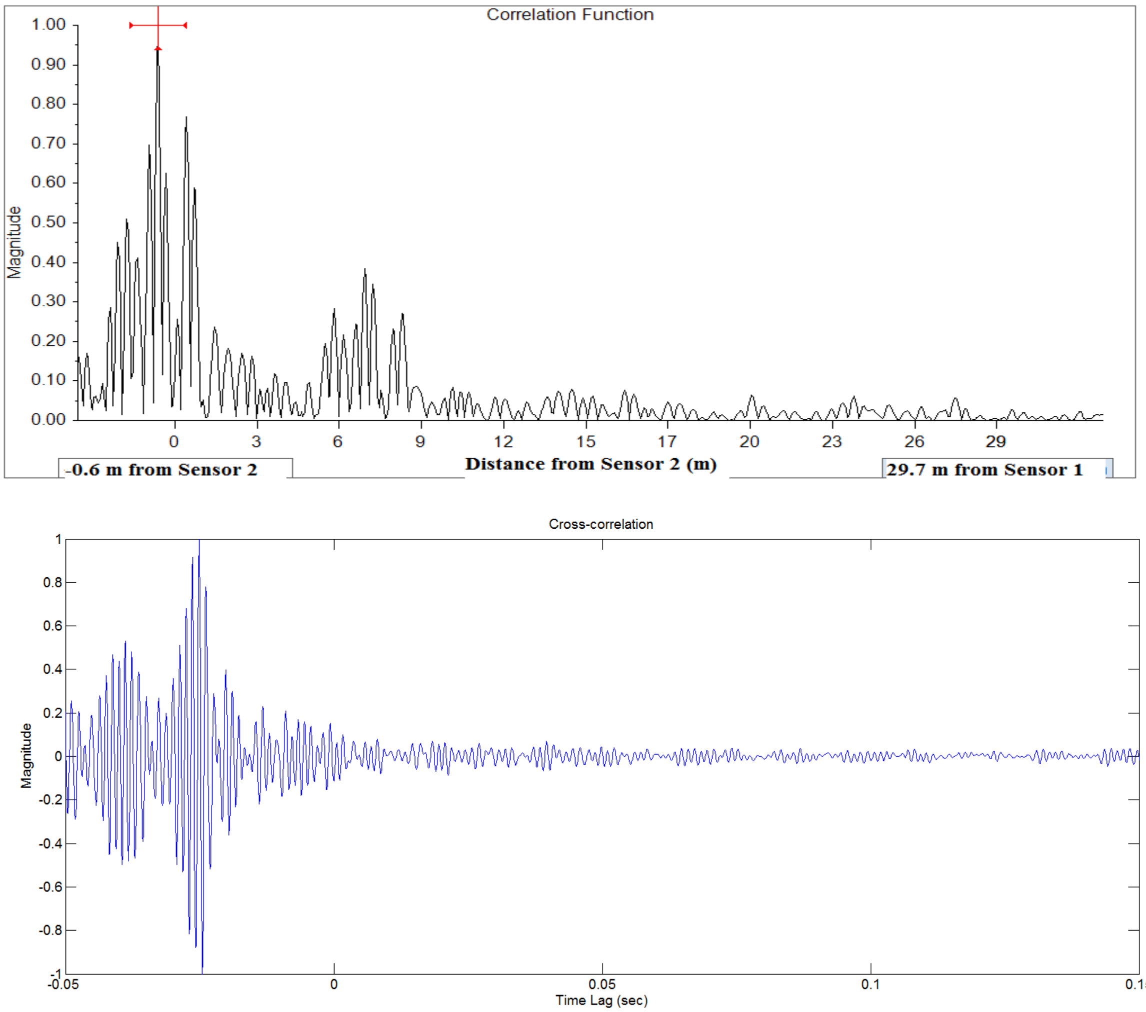


Figure 3-11 Leak location determination between water main and curb stop

Another set of acoustic emission testing was then carried out with one sensor at the curb stop valve (sensor 2) and the other on the gate valve at the private house (sensor 1). Figure 3-12 and 3-13 shows coherence and cross-correlation of the acoustic signals. In Figure 3-12, coherence magnitudes of 0.4-0.6 over the 500-900 Hz of frequency band are higher than the coherence magnitudes in other frequencies, indicating again a common source of noise in this frequency band. The magnitude of cross-correlation function is the highest near the curb stop and at the time lag of close to or less than zero in Figure 3-13. Thus, the location of the noise was expected to be near the curb stop. A leak at this location was later confirmed through excavation.

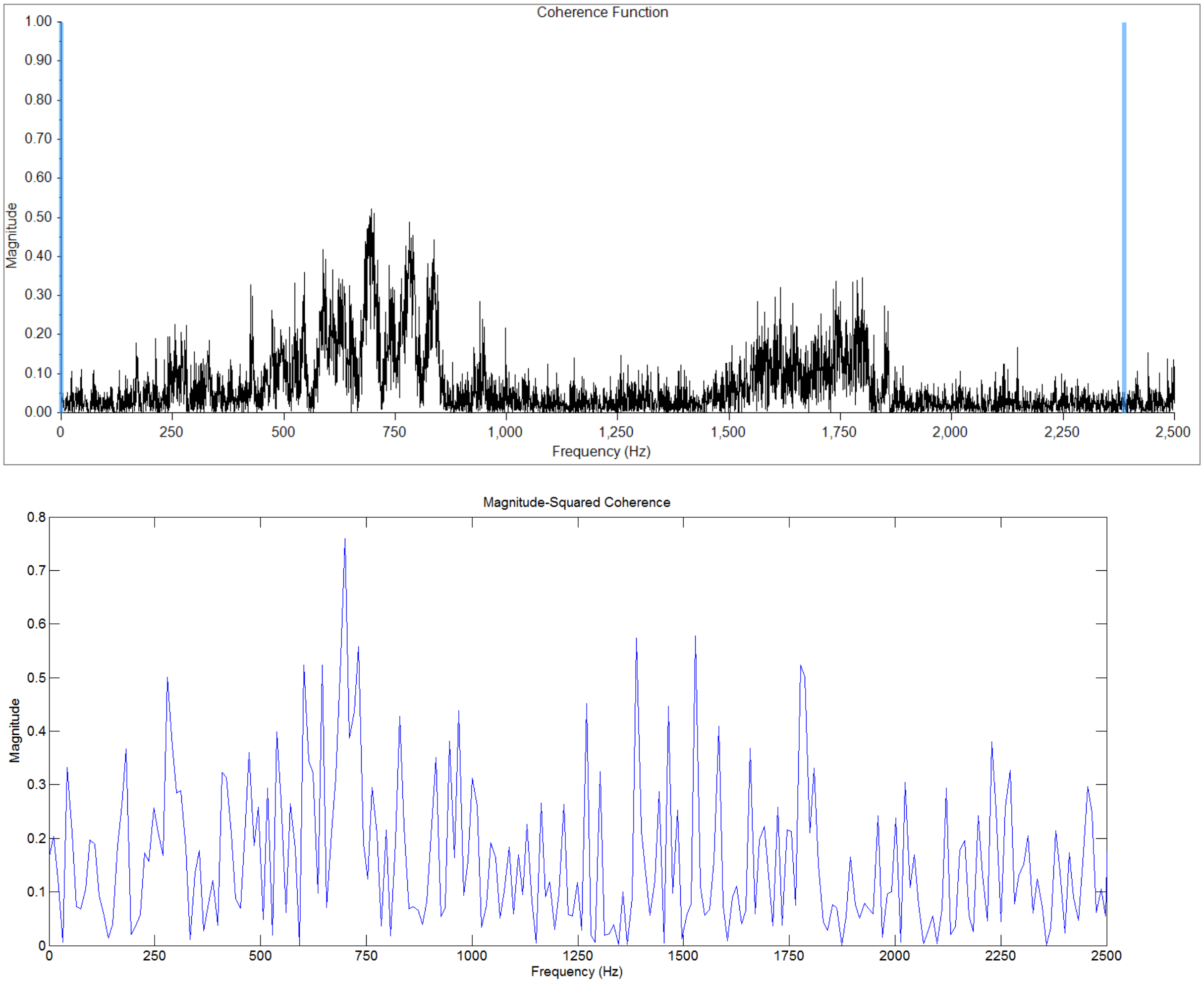


Figure 3-12 Coherence of signals between curb stop and gate valve

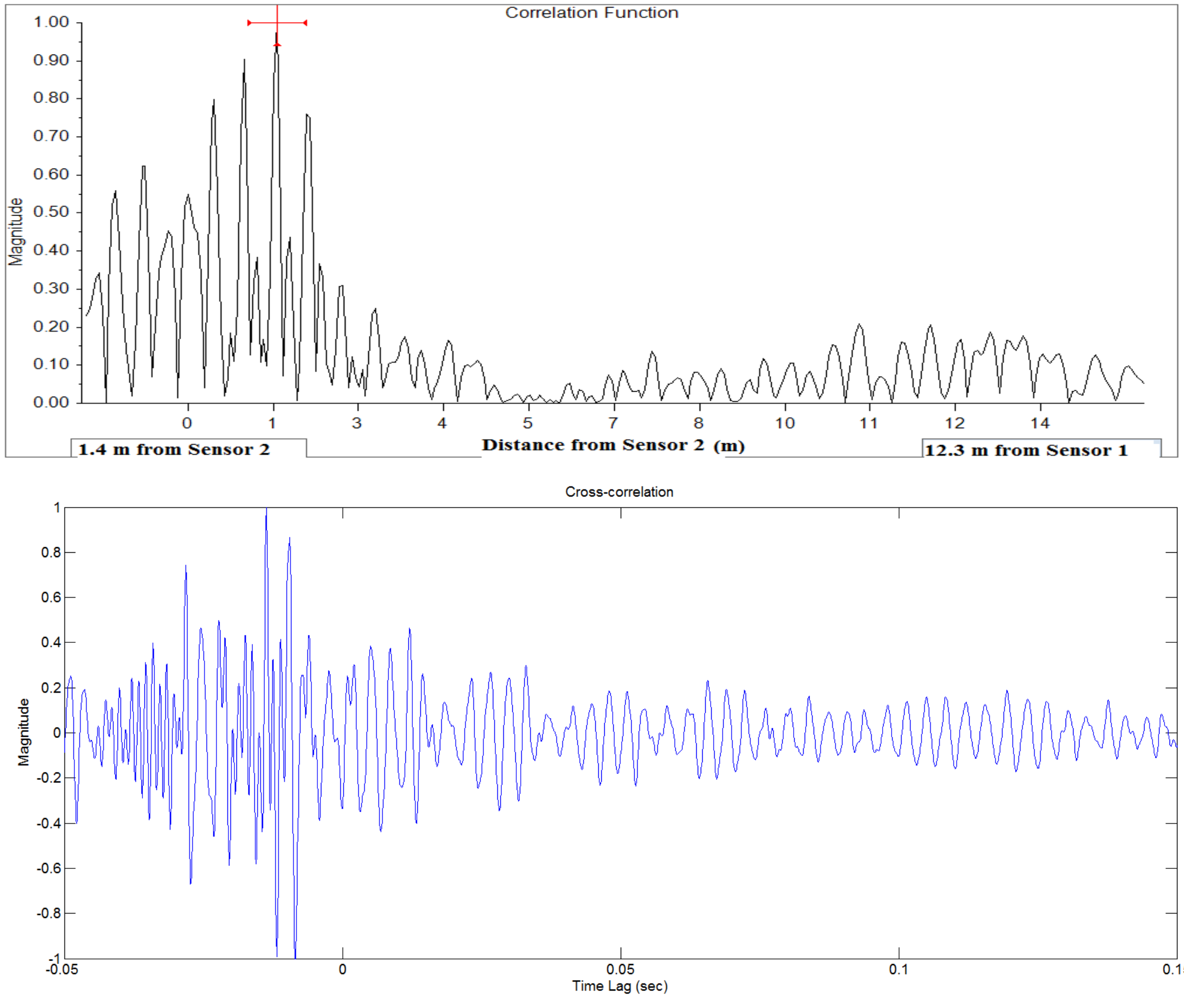


Figure 3-13 Leak location determination between curb stop and gate valve

3.7.2 **Case Study 2: Leak on a Water Main**

In Case study 2, leak on a city water main was located (Figure 3-14). The test was conducted in the summer of 2015 (on May 26, 2015). The water main is a 152 mm ductile iron pipe with wall thickness of 9.5 mm. The burial depth and backfill soil condition were similar to the pipe described in Case study 1 above.

For the water main within this site, there was only one fire hydrant and a few curb stops as the access points to the pipe (Figure 3-14). Acoustic sensors were place on the fire hydrant and a curb stop valve (curb stop valve 1 in Figure 3-14) located 89.12 m apart from the fire hydrant. Apparently 10 laterals exist between the sensors.

Figure 3-14 Site for leak detection in a city water main

Acoustic signals recorded at the fire hydrant and the curb stop valve 1 are shown in Figure 3-15. Amplitudes of the signals are less in the sensor at curb stop valve, which is apparently far from the sound source. Response spectrums corresponding to the recorded signals are obtained applying Fast Fourier Transform, as discussed earlier, that are shown in Figure 3-16. As seen in Case Study 1 discussed above, the frequency spectrums from the commercial software are similar to the frequency spectrum obtained from MATLAB analysis in the figure.

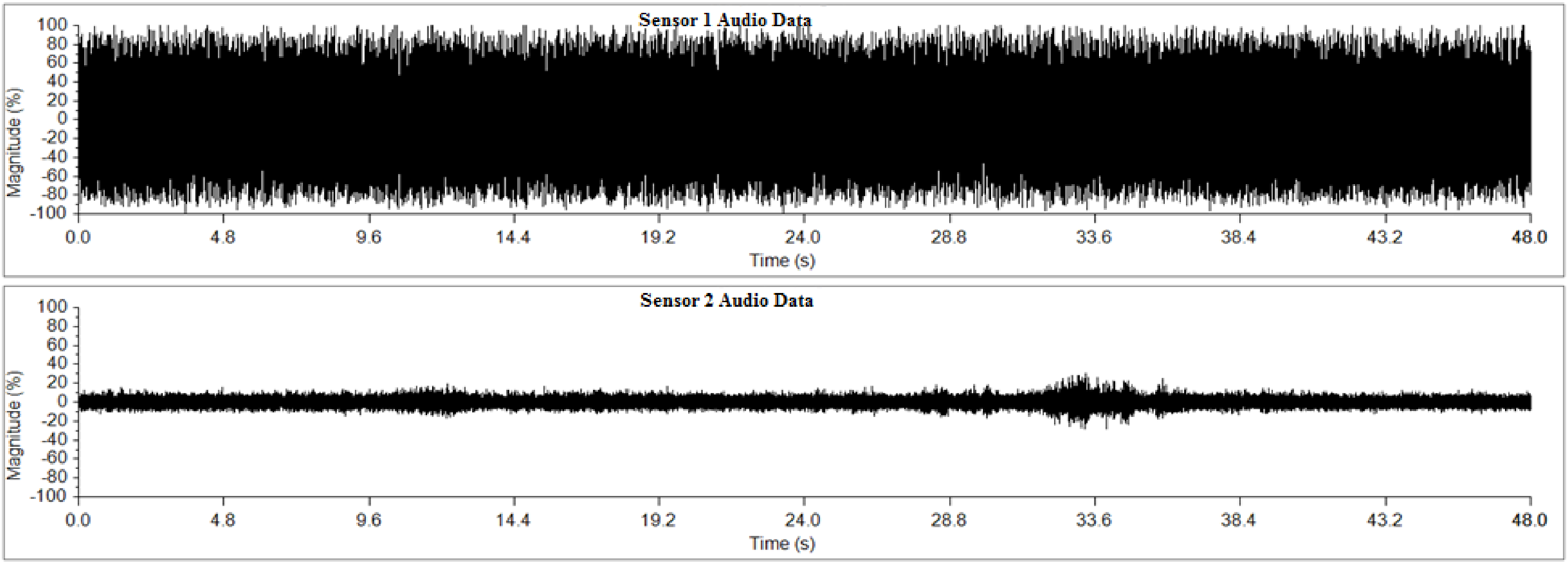


Figure 3-15 Acoustic signal for water main a) sensor 1 and b) sensor 2

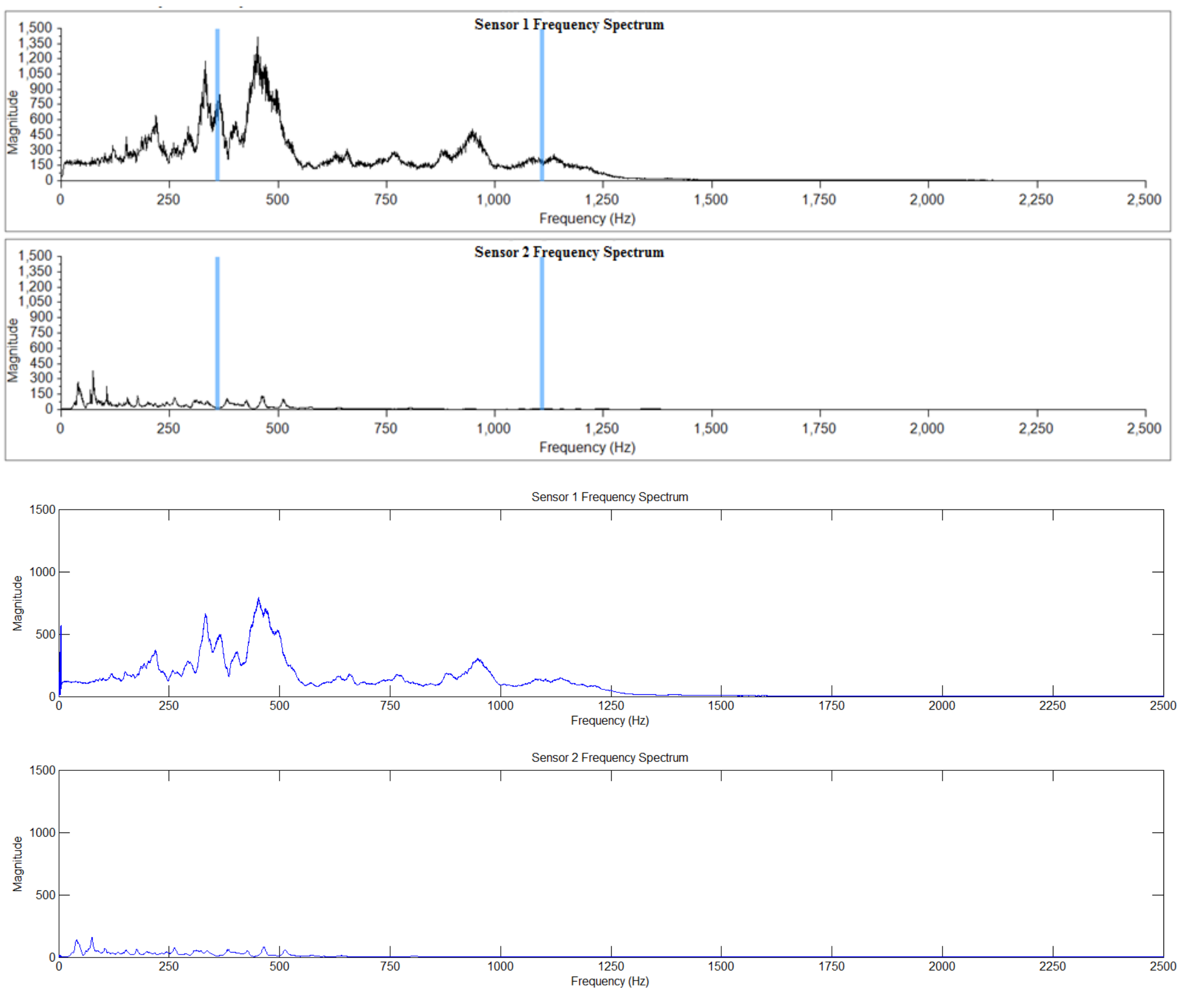


Figure 3-16 Frequency spectrum of recorded signals

Figure 3-17 presents the results of coherence analysis of recorded signals. The magnitudes of the coherence are higher in the frequency band 250 – 1250 Hz with magnitudes ranging from 0.7 to 0.9. A common source of noise is anticipated within this frequency band. The results from the commercial software and MATLAB analysis are similar in Figure 3-17.

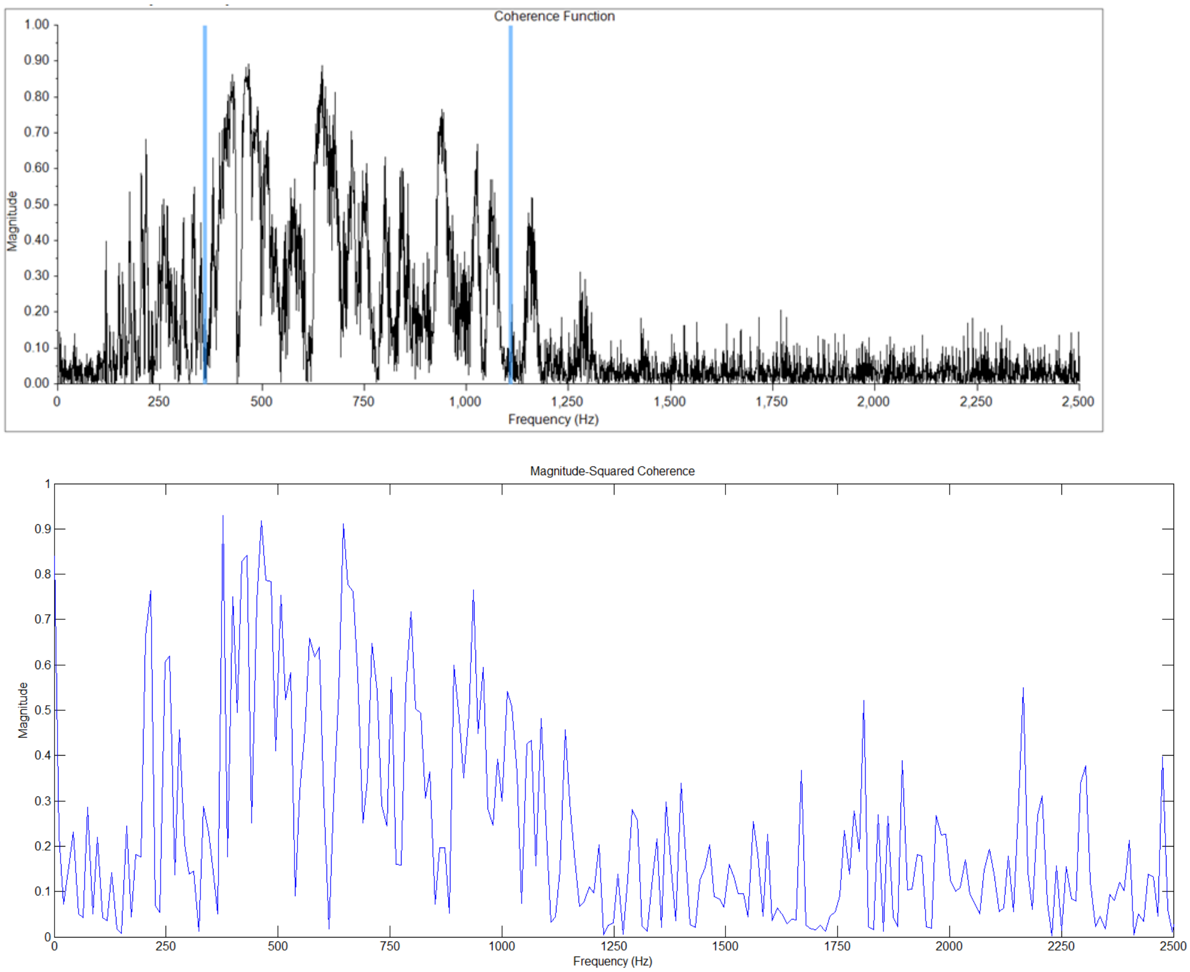


Figure 3-17 Coherence between two recorded signals

Cross-correlation function of the signals (Figure 18) demonstrates the sound source at a distance of 28.7 m from sensor 1 (sensor at the fire hydrant) where the magnitude of the cross-correlation function is the highest. The wave propagation velocity 1290 m/s was used (based on the value obtained for a 152 mm diameter ductile iron water mains, discussed earlier) for calculation of distance from the time lag.

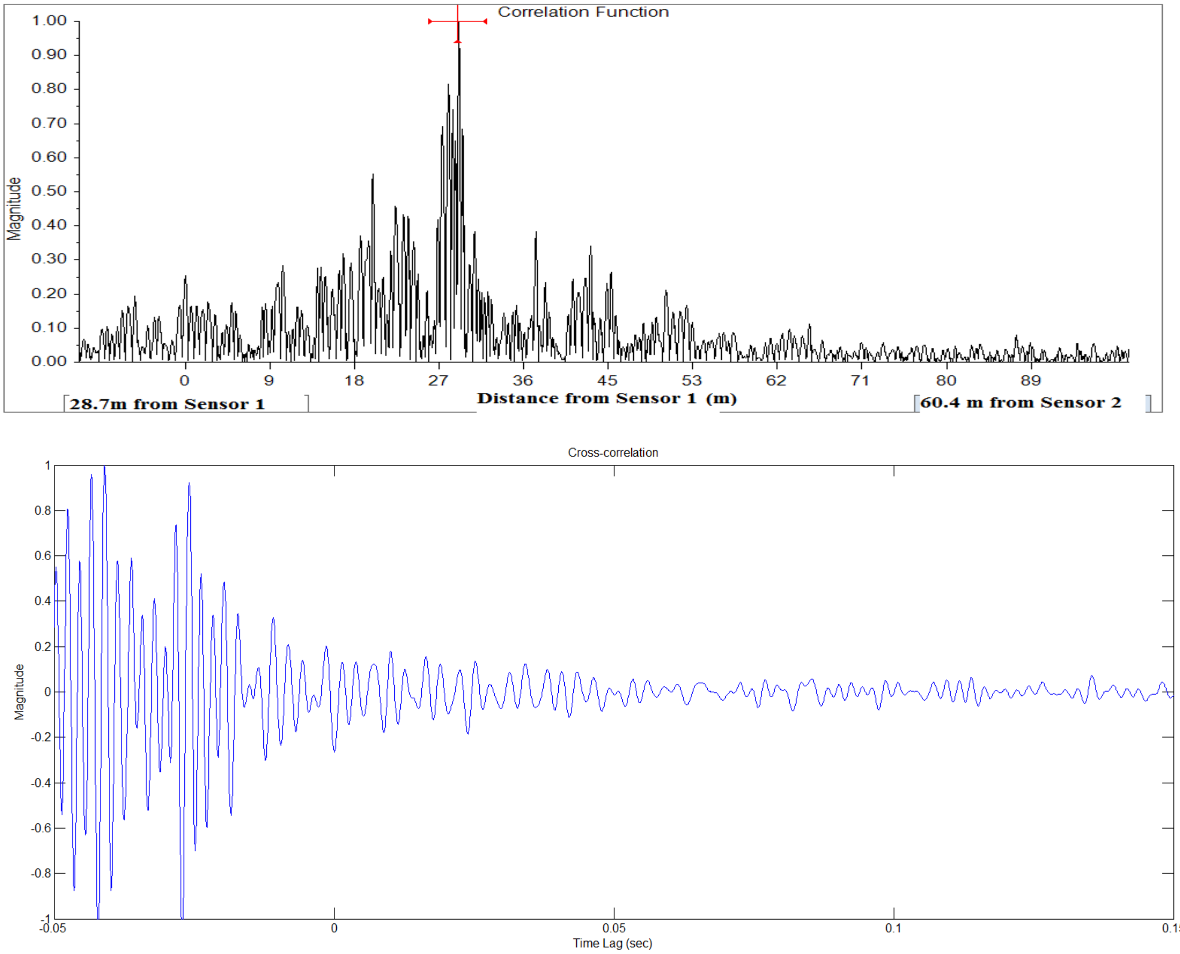


Figure 3-18 Leak location determination from correlation function

Since the amplitudes of the signals in sensor 2 were not high (Figure 3-15), a confirmatory acoustic emission testing was carried out with one sensor again on the fire hydrant (sensor 1) and the other sensor on curb stop valve 2 (see Figure 3-14). The distance between the sensors locations were 61.41 m, which is closer than the distance in the prior test (i.e., 89.12 m). Amplitudes of the noise in sensor 2 was higher in this case than the amplitudes measured by this sensor when it was placed at curb stop valve 1, which was farther than the apparent noise source. Figure 3-19 shows the coherence for this case where the coherence magnitudes are higher within the frequency band of 450 Hz to 1250 Hz, similar to those observed previously, discussed above. The commercial software and MATLAB analysis again provided similar results (Figure 3-19).

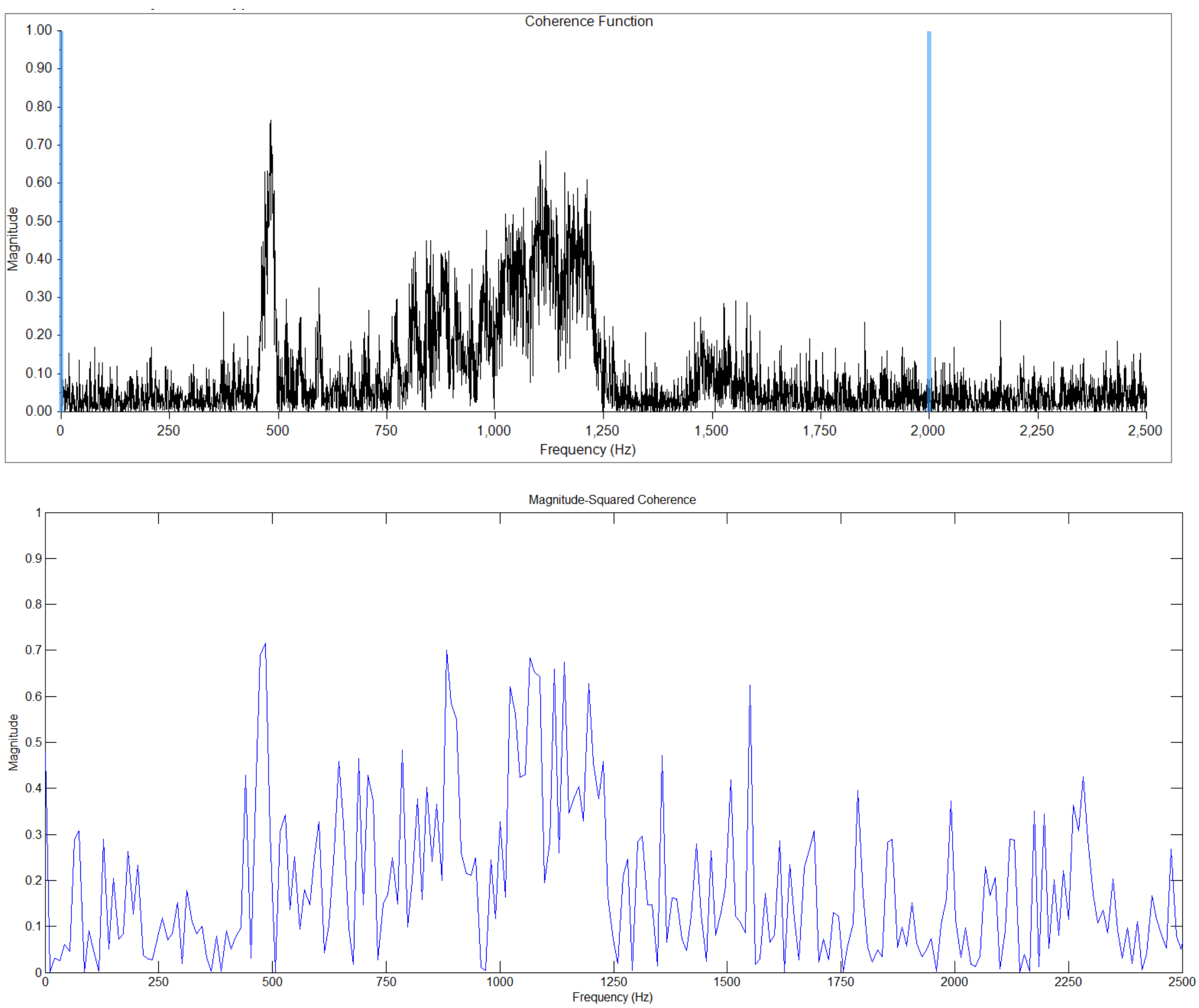


Figure 3-19 Coherence of signals for closer sensors

However, the coherence magnitudes are somewhat less (ranges from 0.5-0.75) than those with the sensors at 89.12 m apart. This indicates that the coherence magnitudes do not necessarily depend on the distance between the sensors, but on the relationship between the measured signals, which is influenced by a number of factors in the propagating medium. From the cross-correlation (Figure 3-20), the location of leak was determined to be 28.34 m, which is similar to the distance obtained from the previous test. Leak at this location was then confirmed through excavation. Thus, the acoustic emission method was successful in leak detection with sensors located as far as around 91.44 m. However, the cross-correlation provided a pronounced peak for the closer sensors (Figure 3-20).

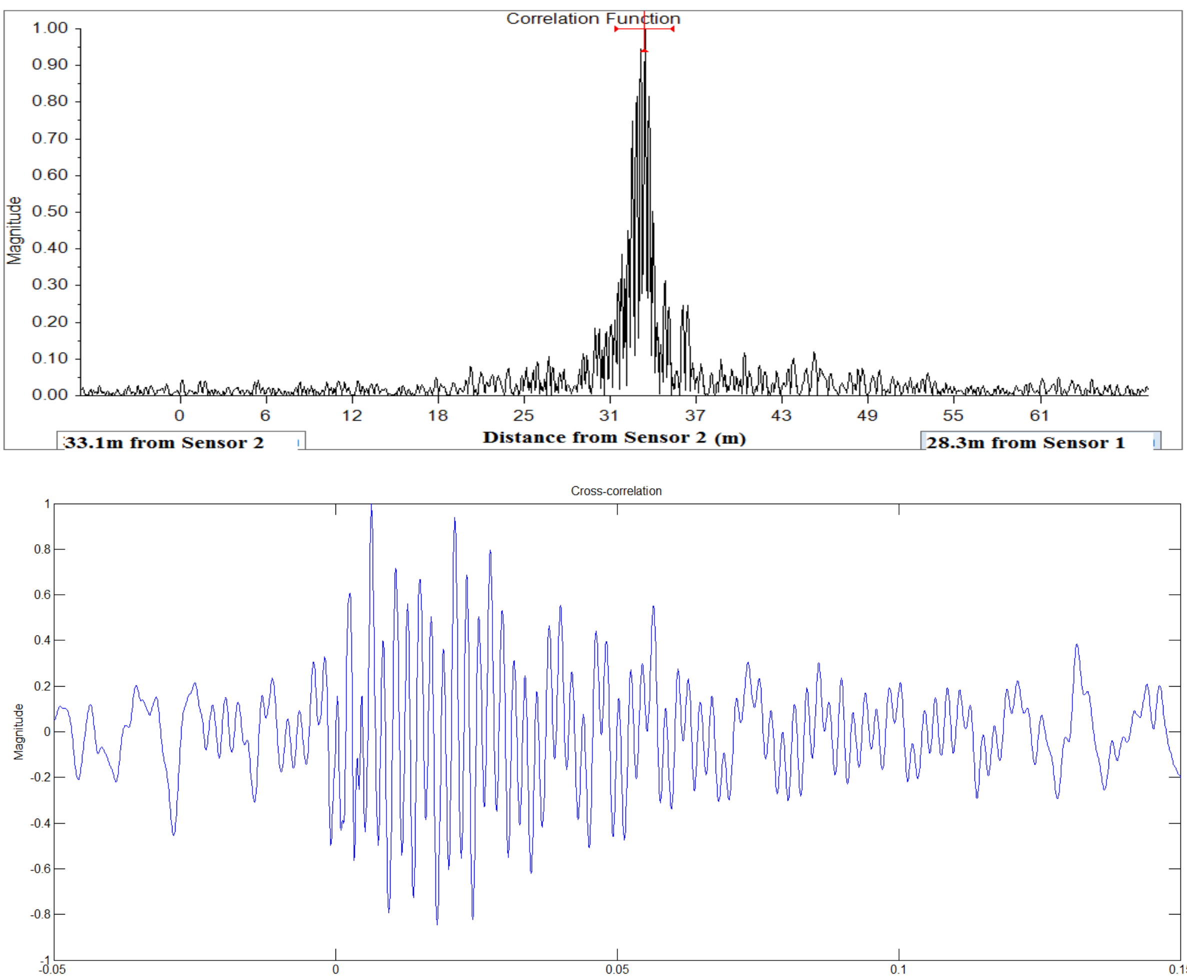


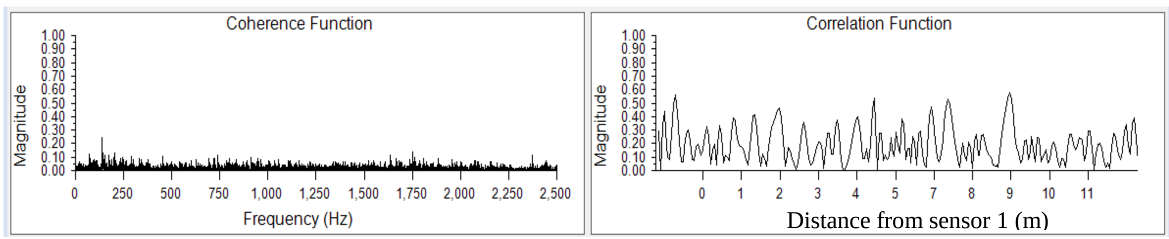
Figure 3-20 Leak location determination from the closer sensors

The comparison of results obtained from MATLAB analysis with those given by the commercial software in Case Study 1 and Case Study 2 above reveals that the MATLAB code can reasonably be used to interpret the leak noise and determine the leak location. The commercial software directly provides the cross-correlation against the distance from the sensors. However, MATLAB analysis provides cross-correlation against time lag that is used to calculate the distance from the sensors. Analysis of acoustic signals using the commercial software are only included in the following sections.

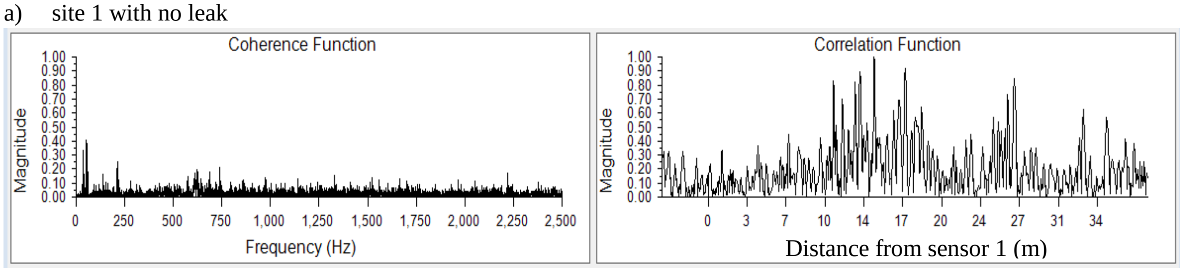
3.7.3 **Case Study 3: Sites with no Leak**

Two cases on the application of acoustic emission method is presented here for situations with no leak in the water mains. Test sites were selected on two cul-de-sac with no anticipated leak based on the city records. Tests were conducted on May 29, 2015 and July 6, 2015, respectively. The acoustic signals and the corresponding response spectrums are not included for these tests for brevity. Figure 3-21 shows the coherence and cross-correlation functions from these tests. Coherence in the figure shows a few jumps at different frequencies. However, magnitudes of the coherence are consistently less than 0.4. On the other hand, the cross-correlation does not show any peak in one of the cases (Figure 3-21a) while peaks are observed for the other case (Figure 3-21b). The distance to the peak for the later, is about 14 m from one of the sensors. For this second site, tests were then conducted a few times and the distance to the peak was found to vary each time. This indicates that the locations of the source of noise for these tests are different.

However, if the noise were from a leak, the location of the source from each test would be the same. It is therefore concluded that there is no leak on this pipe. The coherence magnitudes also indicate no presence of leak (coherence magnitudes less than 0.4). This justify the use of coherence and cross-correlation functions together for identification of leak using the acoustic method.



a) site 1 with no leak



b) Site 2 with no leak

Figure 3-21 Coherence and cross-correlation for pipes with no leak

3.8 Discussion and Conclusions

In the case studies presented, the acoustic emission method was successfully used for leak detections in water mains in the City of Mount Pearl. Methodologies undertaken for successful leak detection on a lateral and on a water main are presented above.

The leak detection using the acoustic method involves identification of leak in a pipe segment and determination of leak location. The coherence is usually used to confirm the presence of leak from the acoustic signals measured at two locations on the pipeline. The coherence essentially is a measure of relationship between two time series irrespective of leak noise or noise from any other sources. Therefore, confirmation of the leak noise from the coherence values is a major challenge for the leak detection using the acoustic method. On the other hand, the leak location is determined from the propagation velocity of the sound wave that depends on a number of factors including pipe geometry, pipe material and burial condition. In this regards, a database on the coherence values and the frequency band corresponding to the leak noises as well as the propagation velocity from real-time application would be useful for successful application of the method. The coherence values and noise frequencies corresponding to the leak noise and the wave propagation velocities based on real-time data are described in the case studies discussed above. Additional data were collected from 20 other sites in the City of Mount Pearl where leaks were confirmed through excavations. Tests were completed between May to August of 2015. Table 3-3 presents different parameters obtained from these data. The buried depths of the pipes were generally 2.43 m to 3.0 m. Pipe backfill material was sandy crushed rock/gravel. Water pressure in the city water mains varied from 480 kPa to 620 kPa. Rate of water loss from the leak could not be measured during the tests. However, the total water loss from the leaks was estimated based on the city water required for a month (i.e., October 2014) last year and the water required in the same month on the following year (i.e., October 2015) after the leaks were repaired. Much less water was required in 2015 due to repairing of the leaks. The difference is attributed to the water loss through the leaks. An average leak rate is then estimated from the information on the total number of leaks repaired (i.e. dividing the total water loss by the number of leak repaired). A total of 48 leaks were identified and repaired by the end of September 2015. The average leak rate thus estimated is 4200 m^3 per month or 1.6 litres per second.

As shown in Table 3-3, wave propagation velocities for ductile iron pipes with diameters of 152 mm, 203 mm, and 254 mm in. were 1290 m/s, 1263 m/s and 1224 m/s that provided leak locations with reasonable accuracy for the sites considered. The propagation velocity in the 19 mm diameter copper pipe was 1164 m/s.

Table 3-3 Acoustic emission test results

Site No.	Date	Distance	Pipe material	Pipe dia.	Pipe thick	Wave velocity	Maximum coherence	Frequency band	Maximum cross-correlation
		m		mm	mm	m/s		Hz	
1	7/20/15	116	Ductile Iron	152	9.53	1290	0.9	250-1250	0.99
2	6/30/15	104	Ductile Iron	152	9.53	1290	0.8	250-900	0.99
3	6/11/15	27	Ductile Iron	203	9.53	1263	0.7	450-1250	1
		6	Copper	19	1.65	1164			
4	8/10/15	132	Cast Iron	152	9.53	1232	0.8	250-1000	0.99
5	5/22/15	101	Ductile Iron	152	9.53	1290	0.75	500-1500	0.97
		22	Copper	19	1.65	1164			
6	5/22/15	112	Ductile Iron	203	9.53	1263	0.88	250-1000	0.98
7	6/01/15	117	Ductile Iron	152	9.53	1290	0.9	300-1250	0.99
8	6/12/15	43	Ductile Iron	305	10.92	1224	0.9	200-1250	0.97
9	5/28/15	76	Ductile Iron	203	9.53	1263	0.75	250-1250	0.98

10	8/03/15	40	Ductile Iron	152	9.53	1290	0.7	150-1050	0.95
		16	Copper	19	1.65	1164			
11	6/10/15	119	Ductile Iron	152	9.53	1290	0.88	150-1500	0.97
12	7/06/15	85	Ductile Iron	203	9.53	1263	0.85	0-850	0.98
13	6/29/15	109	Ductile Iron	152	9.53	1290	0.85	100-1050	0.99
14	5/28/15	9	Ductile Iron	152	9.53	1290	0.72	0-1750	0.95
		12	Copper	19	1.65	1164			
15	7/10/15	13	Copper	19	1.65	1164	0.95	650-1650	0.98
16	7/16/15	10	Copper	19	1.65	1164	0.7	0-2000	1
17	7/08/15	26	Ductile Iron	152	9.53	1290	0.65	250-1500	1
			Copper	19	1.65	1164			
18	6/15/15	11	Copper	19	1.65	1164	0.85	250-1750	0.97
19	5/25/15	10	Copper	19	1.65	1164	0.75	0-2000	0.98
20	6/19/15	17	Copper	19	1.65	1164	0.85	0-2000	0.98

Frequency bands corresponding to the leak noise was found to vary up to 2000 Hz. Figure 3-22 shows the variation of the frequency bands for the different sites considered. The average of the lower bound and upper bound of frequencies were around 220 Hz and 1400 Hz, respectively.

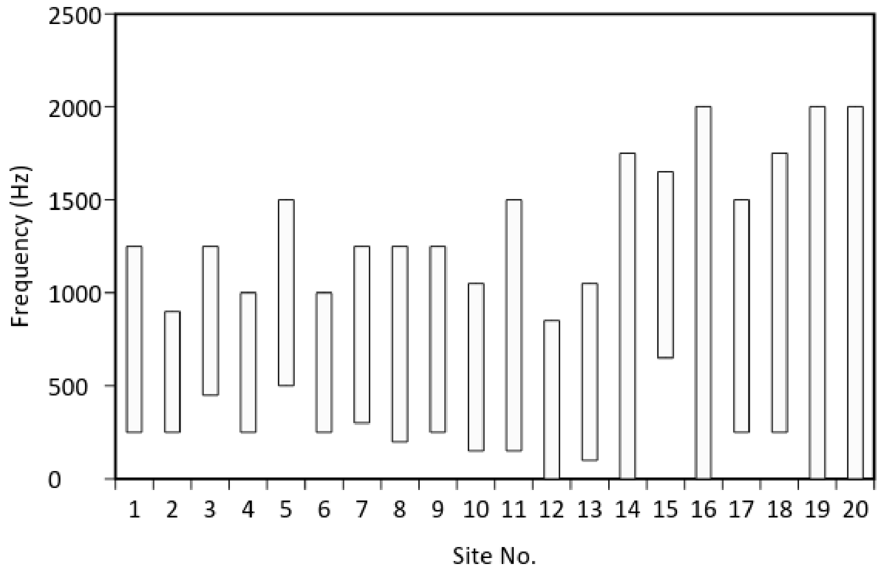


Figure 3-22 Frequency band estimated for leak noise through water mains

A coherence magnitude higher than 0.5 was found to represent a correlation for leak noises between the sensors for the cases presented. The coherence magnitudes were higher within the frequency bands corresponding to the leak noises (i.e., average 220 Hz to 1400 Hz).

In conclusion, this chapter presents the effectiveness of the acoustic emission method for leak detection in water distribution pipes. However, application of the method requires estimation of a number of parameters used for interpretation of acoustic signal for identification leaks and determination of leak locations. The parameters based on field data obtained from the City of Mount Pearl are presented.

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Chapter 4. Preliminary Laboratory Investigation

4.1 Introduction

Leaks in buried water mains impose major challenges to the municipalities in transporting potable water to the city dwellers. The water loss and the damage caused by the escaping water result in a significant economic burden to the municipalities. To address the issues, the municipalities are focusing on leak detection in their water main infrastructure and maintain the integrity of the infrastructure proactively. Several methods such as tracer gas, infrared thermography, ultrasonic and electromagnetic scanning, acoustic emission, flow and pressure modelling, and ground penetrating radar were used in the past to detect leak in water pipeline. Most of these methods have a number of limitations that are being addressed through research.

In the recent years, acoustic emission method is becoming popular for leak detection in municipal water mains. In this method, hissing sound from leak are recorded using two or more sensors located on both sides of a suspected leak. Mathematical algorithms are then used to interpret the acoustic signals for determination of the locations of leaks, if any. The acoustic signals are however affected by a number of parameters including pipe diameter, leak size, and the surrounding ground conditions. The affects are not well-understood that sometime leads unsuccessful leak detection using the method.

To improve the performance of leak detection using the acoustic emission method, a few studies were carried out for plastic water pipes (e.g. Hunaidi and Chu, 1999, Gao et al., 2005, Papastefanou et al., 2012 and Martini et al., 2015). Hunaidi and Chu (1999) studied the acoustic characteristics of leak noise in plastic pipeline. They found that the frequency band of the acoustic signals for leaks in PVC pipes is below 50 Hz. The propagation velocity of the wave was independent of the frequency. However, only a limited study is available in the published literature on the application of the acoustic emission method on metal pipes. The literature lacks information on the applicability of the method under various surrounding conditions, including leak sizes, pipe diameters and burial conditions. Brunner and Barbezat (2006) experimentally investigated acoustic emission signals on a 50 mm diameter aluminum pipe under compressed air pressures between 400 and 800 kPa. Distinct differences in the power spectra for the pipes with and without a leak were noticed in the experiments. It was concluded that there might be a lower limit of the leak diameter for the gas pipes that can reliably be detected using the acoustic method. The gas leakage-induced acoustic waves generally propagate along multiple paths with different velocities that need to be correctly determined for leak detection and determination of leak location, Li et al. (2014).

Anastasopoulos et al. (2009) presented several case studies on acoustic emission method of leak detection for liquid filled buried pipelines (water mains). In this study, a number of test pits were used for mounting of multiple acoustic sensors on the pipes at various spacing along the length ranging from less than 100 m to 125 m. The acoustic signals are then analysed to identify the leak and determine the leak location. Excavation of multiple test pits is no longer used for leak detection in municipal pipeline. The current practice is to mount the acoustic sensors at convenient access points to the pipe (e.g. fire hydrants) typically on either side of the leak (two point measurements). The acoustic signals from two point measurements require careful interpretation with proper understanding about the source of the leak noise and the characteristics of the acoustic wave. As discussed in Chapter 3, the parameters used for the interpretations (i.e., frequencies and the coherence value) varies over wide ranges for the field tests conducted.

There are debates among the researchers about the source of acoustic noise from a leak in water pipe. Anastasopoulos et al. (2009) postulated that eddy breaking through the leak would be a possible source of leak noise. However, the experimental work by others has revealed a different scenario where the interaction of the escaping water with surrounding material was found to contribute more significantly to the leak noise (Juliano et al., 2013, Miller et al., 1999). Juliano et al. (2013) experimentally investigated the acoustic emission for leak detection in a 305 mm diameter steel pipeline buried in sandy soil where the method was found successful for leak rates ranging from 15.2 to 16.6 mL/s with sensor separation of 46.3 to 65.5 m. However, the method for these leak rates was unsuccessful for sensor spacing of 78 m. In this regard, further experimental work is required to develop a better understanding of the leak noise and identify the contributing factors to the noise. This chapter presents a laboratory set-up developed to investigate leak noise in a controlled laboratory environment. Acoustic wave characteristics of leak noise under different boundary conditions are investigated.

4.2 Laboratory Setup

The laboratory setup includes a test bed to house a pipe with an artificial leak, a prepared pipe sample, two acoustic sensors and a data acquisition system.

4.2.1 **Test bed**

The test bed is a 4 m long, 61 cm wide and 20 cm deep flume in the Hydraulics Lab at Memorial University (Figure 4-1). The bed is made of steel plates, supported on a steel frame. The ends of the bed are connected to two water tanks to allow drainage of water.

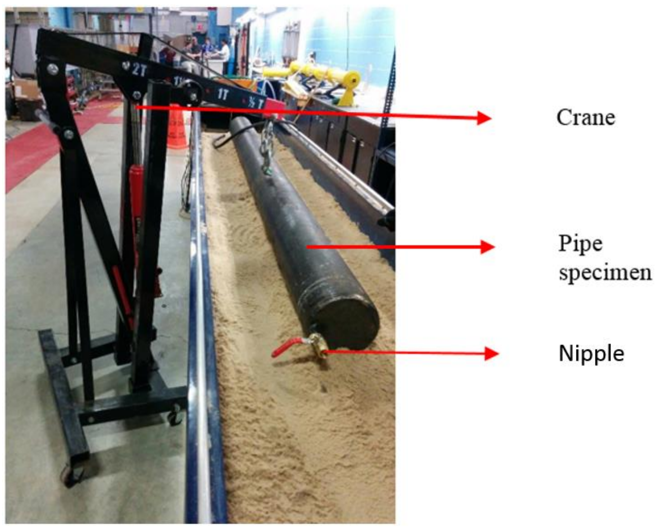


Figure 4-1 Test bed for pipe leak test

4.2.2 **Acoustic Sensors**

Two acoustic sensors are used to measure the noise on both side of the leak. Figure 4-2 shows an acoustic sensor used in the current research that is attached to the pipe wall. It is a R. 45I sensor from Physical Acoustics with a frequency bandwidth of 1 to 30 kHz and resonance frequency of 20 kHz. High sensitivity and low-noise input capabilities make this sensor suitable for recording acoustic signals from leak in water main. An integrated

40dB preamplifier in the sensors enables deriving the signals without any external amplifier.

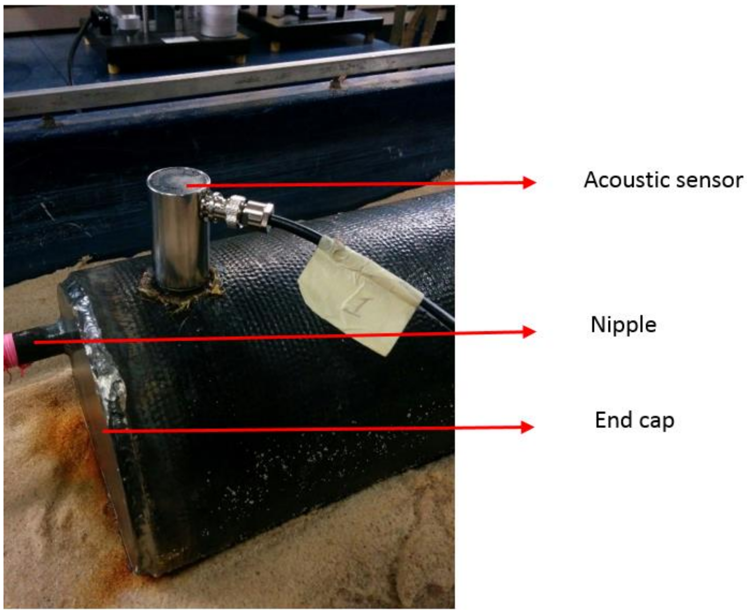


Figure 4-2 Acoustic sensor

4.2.3 **Data Acquisition System**

The data acquisition system consists of Data acquisition (DAQ) module and personal computer equipped with LabVIEW Signal Express (Figure 4-3). The DAQ module consists of two components NI 9218 D-sub connectivity and NI 9982D Screw Terminal Block. The NI 9218 can read dynamic universal simultaneous analog input from two channels at 51.2 kS/s per channel. This module has Built-in support for accelerometer, powered sensor, full-bridge, and voltage measurements. It can support for 1/4-bridge, 1/2-bridge, 60 V, and current measurements via measurement-specific adapters.

The NI 9218 is connected with personal computer using USB cable. The sensors are connected to the system using NI 9982D screw terminal block.

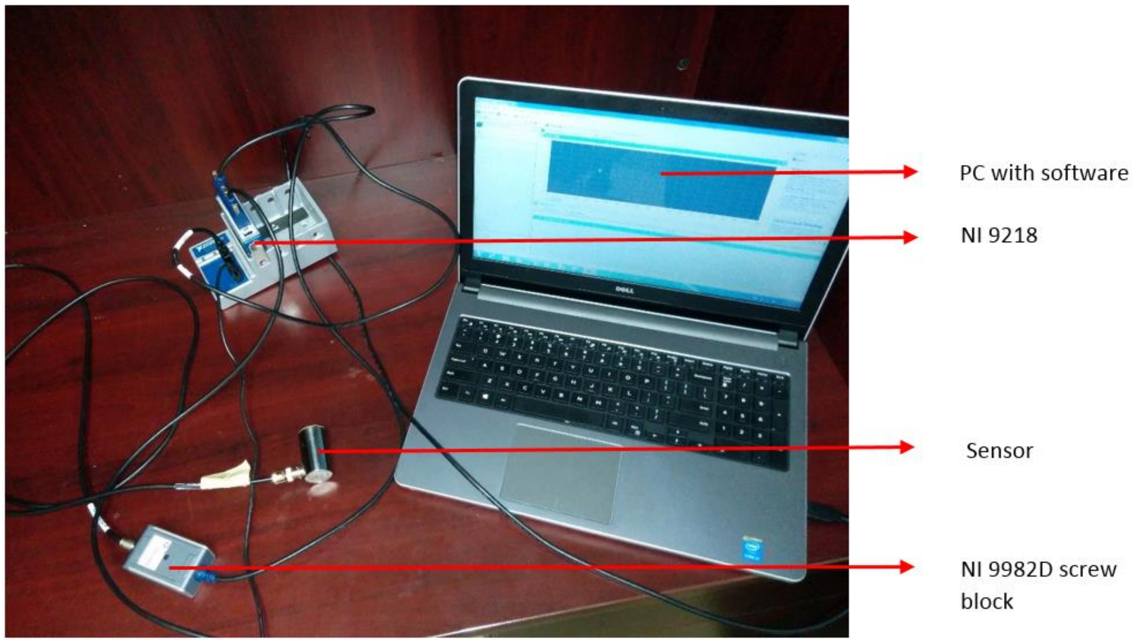


Figure 4-3 NI 9218 connected with NI 9982D Screw Terminal Block

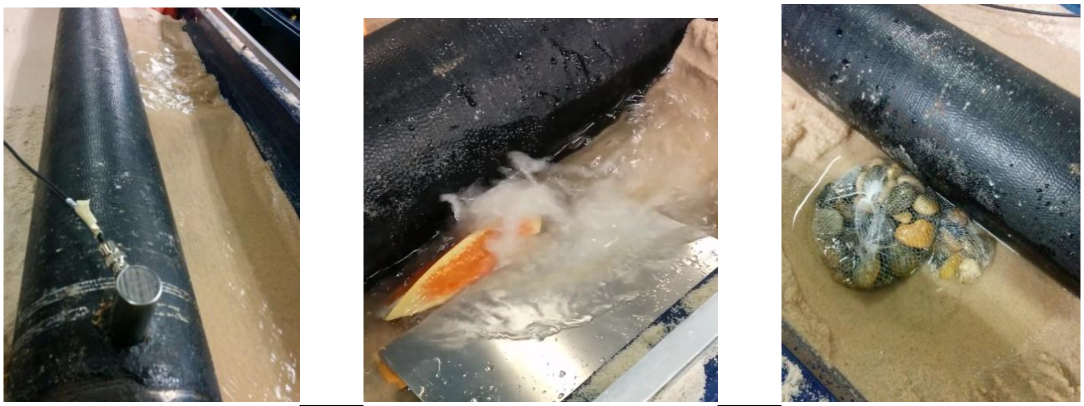
4.2.4 Pipe Sample

A pipe sample was prepared for the test. The pipe sample consists of a 15.25 cm diameter ductile iron pipe segment of approximately 3 m length. Ends of the pipe segment were capped using two steel plated welded at the ends (Figure 4-4). The ends are tested for leaks using 0.5 MPa air pressure. Two nipples with 12.7 mm diameter and 7.6 cm length are connected at the ends to facilitate water circulation and the attachment of a flow control mechanism. One of the nipples is connected to a water line. The nipple on the other end is equipped with a flow controlling valve. An artificial leak of diameter of 4.75 mm was created on the pipe wall at approximately 70 cm from one end of the pipe.

Figure 4-4 Pipe sample

4.3 Test Program

A test program is designed to investigate the source of leak noise in ductile iron pipe. A leak with different obstacles in front of the leak is considered. Three conditions of obstacles are presented in the present study. These include a test without any obstacles in-front of the leak other than the fine sand backfill (Test 1), a test with a wood block as the obstacle (Test 2), and a test with river bed stones as the obstacle (Test 3), Figure 4-5. The collected data are analysed using signal processing algorithms.



a) Test 1 b) Test 2 c) Test 3

Figure 4-5 Test program with different obstacles in front of the leak

4.4 Signal Processing

The acoustic signal are recorded at 25641 data/sec (default value) using the LabVIEW signal express software. A data sampling rate of lower than 25641 data/sec was successfully used in the water main leak detection using LeakfinderST^{TM}. The signals are stored in personal computer (PC). The data are then exported to text file and interpreted using MATLAB program. The MATLAB program convert the data to sound wave and store in the PC. This sound wave are then analyzed to get the frequency spectrum. Moving average filter have been used to remove noise from frequency spectrum. A moving average is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. The threshold between short-term and long-term depends on the application. The parameters of the moving average are set accordingly.

The moving average is a simple and effective filter to remove noise from signal. This filter operates by taking some points from input sample and producing output signal by averaging them (Eq. 4-1).

$$y[i] = \frac{1}{M}\sum_{j=1}^{M} x[i+j] \tag{4-1}$$

Where *x* [ ] is the input signal, *y* [ ] is the output signal, and *M* is the number of points in the average.

The degree of association of the signals recorded by two sensors are then determined. A higher degree of association (relationship) would indicate that the noise measured in two sensors is from the same source (i.e., potential leak). "Coherence" is a measure the degree of association between time series as a function of frequency, which is defined as (Eq. 4-2):

$$C_{xy}(f) = \frac{|p_{xy}(f)|^2}{|p_{xx}(f)||p_{yy}(f)|} \tag{4-2}$$

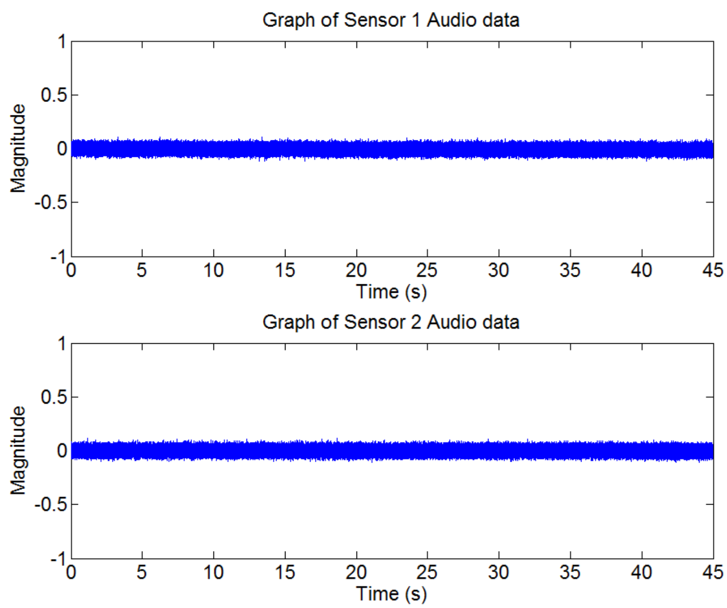
Where, $p_{xx}(f)$ and $p_{yy}(f)$ are the power spectrum densities corresponding to *x* and *y* sound waves and $p_{xy}(f)$ are the cross power spectrum for *x* and *y*.

The magnitudes of the coherence range from 0 to 1 depending on the strength of association of two time series. A coherence magnitude of zero would mean that the time series are statistically independent whereas a magnitude of '1' would mean the two time series as linearly dependent. However, the degree of relationship between time series is often more complex than the magnitude of the "coherence" only. For example, a high value of coherence not necessarily indicates a strong correlations or a very low value of the coherence does not mean that there is no relationship between the time series (McNames, 2005). The definition of the degree of relationship generally varies depending on the application.

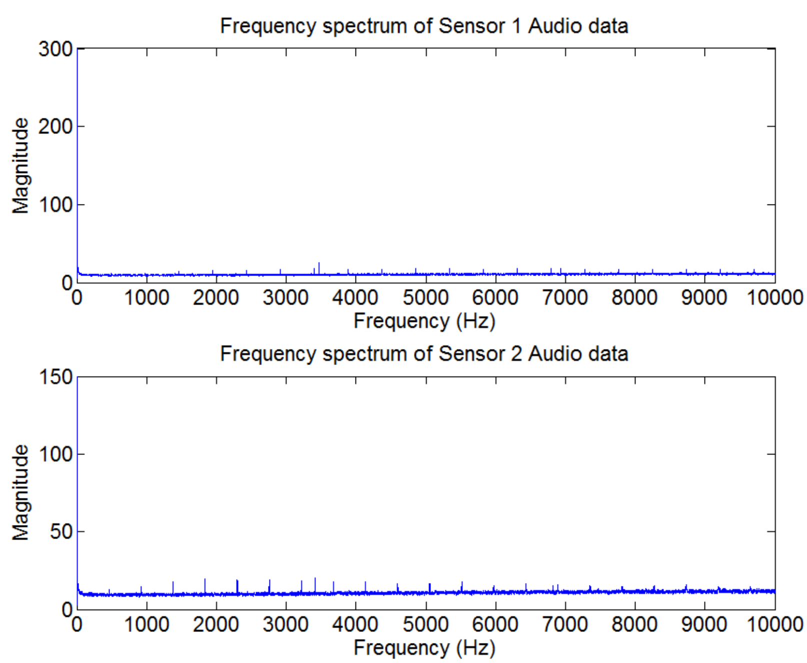
4.5 Test 1: Leak without any Obstacles

In this test, no obstacle was placed in-front of the leak except the bedding sand. However, the bedding sand was washed away by the flowing water from the leak. Water was passed into the pipe from one end through the water line. The flow control valve on the other end of the pipe was closed. Water discharged from the pipe through the leak.

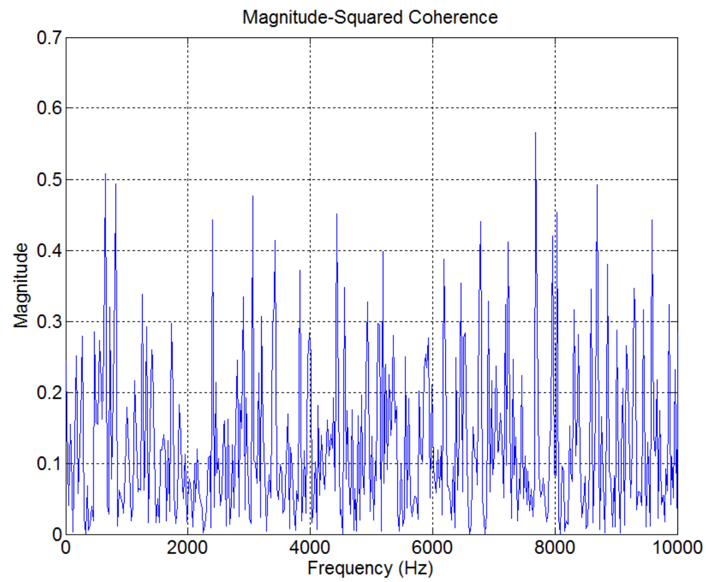
The acoustic signals was measured using the acoustic sensors located near the ends of the pipe. LabVIEW software was used for data acquisition. The measured signals are then analyzed using MATLAB software. The results of the data analysis are shown in Figure 4-6. Figure 4-6(a) shows the amplitudes of the audio signal, which are very less. The leak noise and the background noise are inseparable from the amplitudes in the figure. The frequency spectrum and coherence analysis from the leak noise response spectrum are shown in Figure 4-6(b) and (c), respectively. High value of coherence are not consistently seen in Figure 4-6(c), indicating low degree of association of the signals measured using the two sensors. Thus, the measured noises do not correspond to the leak noise. The cross-correlation function (Figure 4-6d), used to calculate time lag, is also not clearly depicted in the figure. This implies that the leak noise is not detectable in this test without any obstacle in front of the leak. In other word, there was no detectable noise from the leak. This observation is consistent with the findings from Juliano et al. (2013) who reported that the interaction of the escaping water with surrounding material is the major source of the noise from water main leak. In Test 1, there was no surrounding material (obstacle) for interaction of the escaping water.



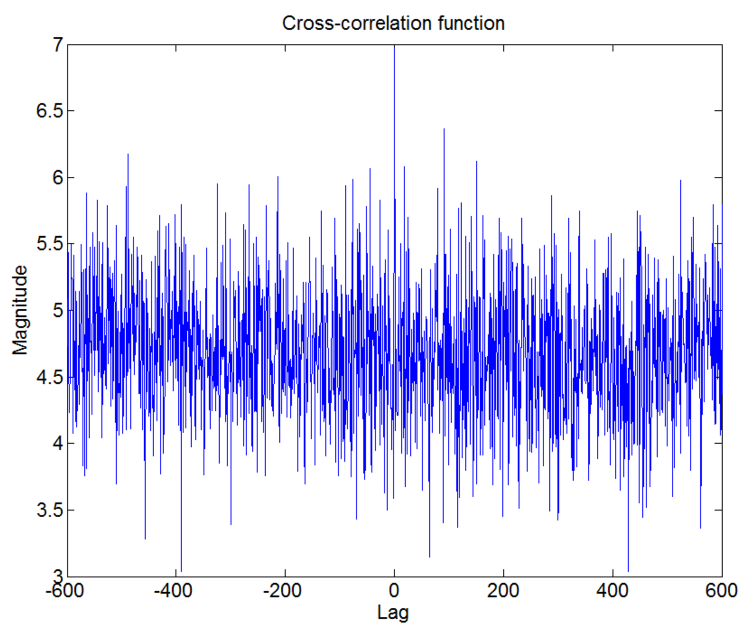
(a) Acoustic signal



(b) Frequency spectrum



(c) Coherence of acoustic noise

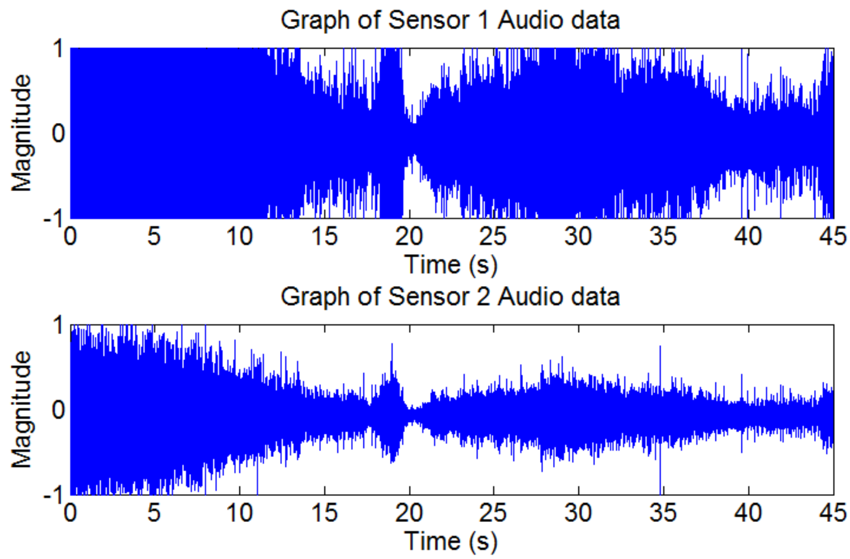


(d) Cross-correlation to get time lag

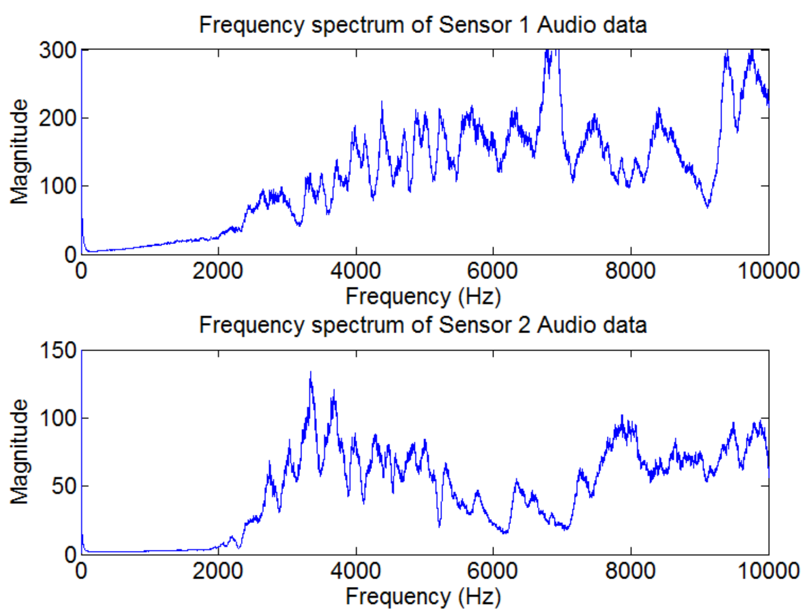
Figure 4-6 Acoustic signal analysis for Test 1

4.6 Test 2: Wooden Block as Obstacle

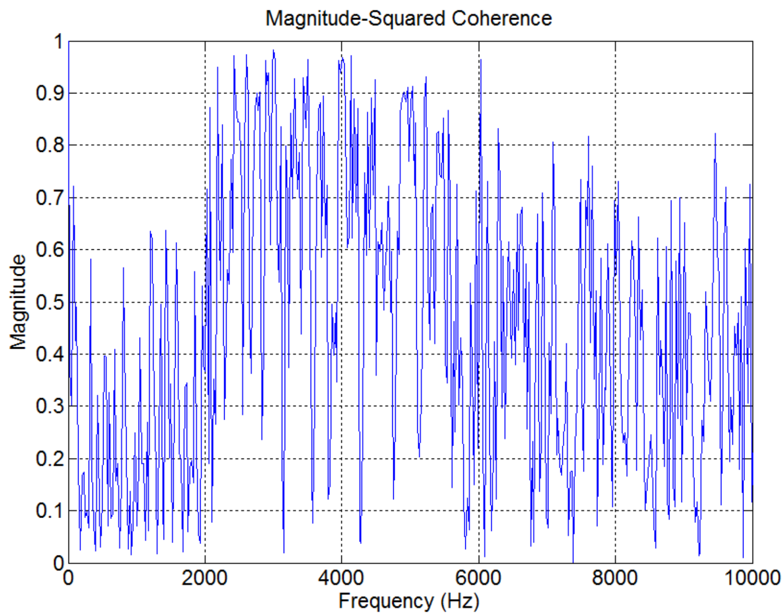
Since no detectable noise was found in Test 1, tests were conducted with obstacles in front of the leak hole to investigate the interaction of the escaping water with surrounding obstacle. In Test 2, a wooden obstacle is placed in front of the leak. As in Test 1, water is entered from one end of the pipe that escapes from the leak. Acoustic noises are measured near the ends of the pipe segment that are analysed. The results of analysis are shown in Figure 4-7. Figure 4-7(a) shows the relative magnitude of the measured audio signals. High magnitude of signals are measured in this test. Response spectrum of the signals are obtained applying Fast Fourier Transform. The resulting frequency spectrum from Fast Fourier Transform is shown in Figure 4-7(b). The frequency of the high amplitude noise (i.e., leak noise) range from 2000 Hz to 10000 Hz in the figure. The result of coherence analysis from the leak noise response spectrum is shown in Figure 4-7(c). The magnitude of coherence is as high as 0.95 in the figure. Magnitude of coherence is higher than 0.75 within the frequency band of 2000 to 7000 Hz. Thus, high correlation exists between the signals measured using the sensors. Similarly, high magnitude of cross-correlation (Figure 4-7d) is also obtained. These observations clearly indicates that the sensors identified a common source of noise, which is the leak noise. From the cross-correlation analysis (Figure 4-7), the time lag of 31 (corresponding Δt =is 0.0012 second) is estimated that provides the leak location as 2.12 m from sensor 1, which is almost the same as the actual distance measured during the test (i.e., 2.15 m). The leak noise is potentially created through interaction of the escaping water with the wooden block.



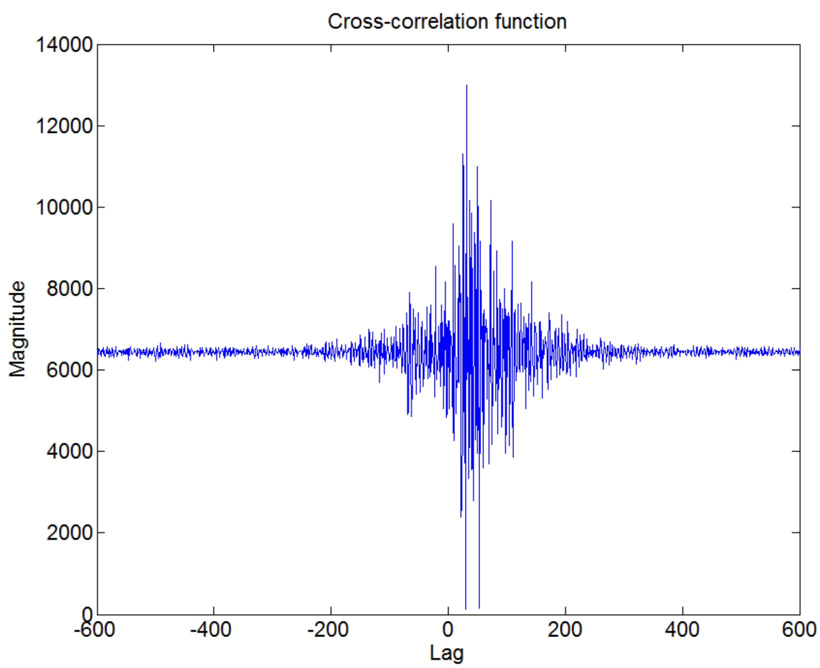
(a) Acoustic signal



(b) Frequency spectrum



(c) Coherence of acoustic noise

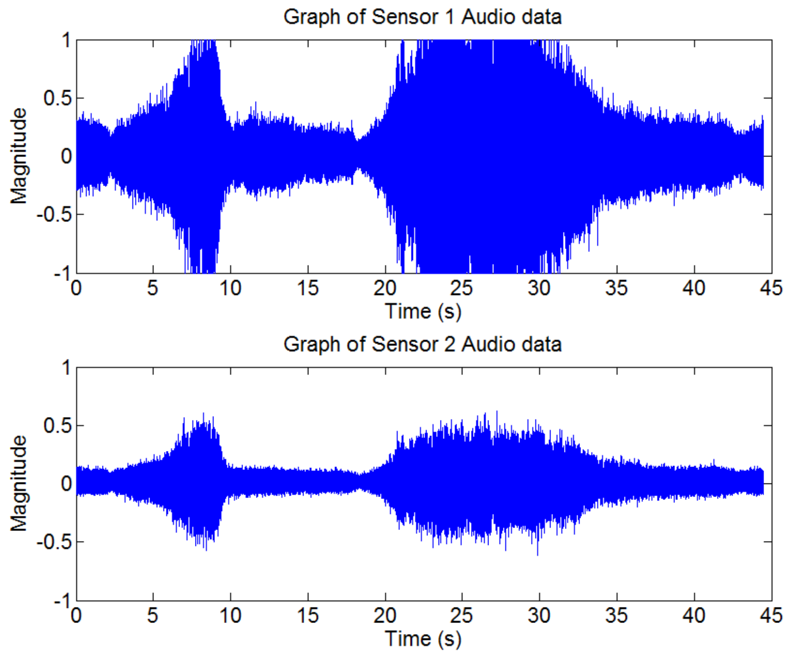


(d) Cross-correlation to get time lag

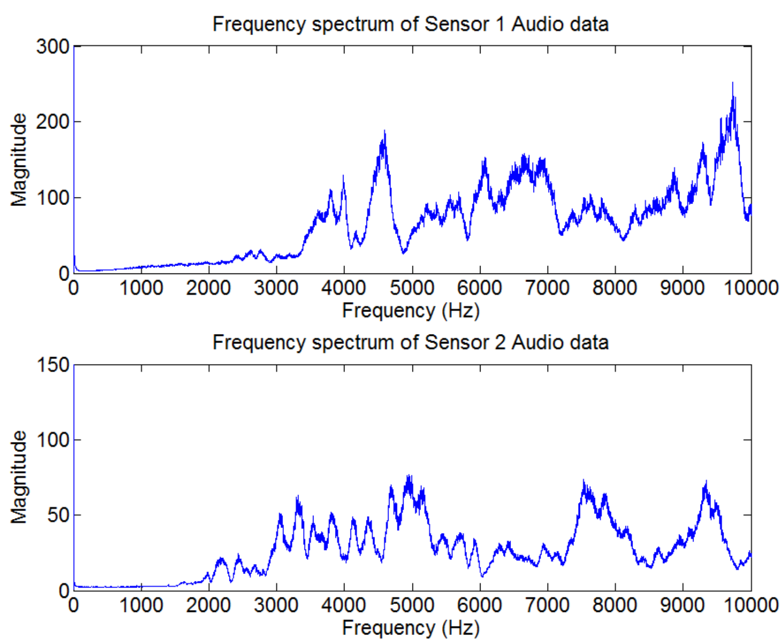
Figure 4-7 Acoustic signal analysis for Test 2

4.7 Test 3: River Bed Stone as Obstacle

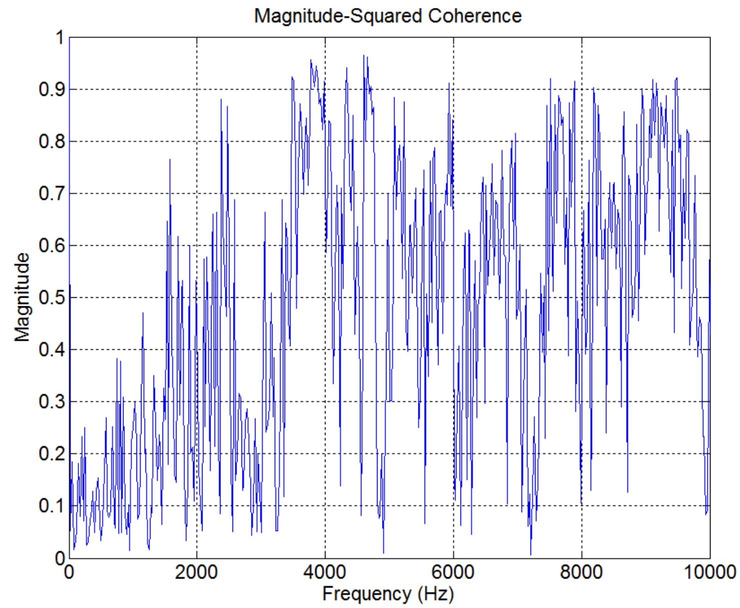
This test is conducted with riverbed stone in-front of the leak hole as the surrounding obstacle. As before, the acoustic signals are measured near the ends of the pipe segment. The results of analysis of the acoustic signals are shown in Figure 4-8. As in the case of Test 2, high amplitude of audio data is obtained in this test (Figure 4-8a). This implies that the interaction of the escaping water with the riverbed stone created a detectable noise. The frequency of high amplitude noise (leak noise) ranges from 2500 Hz to 10000 Hz (Figure 4-8b), similar to those observed in Test 2. The result of coherence analysis are also similar to those observed in Test 2 (Figure 4-8(c)). The magnitude of coherence is as high as 0.95 in the figure. Magnitude of coherence is higher than 0.75 within the frequency band of 2700 to 10000 Hz. High magnitude of the cross-correlation function is also obtained from this test (Figure 4-8d). Thus, the sensors identified a common source of noise (the leak noise), which created through interaction of the escaping water with the riverbed stones.



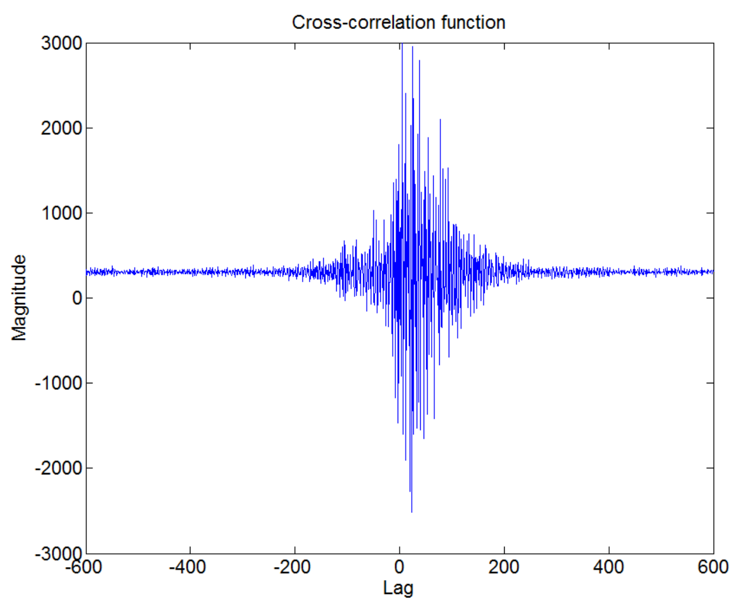
(a) Acoustic signal



(b) Frequency spectrum



(c) Coherence of acoustic noise



(d) Cross-correlation to get time lag

Figure 4-8 Acoustic signal analysis for Test 3

4.8 Conclusion

This chapter presents the results of laboratory tests conducted to develop a better understanding of the source of leak noise and the effects of surrounding conditions on the noise in a ductile iron water main. The study reveals that the leak noise is governed significantly by the surrounding obstacles. No detectable noise was encountered when no obstacle was placed in front of the leak hole. However, the leak noise was detected when obstacles such as wooden block and river stone was placed in front of the leak hole. The finding is consistent with the experimental work of Juliano et al. (2013) who revealed that the interaction of the escaping water with surrounding material/obstacle contribute more significantly to the leak noise.

For the leaks with a surrounding obstacle, frequency of the leak noise ranges from 2000 Hz to 10000 Hz. The frequency band appears to vary depending upon the type of obstacle. A coherence magnitude higher than 0.75 was found to represent a correlation for leak noises between the sensors. The coherence magnitudes were higher within the frequency bands corresponding to the leak noises. Cross-correlation function for leak location determination was also consistently higher.

The study concludes that the acoustic emission method can effectively be used to detect the leak in water mains through proper interpretation of the acoustic signals.

4.9 References

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Chapter 5. Laboratory Facility Development and Acoustic Emission Testing

5.1 Introduction

In order to develop a better understanding of the wave propagation through buried pipe, an experimental investigation under controlled conditions is required. A full scale pipe test would be ideal for the experimental investigation. Full-scale experiments are however complex and expensive. Literature on full-scale testing on acoustic wave propagation is therefore limited. Juliano et al. (2013) tested a 304.8 m long buried steel water pipe for leak detection using acoustic emission technique. They used a 305 mm diameter, welded steel pipeline. Vertical access tubes were used to gain access to 17 different locations along the pipe. In their tests, a range of leak rates from 15.2 mL/s to 16.6 mL/s was successfully detected when the maximum sensor distance was 65.5 m. However, for a sensor distance of 78 m or above, the acoustic emission method was not successful, potentially due to the attenuation of the sound wave. The attenuation characteristics were however not investigated.

Pollock and Hsu (1982), Lee and Lee (2006) and Thenikl et al. (2012) studied attenuation characteristics of acoustic wave propagation during leak detection using amplitude ratio. In this method, noise is recorded at two different locations along the length of the pipe and ratio of the averaged amplitude was taken to determine the exponential law of attenuation. The attenuation characteristic is given by Equation 5-1.

$$\frac{A_1}{A_2} = \frac{e^{-\alpha d_1}}{e^{-\alpha d_2}} \quad \text{(5-1)}$$

Here, A_1 and A_2 are the recorded amplitudes at the respective distances of d_1 and d_2 from the noise source and α is the attenuation parameter. Thenikl et al. (2012) used cross-correlation method to find the distances to leak from two points where the acoustic sensors were placed. The amplitudes measured at these points are then used to determine attenuation parameter, α. They calculated the value of attenuation parameter, α as 0.6 dB/m for a 100 mm diameter pipe. This parameter is then used to determine the leak location for other two cases. In those cases, diameter of the steel pipe without insulation were 100 mm and 300 mm and the AE sensor distance were 52 mm and 46 mm, respectively.

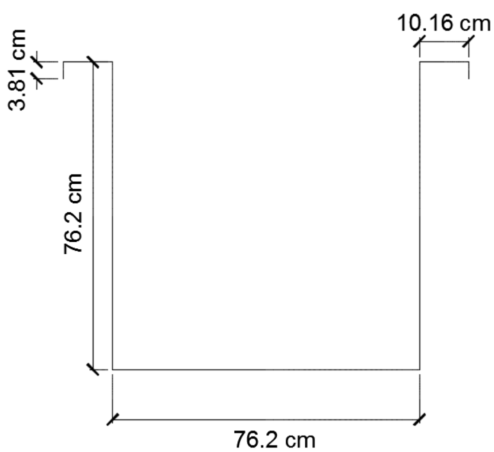
This chapter describes the development of a new laboratory facility and the experiments conducted in the facility to study leak noise propagation through water pipe. Experiments are carried out to investigate the attenuation characteristics of leak noise in fluid filled pipe placed in an open air and a buried condition.

5.2 Design of Laboratory Facility

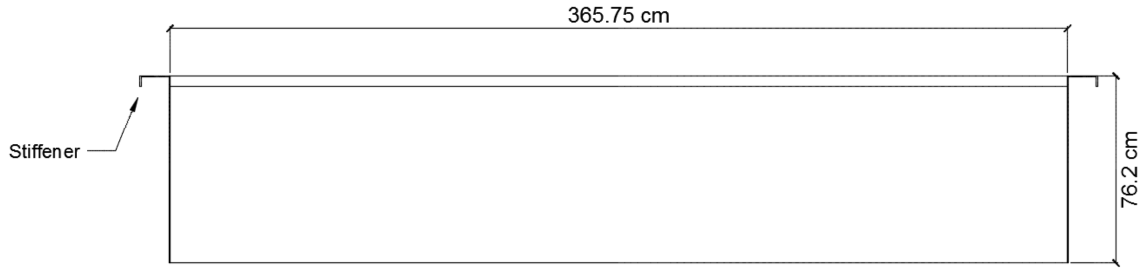
A new test bed has been designed to investigate the acoustic wave propagation through buried pipe. The test bed has been designed to house a pipe buried in backfill soil. A test setup has been designed to maintain a water flow in the pipe and measure the flow of the water.

5.2.1 **Test Bed**

The test bed has been designed to house a typical water main of 152 mm diameter. The length of the test bed was to accommodate a 3 m long pipe. About 0.3 m clear spacing was provided to accommodate fittings at two ends of the pipe segment. Considering the clear spacing, the length of the tank was chosen to be 3.66 m (Figure 5.1(b)). The width of the soil layer surrounding the pipe segment was chosen to be approximately two times of the diameter of the pipe. The width and depth of the test bed is thus 76.2 cm (Figure 5-1(a)).



(a) Cross-section



(b) Longitudinal section

Figure 5-1 Schematic views of the test bed

The test bed is made of aluminium, which is a cost effective material. Aluminium is also less likely to have corrosion. The wall thickness of the bed is designed to carry the lateral load from the soil-pipe system. The thickness of the test tank is 4.76 mm. Horizontal stiffeners are used at the top of the facility. Figure 5.2 shows a picture of the developed test bed.

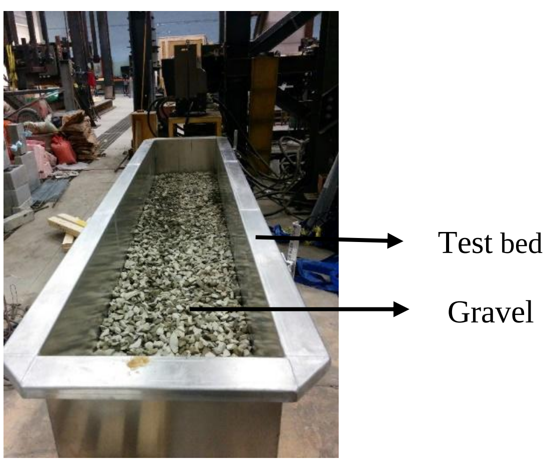


Figure 5-2 Test bed developed for buried pipe testing

Water escaping from the pipe through the leak during tests is expected to be accumulated in the test bed. A facility is designed to drain out the accumulated water. The facility includes a bulb near the bottom of the test bed (Figure 5-3). The bulb is connected to a hose that dispose water to a drain. However, the bulb is found to be insufficient to drain water during the test. A fountain pump is therefore placed inside the tank between wall of test bed and pipe bed to facilitate draining of accumulated water (Figure 5-4). The capacity of the fountain pump is 320 gallons per hour (1211 litres per hour).

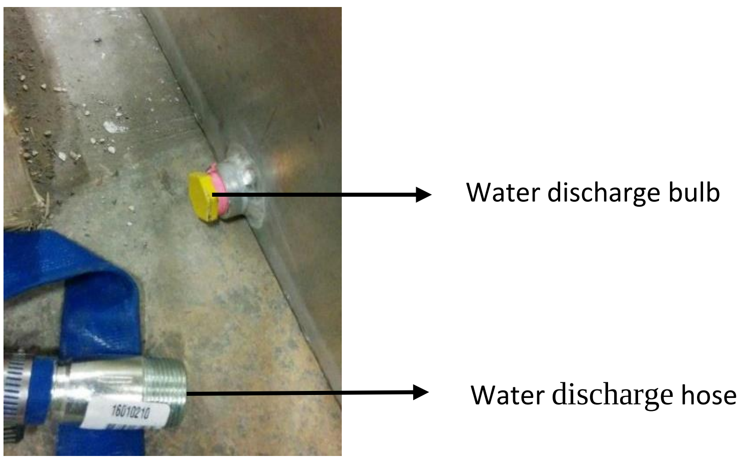


Figure 5-3 Bottom drainage facility

Figure 5-4 Fountain pump

5.2.2 **Backfill Material**

During the preliminary tests, discussed in Chapter 4, sand particles were found to be washed out by the water escaping from leak. Therefore, gravel is chosen as the backfill material for the pipe. Gravel is generally used for backfilling the pipes in the field. To assess the particle size distribution, sieve analysis of the backfill material was conducted according to ASTM standard test method and the results are presented in Table 5-1 and Figure 5-5. Figure 5.5 reveals that the gravel particle dimeters range from about 0.12 mm to 40 mm.

Table 5-1 Data from Sieve analysis

Sieve size	Sieve size (mm)	Mass retained, g	Percent retained, g	Cumulative retained, g	Percent Passing, g
1.5	38.10	0	0.00	0.00	100.00
1	25.40	962.8	60.55	60.55	39.45
3/4	19.05	503.6	31.67	92.22	7.78
1/2	12.70	120.7	7.59	99.81	0.19

3/8	9.53	0	0.00	99.81	0.19
#4	4.75	0	0.00	99.81	0.19
Pan		3	0.19	100.00	0.00
		1590.1			

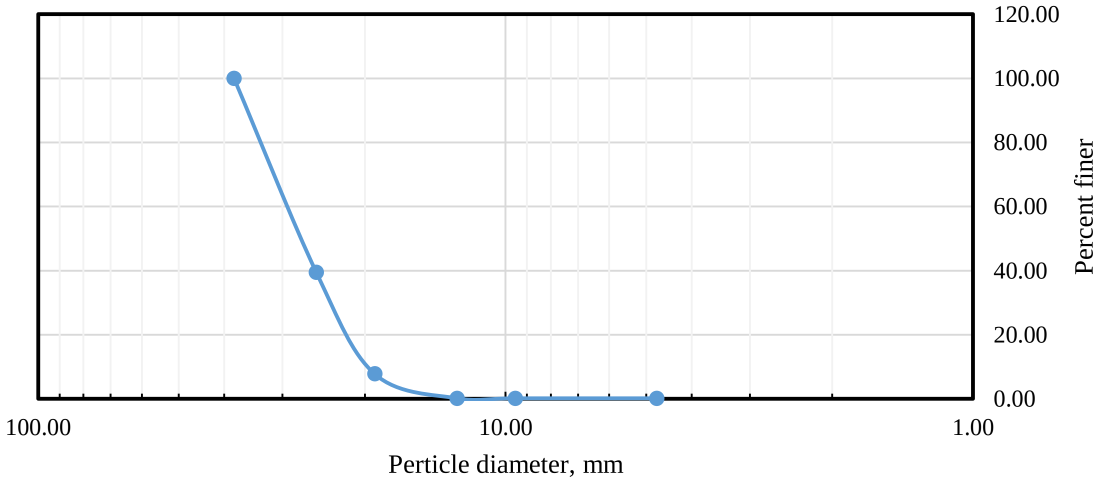


Figure 5-5 Particle size distribution

5.2.3 **Pressure and Flow Measuring Facility**

A multipurpose pressure gauge was attached at both ends of the test pipe to measure the inflow water pressure and outflow water pressure. Based on a typical water pressure in city water mains, pressure gauge with a range of 0-100 psi (0-0.7 MPa) is chosen. Figure 5-6 shows the pressure gauge used. The pressure gauge was manufactured by McMASTER-CARR.

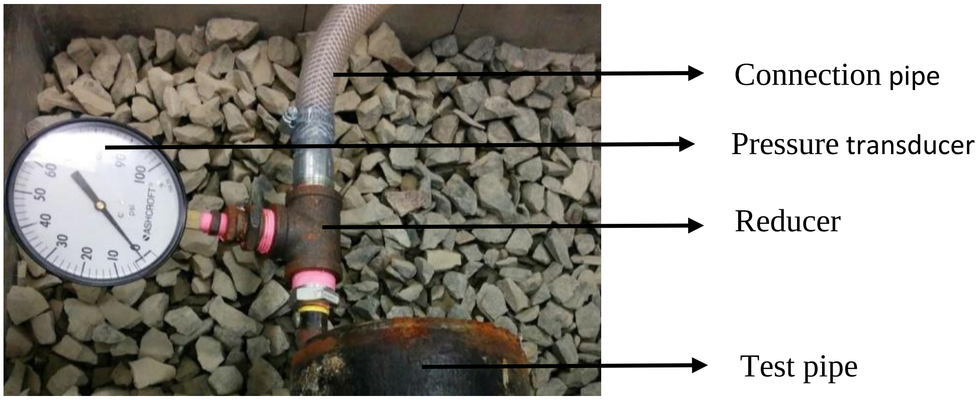


Figure 5-6 Multipurpose pressure gauge

Inline flowmeters are attached at the inlet and the outlet of the pipe to measure the inflow and outflow rate of water flow. The flowmeters have capacity of 1-10 GPM (3.8-38 Liter per min). The flowmeters are also manufactured by McMASTER-CARR. Figure 5-7 shows the inflow flowmeter used.

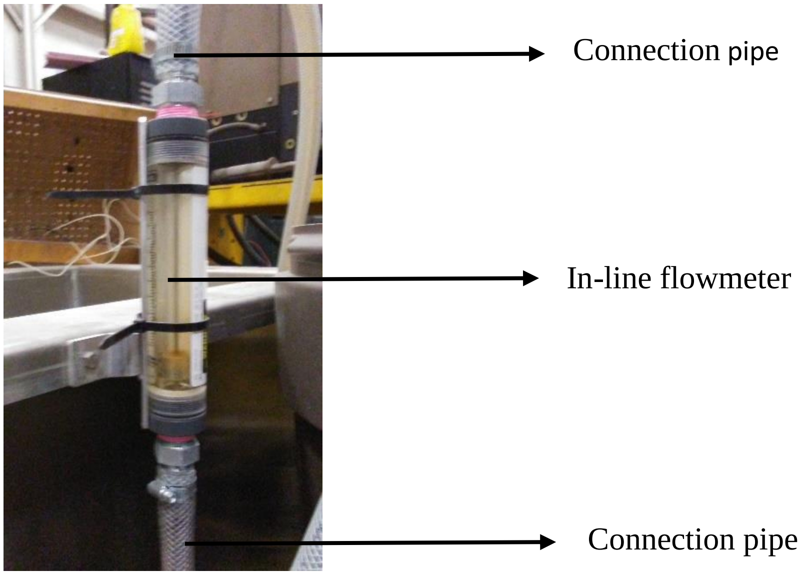


Figure 5-7 Inline flowmeter

5.2.4 **Water Supply**

A 200 litre capacity water tank house the water pump that supply continuous water flow in the pipe within the test bed. Figure 5-8 shows water pump in the water tank. The pump has the maximum flowrate capacity of 3180 GPH (200.6 litres per hour) and the power capacity of 1/3 HP (248.6 watt). The water tank is filled and is connected to a city water line for continuous supply of water. There is a float switch to turn off the pump automatically if the water level goes to a certain low level in the tank.

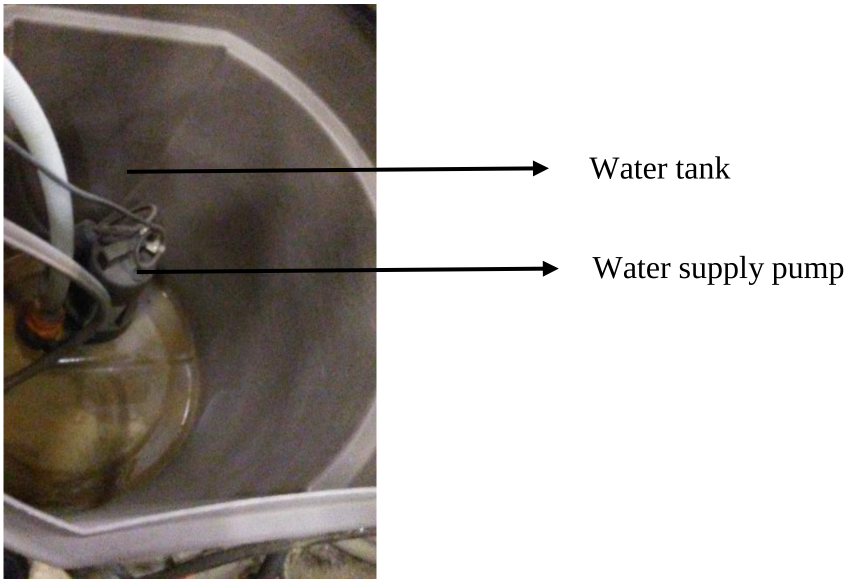


Figure 5-8 Water pump

5.3 Laboratory Test Setup

The laboratory setup includes the test bed that houses a test pipe. The test setup includes a prepared pipe sample, two acoustic sensors, a data acquisition system and a facility to maintain continuous flow of water through the pipe.

Pipe Sample

A pipe sample is prepared that consists of a 15.25 cm diameter ductile iron pipe segment of approximately 3 m long (Figure 5-9). Ends of the pipe segment are capped using two steel plates welded at the ends. Two nipples with 12.7 mm diameter and 7.6 cm length are connected at the ends to facilitate water circulation and the attachment of a flow control mechanism. An artificial leak of 4.75 mm diameter was created on the pipe wall at approximately 70 cm from one of the ends of the pipe.

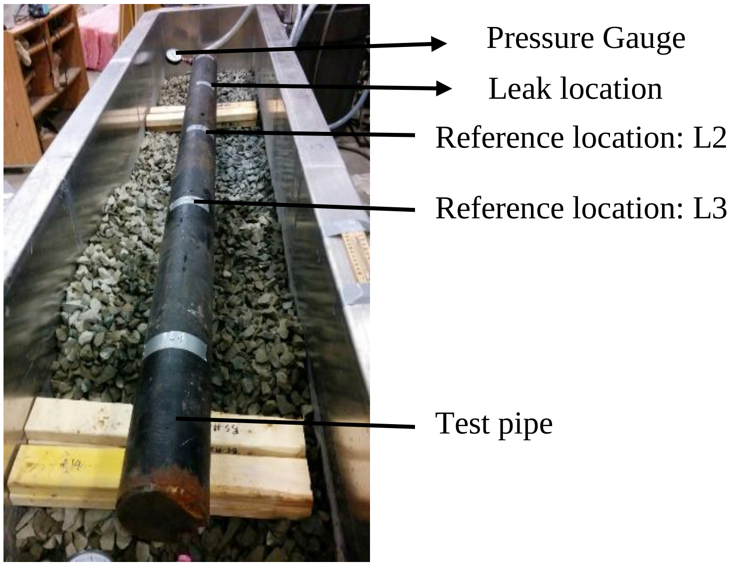


Figure 5-9 Test water pipe

The pipe sample is placed in the test bed (Figure 5-9) and connected to the facility developed to maintain water flow through the pipe in a loop (Figure 5-11). Water from the tank enter to the pipe from one end which is collected from the other end back to the water tank. During the test, the water flow rates and pressures are measured using inline flow-meter and pressure gauge, respectively. The difference between the inflow water and outflow water, measured by the flowmeters, provide the water loss through leak. Figure 5-10 shows a schematic view of the laboratory test setup. Two acoustic sensors are placed at two known locations to measure acoustic signals.

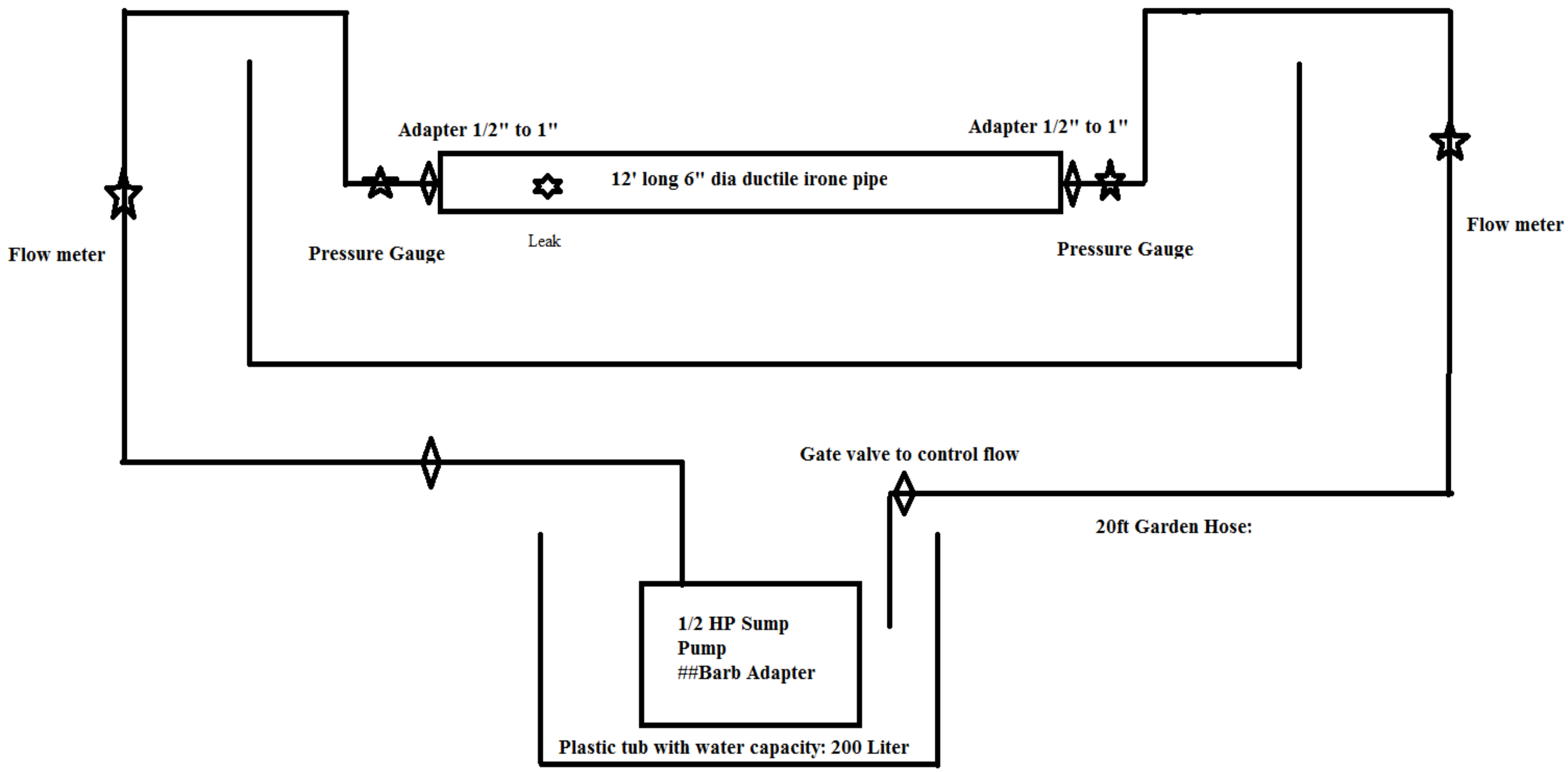


Figure 5-10 Schematic laboratory setup

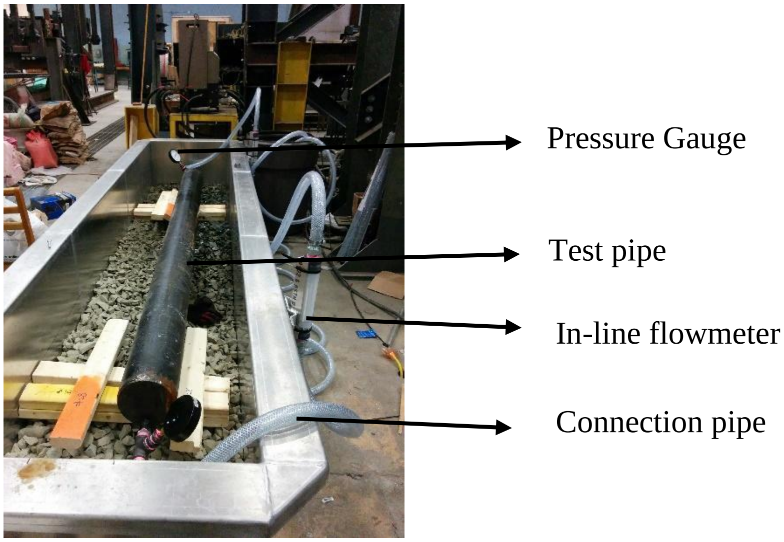


Figure 5-11 Physical connections of the test pipe

The acoustic emission measurement points are at 60 cm (point L2) and 120 cm (point L3) from the leak in the flow direction (Figure 5-12).

Figure 5-12 Acoustic signal measurement points

Sensor

Two acoustic sensors from Physical Acoustics with a frequency bandwidth of 1 to 30 kHz and resonance frequency of 20 kHz are used in this research (Figure 5-13). High sensitivity and low-noise input capabilities make this sensor suitable for recording acoustic signals from leaks in water main.

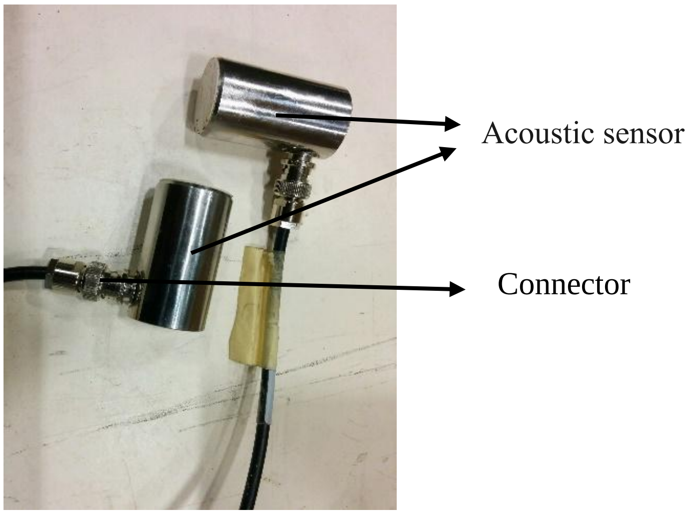


Figure 5-13 Acoustic sensor

Data Acquisition System

The data acquisition system consists of a Data acquisition (DAQ) module and a personal computer equipped with LabVIEW Signalexpress software (Figure 5-14). The NI 9218 is connected with personal computer using USB cable. The sensors are connected to the system using NI 9982D screw terminal block. The data acquisition system is discussed in more details in Chapter 3.

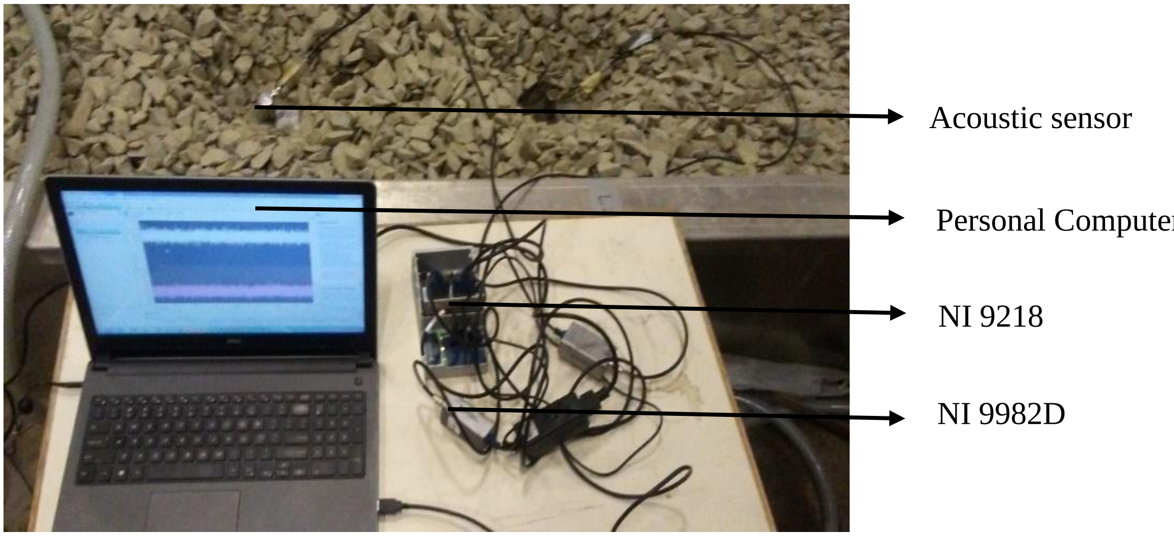


Figure 5-14 Data acquisition system

5.4 Test Program

A test program is designed to investigate the effect of surroundings on the attenuation behaviour of acoustic leak noise through buried water mains. Tests are conducted for a test pipe in the air and the pipe buried in crushed stone (Figure 5-15).

(a) Pipe in air

(b) Pipe buried in crushed stone

Figure 5-15 Test program

5.5 Laboratory Testing

Five tests have been conducted with varying inflow rate. The acoustic signal at reference points have recorded at 25641 data/sec using the LabVIEW Signalexpress software. The signals are stored in a personal computer (PC). The data are then exported to text file and interpreted using MATLAB software. The MATLAB program converts the data to sound wave and store in the PC. This sound wave is then analyzed to obtain the frequency spectrum.

5.6 Pipe in Open Air

In this test, pipe was placed in open air. Water was passed into the pipe from the one end, as shown in Figure 5-16. The flow control valve on the other end of the pipe is opened to maintain the water flow through the pipe. During the test, water escape from the pipe through the leak. The inflow rate of water is measured to be 8.8 gallons per min (33.31 litres per min) while outflow rate is measured to be 4.0 gallons per min (15.14 litres per min). The water loss is thus 4.6 gallons per min (17.4 litres per min). The water escaping from the leak hit the wall of the tank which is 30 cm away from the leak (Figure 5-17). The leak noise is recorded from two locations, L2 and L3 (Figure 5-12).

Figure 5-16 Pipe in Air

Figure 5-17 Water escaping through leak

Figure 5-18 shows the frequency spectrum of the signals measure at locations L2 and L3. The frequency spectrum is obtained based on fast Fourier Transformation using

MATLAB. In Figure 5-18, dominant frequency appears to range from 2500 Hz to 10000 Hz. The amplitude of the noise at frequencies below 2500 Hz is relatively low compared to amplitude within the frequency range between 2500 Hz to 10000 Hz. Frequency spectrum of signal measured at L2 is higher than frequency spectrum of signal measured at L3. L2 is closer to the leak (the noise source), while L3 is farther from the noise source. It indicates that the signal is attenuated from L2 to L3.

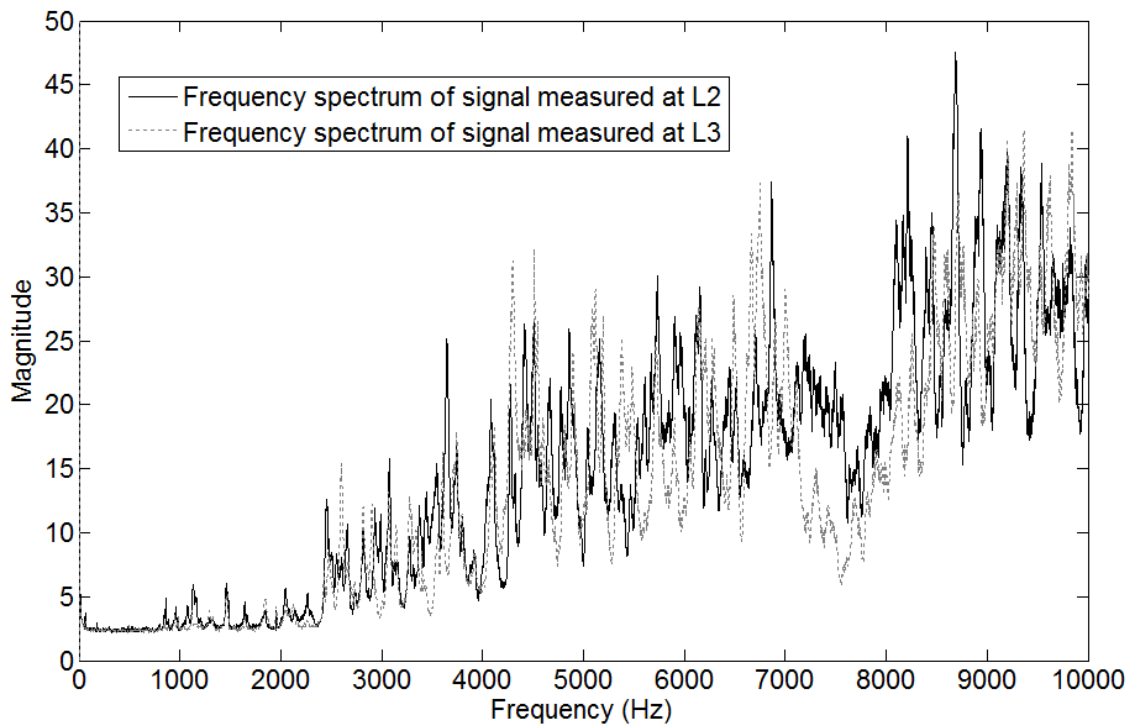


Figure 5-18 Frequency Spectrums of leak noise from pipe placed in open air

The attenuation characteristics over a frequency range from 0 Hz to 10000 Hz are calculated by dividing the amplitude of the frequency spectrum of the two points. The ratio between two spectrums is shown in Figure 5-19. Here A0 is the amplitude of the spectrum from location L2 and A1 is the amplitude of the spectrum from location L3.

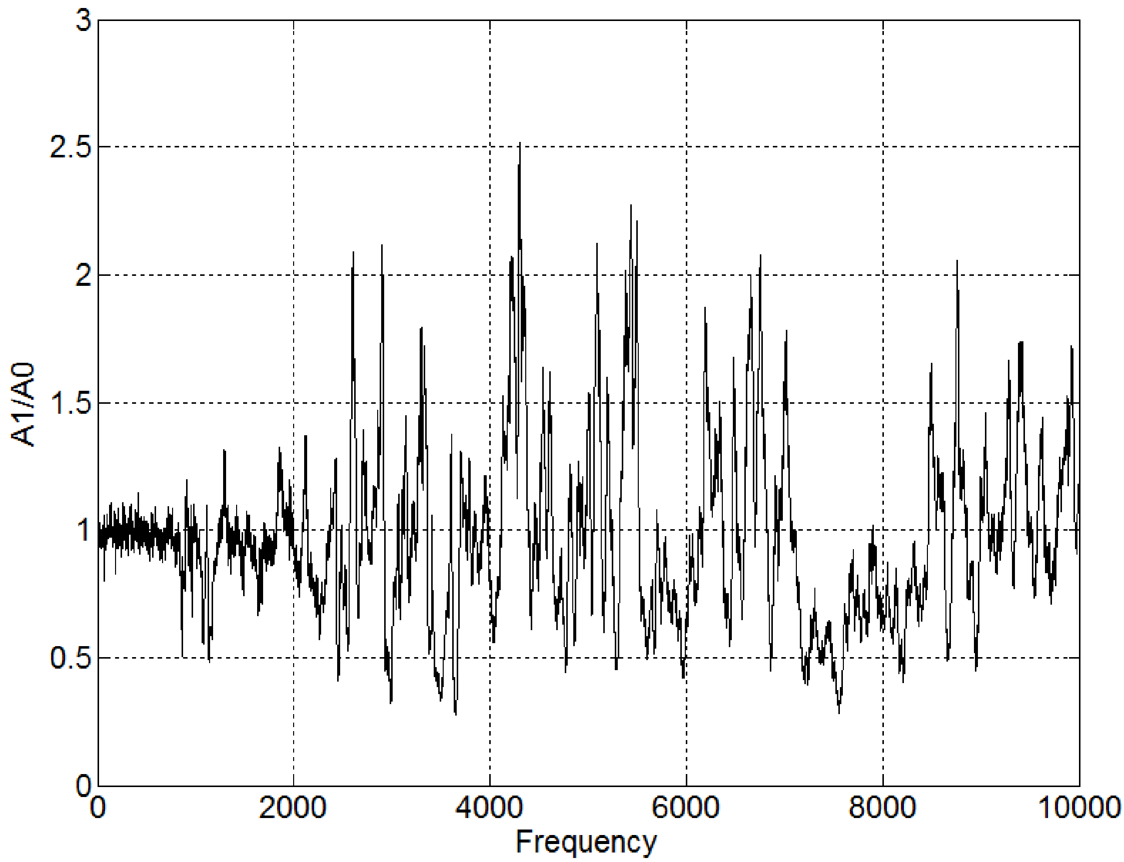


Figure 5-19 Amplitude ratio of leak noise of pipe placed in open air

The noise in the frequency spectrum ratio in Figure 5-19 is attributed to the noise in frequency spectrum diagram (Figure 5-18). The noise in the frequency spectrum ratio is cleared using 100 Hz point moving average as shown in Figure 5-20. In Figure 5-20, the ratio of A1/A0 decreases with the frequency. This implies that the attenuation of sound wave is higher at higher frequencies.

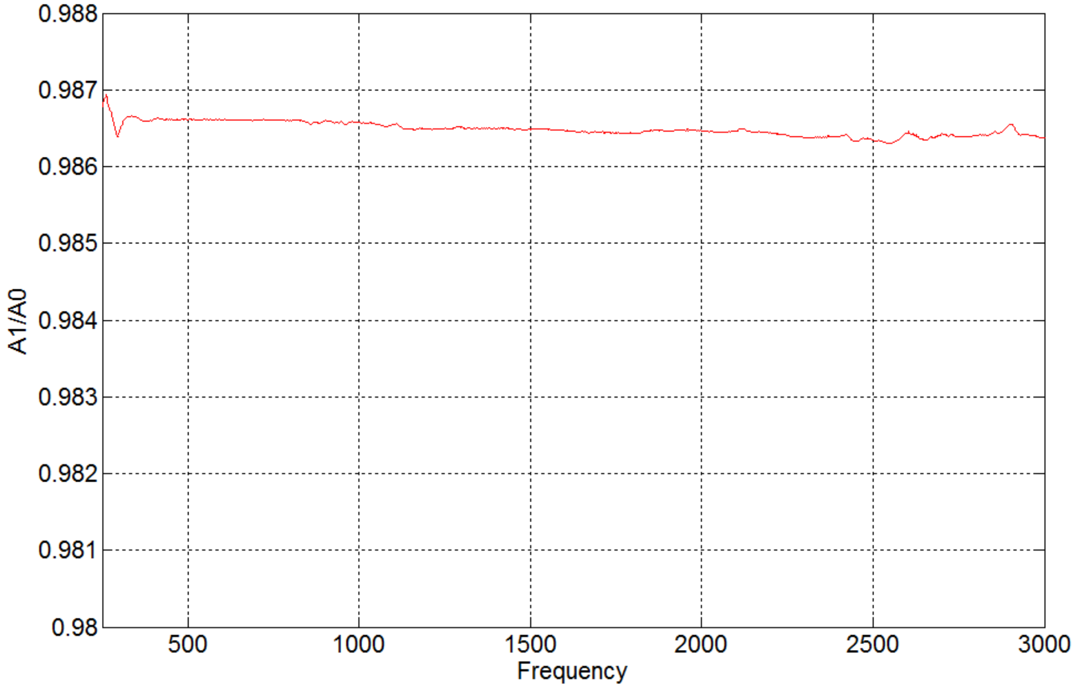


Figure 5-20 Cleared amplitude ratio of leak noise of pipe in air

However the decrease of the amplitude ratio (A1/A0) is very small, which is due to the fact that the sensors are very close to each other.

The attenuation of sound wave under different flow rate of water is studied. Figure 5-21 shows amplitude ratio (A1/A0) of the acoustic wave for different inflow rate. In Figure 5-21, the ratio of A1/A0 is lower for higher inflow rate of water. Thus, the attenuation of leak noise is expected to be higher for water mains with higher inflow water rate.

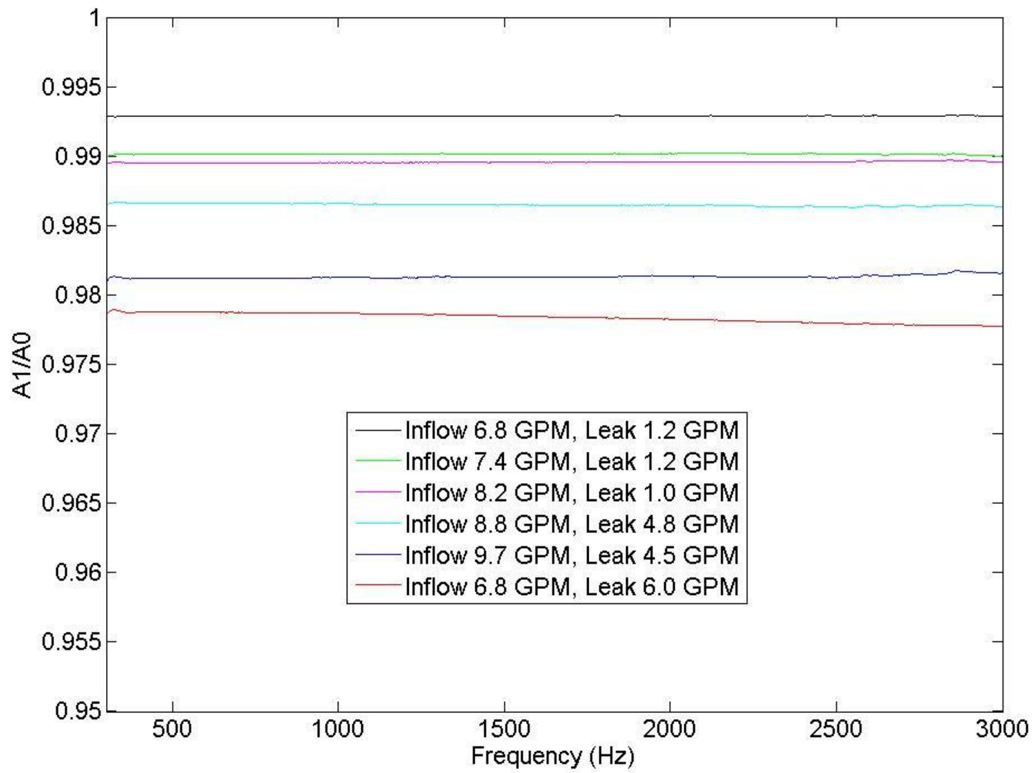


Figure 5-21 Amplitude ratio for different inflow rate for in-air pipe

The rate of change of attenuation of sound wave under different flow rate of water is studied. Figure 5-22 shows amplitude ratio (A1/A0) of the acoustic wave for different inflow rate at three different frequencies. Effect of the frequencies appears to be insignificant on the amplitude ratio. However, the ratio decreases with the increase of the inflow water rate. The rate of decrease increases beyond an inflow rate of 8.4 gallons per minute (31.8 litres per minute). At a flowrate of 6.8 gallons per minute (25.74 litres per min), the amplitude ratio is about 0.993. At a flowrate of 9.7 gallons per minute (36.71 litres per min), the amplitude ratio is 0.981. The amplitude ratio change per gallons-per-minute is 4.13e-3. Based on the amplitude ratios, the attenuation parameter (α) is calculated to be 0.012dB/m and 0.032dB/m, respectively. This parameters are much less than the parameter calculated in Thenikl et al. (2012).

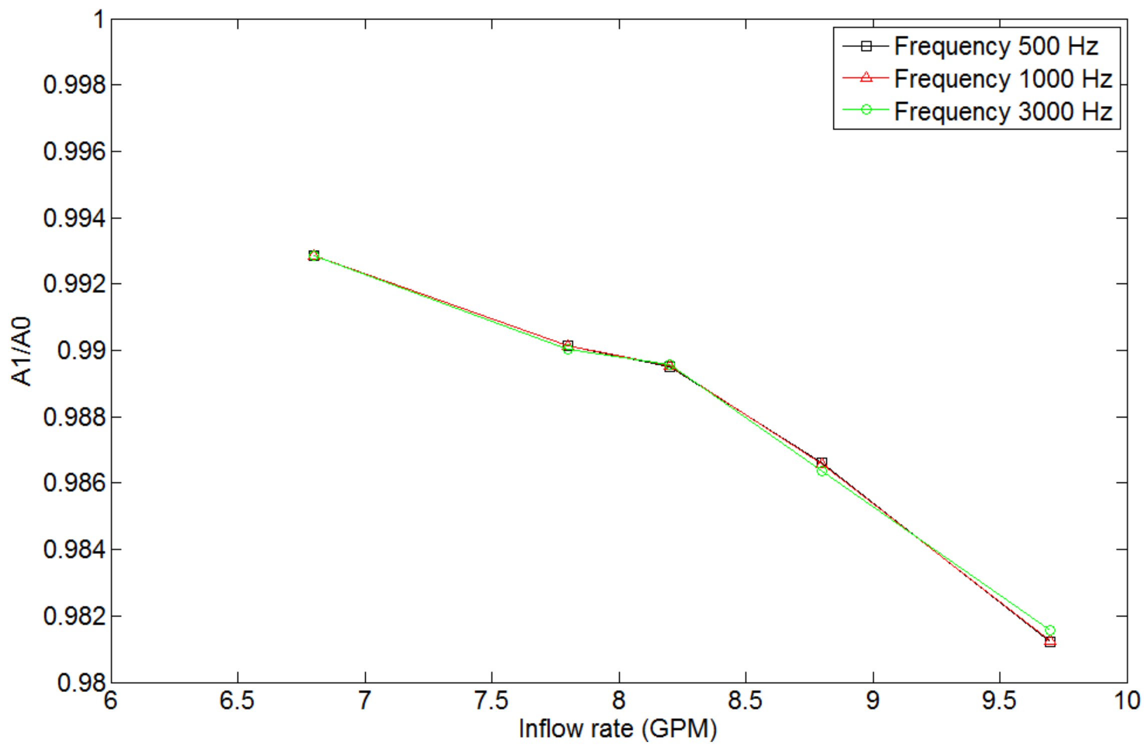


Figure 5-22 Amplitude ratio for different frequencies

5.7 Pipe Buried in Crushed Stone

Tests are conducted to study the attenuation characteristic of acoustic wave for pipeline buried in crushed stone. In this case, water escaping through the leak hit the surrounding crushed stone. As before, the leak noise was recorded at two locations (L2 and L3). The acoustic noise is then analyzed.

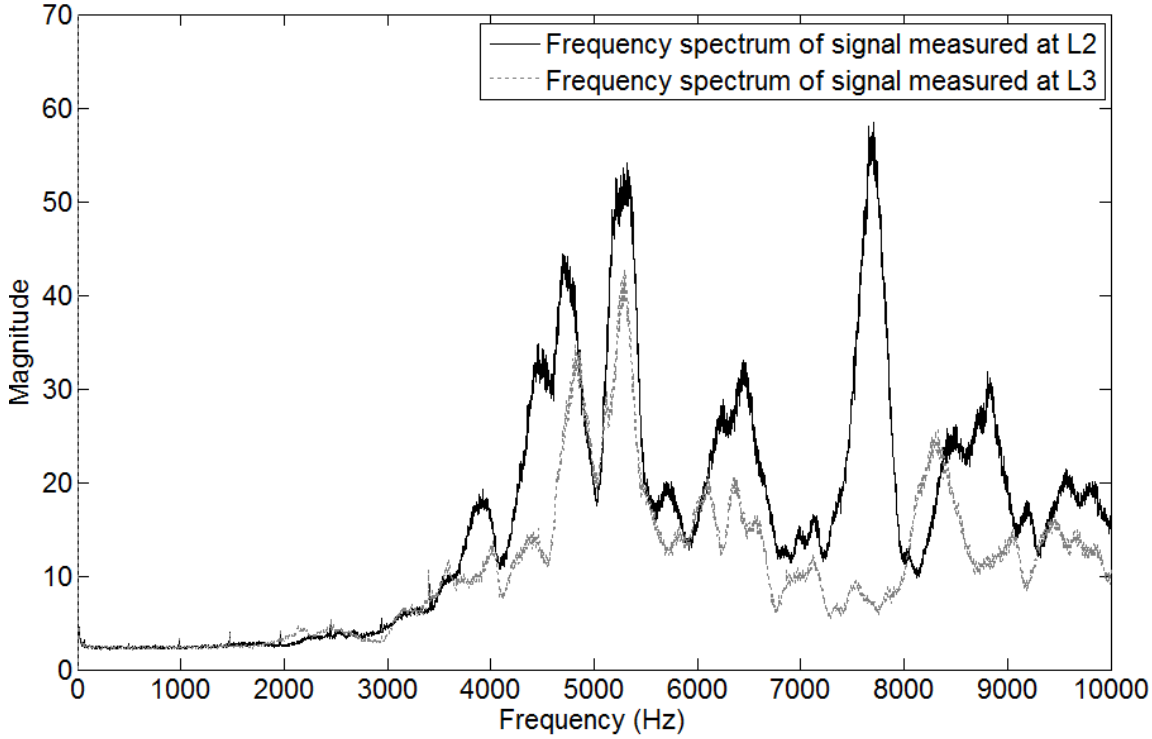


Figure 5-23 Frequency Spectrum of leak noise from pipe in buried condition

The frequency spectrum of the acoustic wave for the pipe buried in crushed stone is provided in Figure 5-23. This frequency spectrum is somewhat different from the frequency spectrum obtained for the in-air pipe. However, amplitude of acoustic amplitude appears to be dominant with a similar frequency range (3000Hz to 10000 Hz). The attenuation (A1/A0) for the frequency spectrum for this case is provided in Figure 5-24.

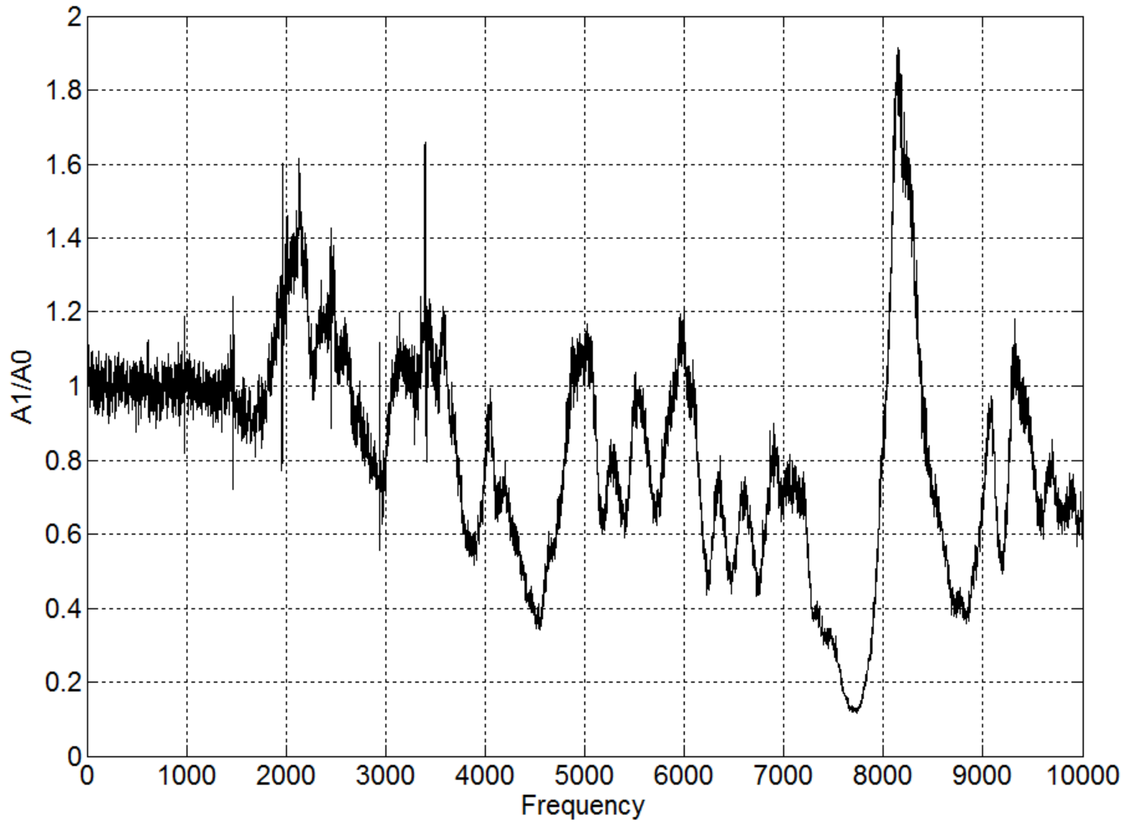


Figure 5-24 Frequency spectrum ratio of leak noise of pipe in buried condition

As in the previous case, noise in the spectrum was cleared using 100 point moving average. The clear spectrum ratio is shown in Figure 5-25, which also shows higher attenuation for higher frequency as in the case of in-air pipe. The attenuation characteristic for an inflow rate of 9.4 gallons per min (35.58 litres per min) and leak rate of gallons per min (15.14 litres per min) is shown in Figure 5-25.

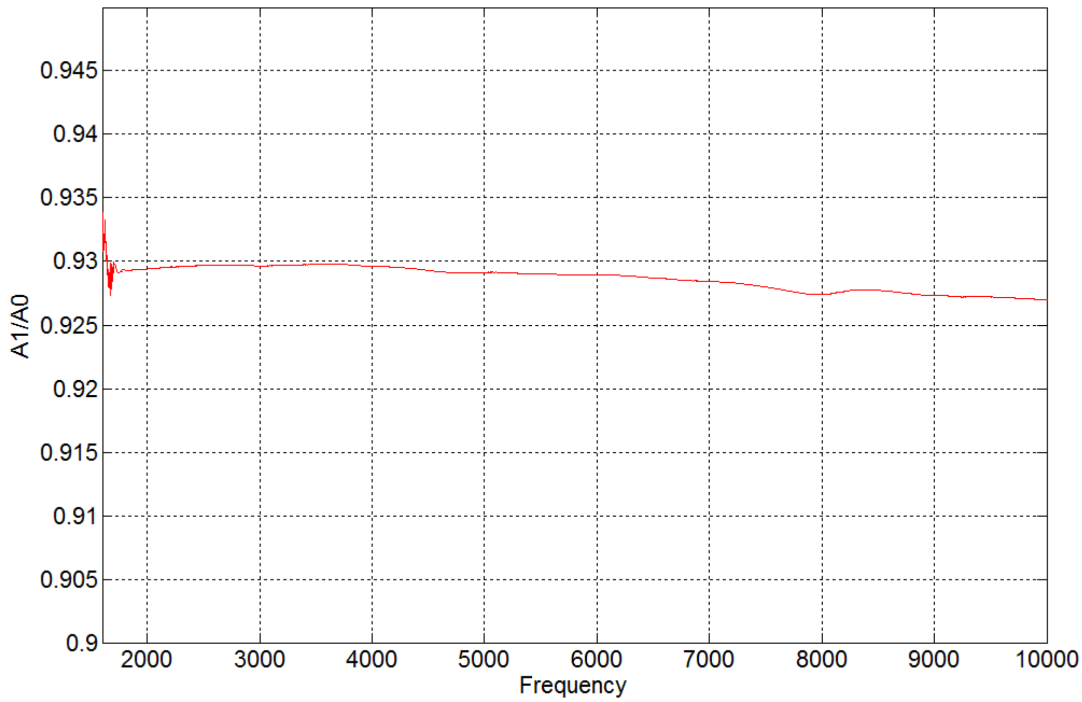


Figure 5-25 Cleared amplitude ratio of leak noise of pipe in buried condition

The attenuation of sound wave under different flow rate of water for buried pipe is studied. Figure 5-26 shows amplitude ratio (A1/A0) of the acoustic wave for different inflow rate for buried pipe. In Figure 5-26, the ratio of A1/A0 is lower for higher inflow rate of water. Similar pattern was seen for in-air pipe. Thus, the attenuation of leak noise is expected to be higher for buried water mains with higher inflow water rate.

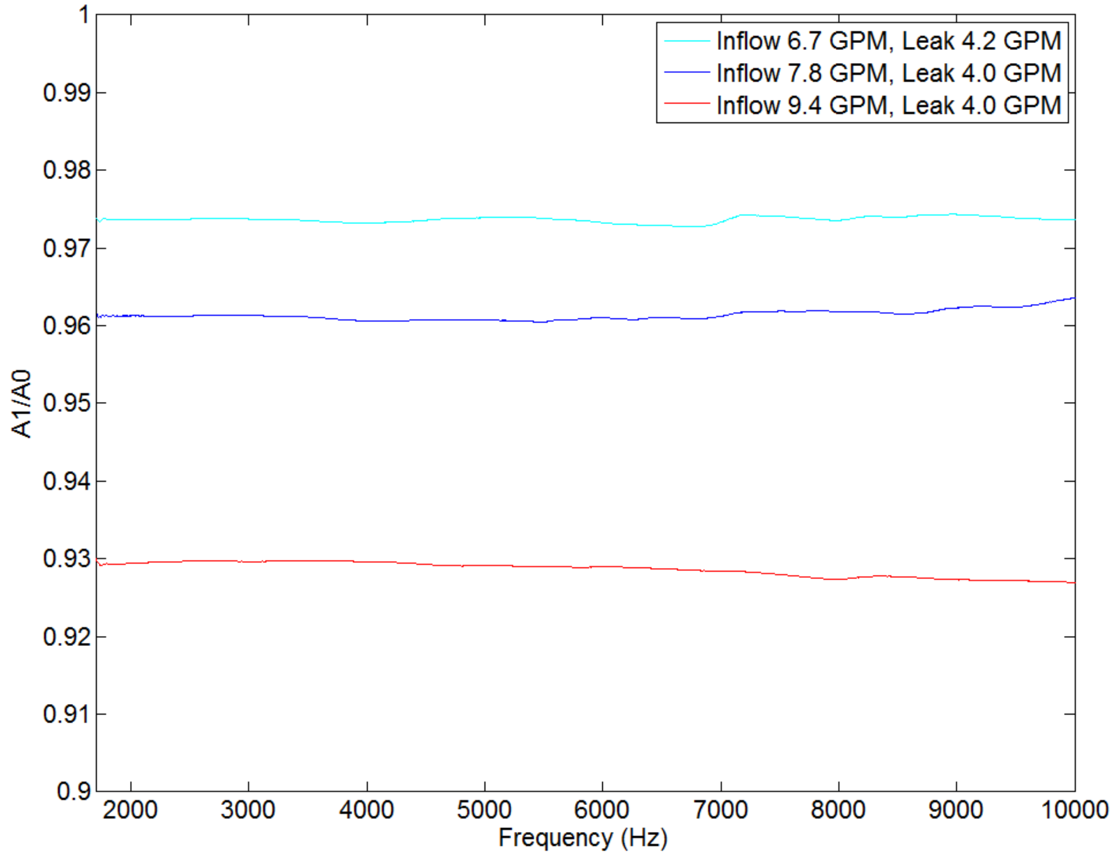


Figure 5-26 Amplitude ratio for different inflow rate for buried pipe

The rate of change of attenuation of sound wave under different flow rate of water for buried pipe is studied. Figure 5-27 shows amplitude ratio (A1/A0) of the acoustic wave for different inflow rate at three different frequencies. As observed for in-air pipe, the amplitude ratio is almost independent on the frequencies considered and decrease with the increase of inflow rate. The rate of decrease is higher beyond 7.8 gallons per minute (29.5 litres per minute). At a flowrate of 6.7 gallons per minute (25.36 litres per min), the amplitude ratio was 0.973 and at a flowrate of 9.4 gallons per minute (35.58 litres per min), the amplitude ratio was 0.93. The amplitude ratio change per gallons per minute is

15.92e-3. Based on the amplitude ratios, the attenuation parameter (α) is calculated to be 0.045 dB/m and 0.12dB/m, respectively, which are lower than the parameter calculated in Thenikl et al. (2012).

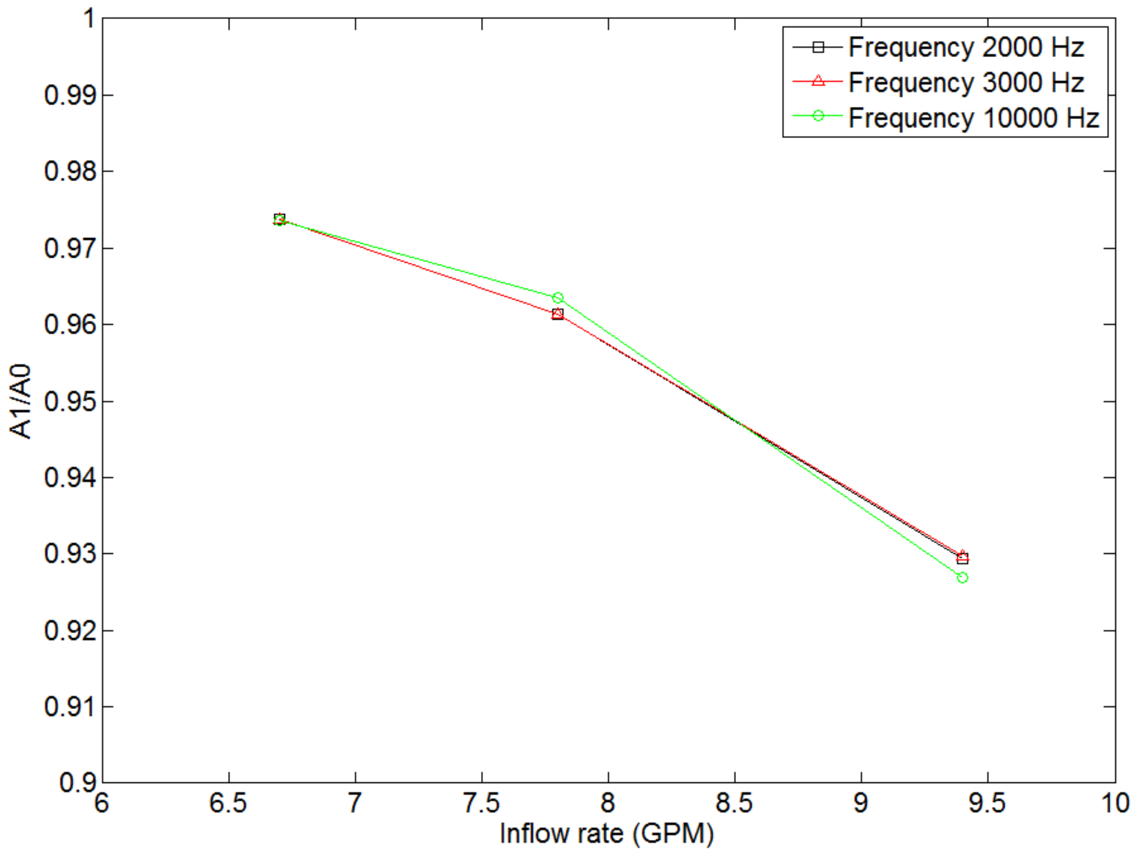
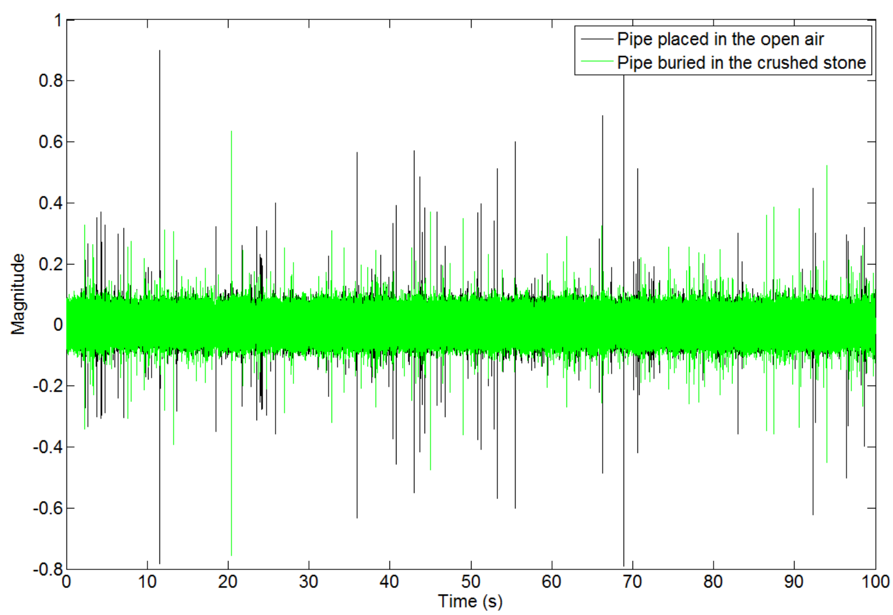


Figure 5-27 Amplitude ratio for different frequencies for buried pipe

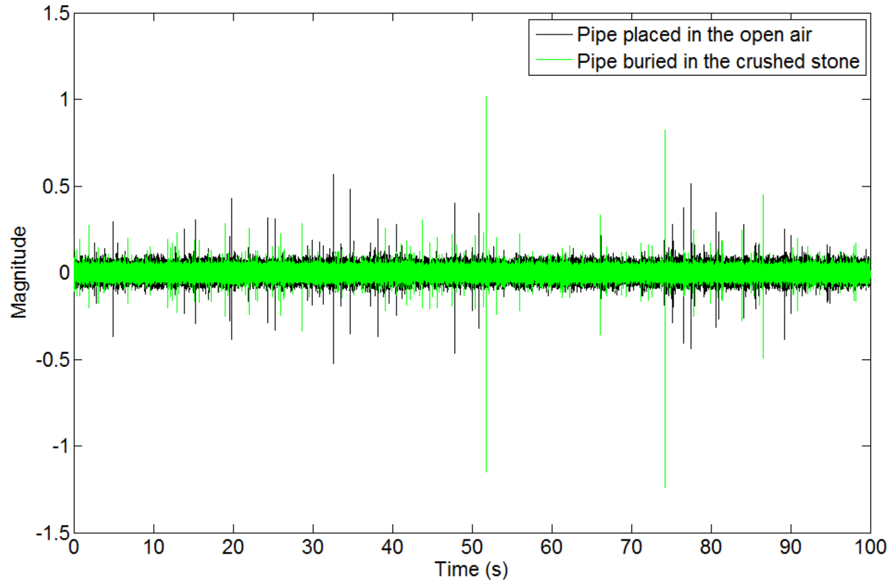
5.8 Comparison for In-Air and Buried Pipes

Sound wave amplitudes are compared for the pipe in air and the pipe buried in crushed stone in Figure 5-28. The black graph represents the sound wave for the pipe placed in the open air and green graph represents the sound wave for the pipe buried in the crushed stone. Sound wave amplitude were almost same for both case at location L2 (Figure 5-

23(a)).The standard deviation of the sound wave were 0.0257 and 0.0258 for pipe placed in-air and pipe buried in crushed stone, respectively. However, at location L3, sound wave amplitude were smaller for pipe buried in crushed stone (Figure 5-23(b)). The standard deviation of the sound wave were 0.0246 and 0.0173 for pipe placed in open air and pipe buried in crushed stone, respectively. L3 is located at 1.2 m from the source of noise, while L2 is located at 0.6 m from the source. Due to surrounding soil, the damping behaviour of pipe have changed which acted as pipe-soil system. The surrounding soil caused higher damping on sound energy and higher dispersion of sound wave which is attributed to the relatively lower amplitude of signal recorded at location L3.



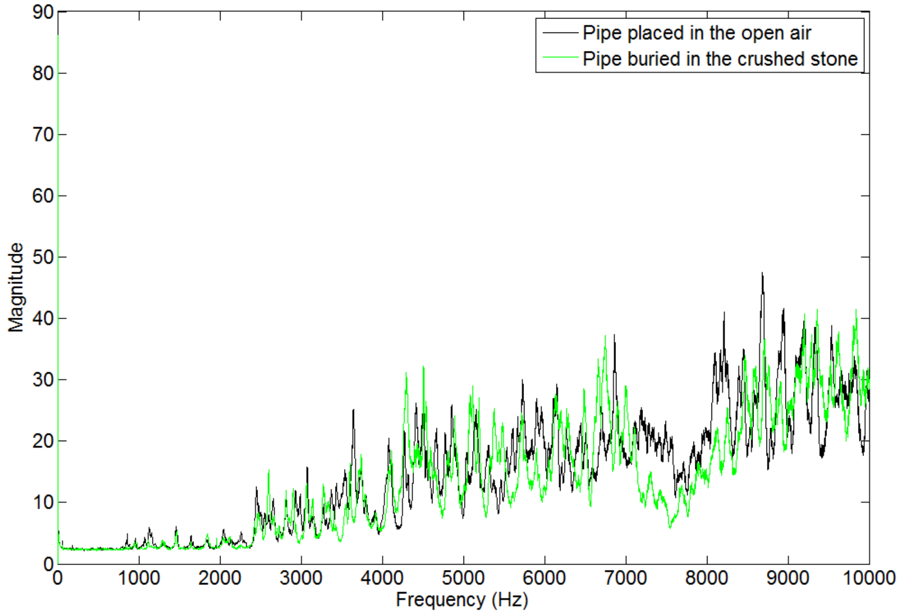
a) Sound wave comparison at location L2



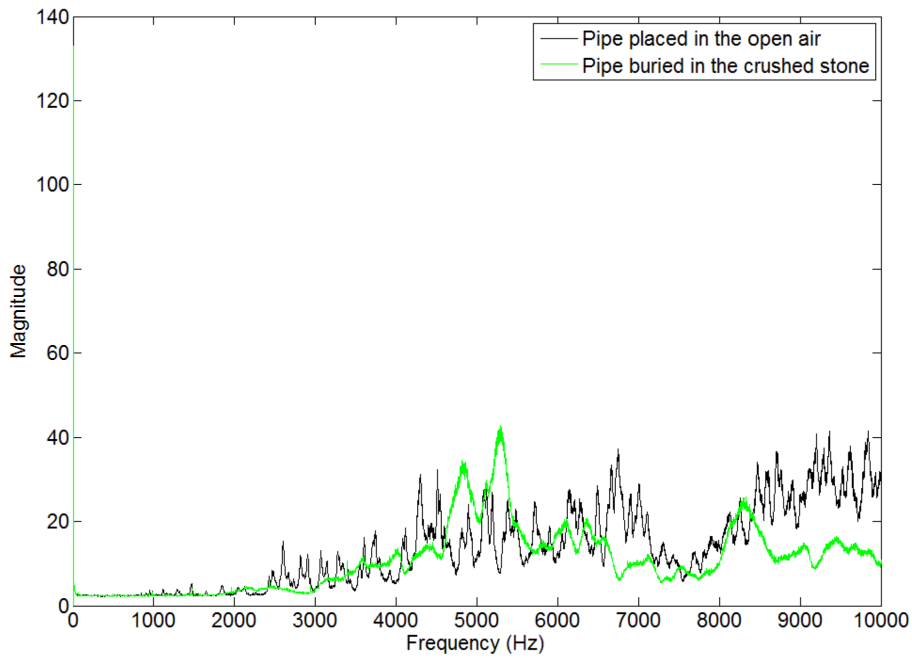
b) Sound wave comparison at location L3

Figure 5-28 Sound wave comparison for pipe placed in the open air and pipe buried in the crushed stone

The frequency spectrum of the sound wave for the two cases are compared in Figure 5-29. The frequency spectrum trend are similar for location L2 for both case as expected (Figure 5-29(a)). For the pipe buried in crushed stone, the amplitudes are somewhat lower except at the frequencies of 4500 Hz to 5500 Hz at the location L3 (Figure 5-29(b)). The amplitude is particularly less at frequencies above 6000 Hz.



a) Sound frequency comparison at location L2



b) Sound frequency comparison at location L3

Figure 5-29 Sound frequency comparison for pipe placed in the open air and pipe buried in the crushed stone

The amplitude ratio for in-air pipe and pipe buried in crushed stone is compared in Figure 5-30. Figure 5-30 reveals that leak noise attenuation is higher for pipe buried in the crushed stone. The ratio A1/A0 is approximately 0.986 for the in-air pipe at the frequency of 2000 Hz, while ratio for the buried pipe is approximately 0.93 at the same frequency.

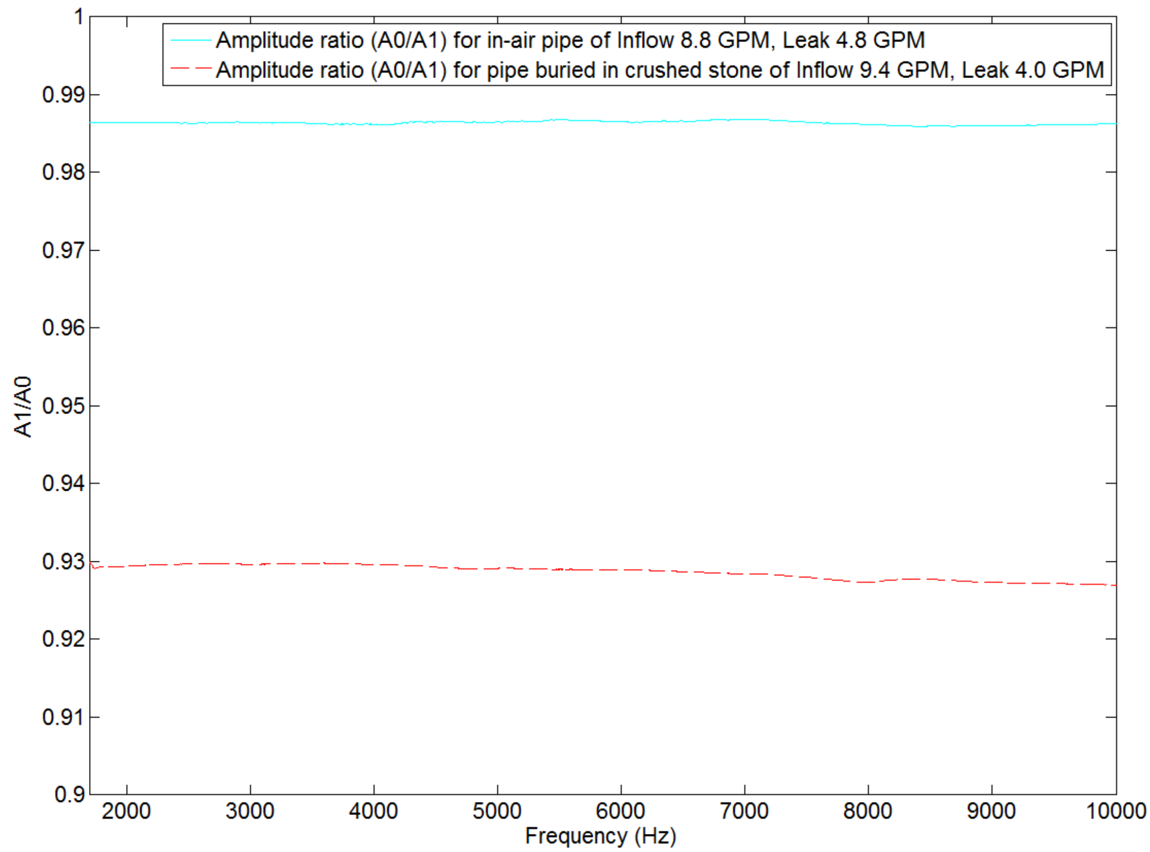


Figure 5-30 Comparison of amplitude ratio (A1/A0) for in-air pipe and buried pipe

The amplitude ratio for in-air pipe and pipe buried in crushed stone for different inflow rate is shown in Figure 5-31. Figure 5-31 reveals that attenuation is higher in buried pipe than in-air pipe as amplitude ratio is lower for buried pipe for different water inflow rate.

For buried pipe, the amplitude ratio range from 0.93 to 0.973, while for in-air pipe, the amplitude ratio range from 0.993 to 0.981.

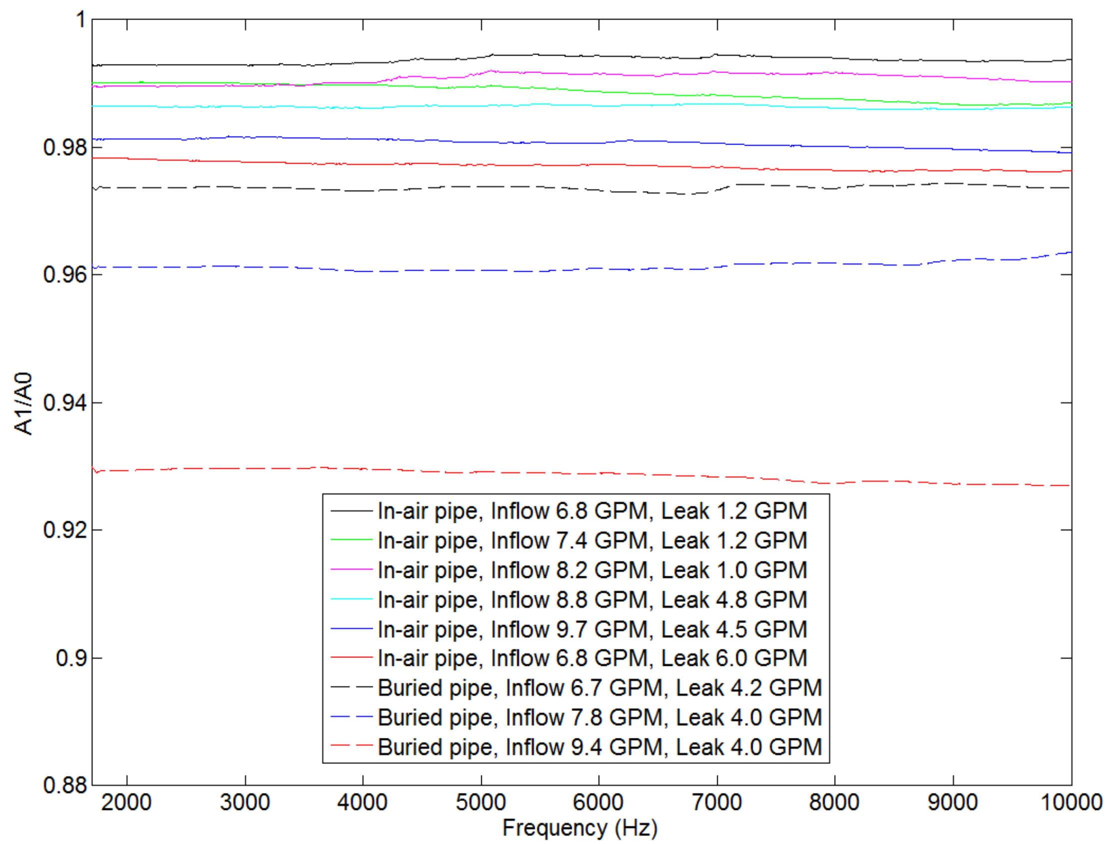


Figure 5-31 Comparison of amplitude ratio for in-air pipe and buried pipe for different inflow rate

The amplitude ratio is compared for in-air pipe and buried pipe for different inflow rate at different frequencies in Figure 5-32. The change in amplitude ratio is 4.13e-3 per gallons per min (1.1e-3 per litres per min) of inflow rate for in-air pipe while the change in amplitude ratio is 15.92e-3 per gallons per min (4.2e-3 per litres per min) of inflow rate for buried pipe. Figure 5-32 reveals that attenuation becomes higher for higher inflow rate and rate of increase of attenuation is higher for buried pipe than in-air pipe, indicating that the inflow rate affect the propagation behavior of the acoustic wave..

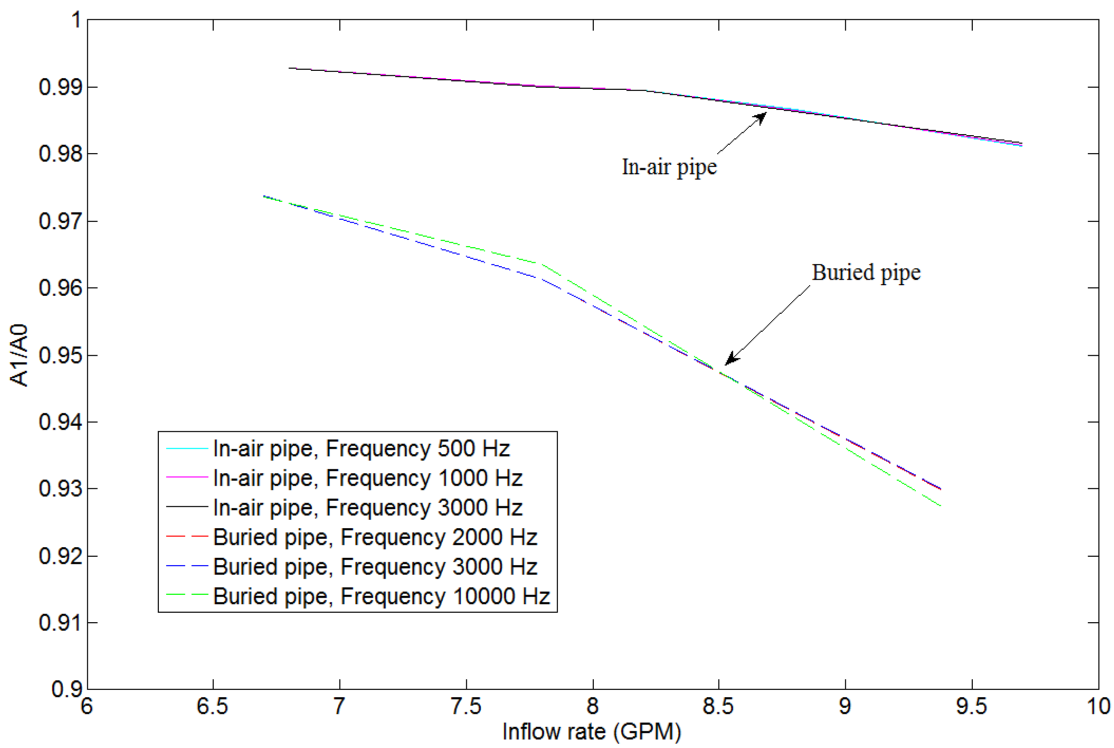
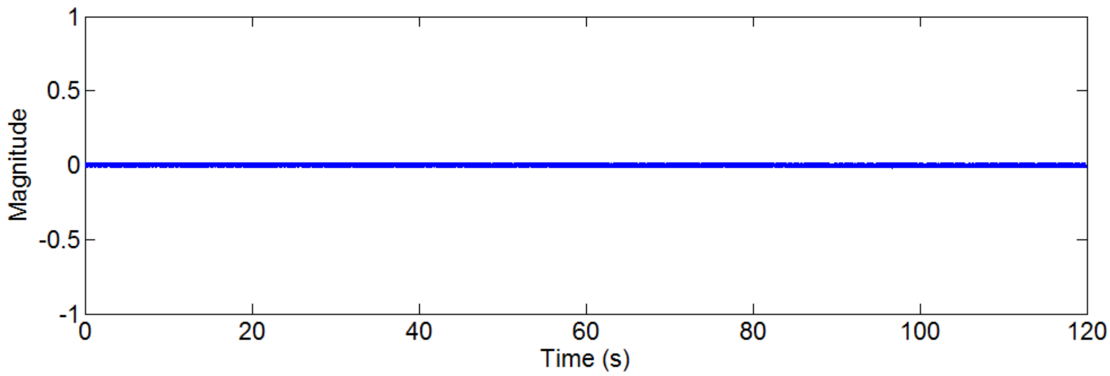


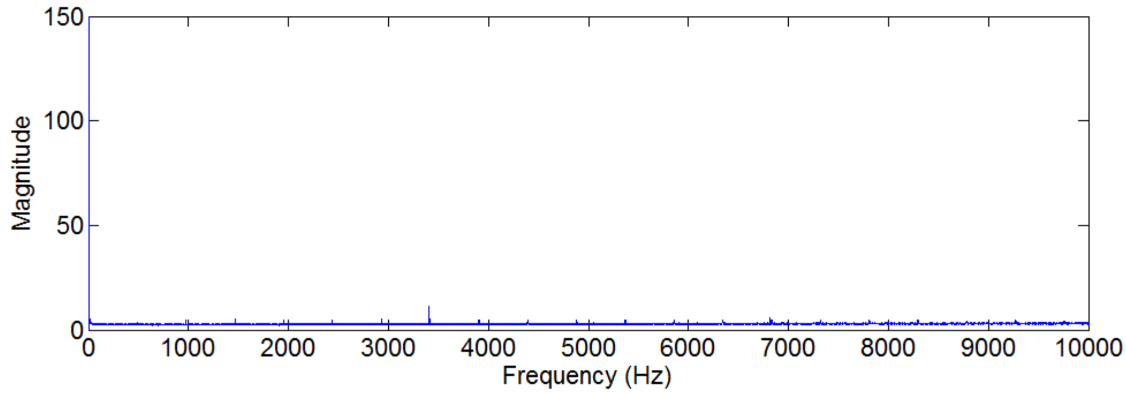
Figure 5-32 Comparison of amplitude ratio for in-air pipe and buried pipe for different frequencies

5.9 Ambient Noise

The noise of environmental sound without the presence of any leak noise is defined as the ambient noise of environment. Ambient noise is measured prior to measuring any leak noise to remove the effects, if any. The sensors are placed in designated locations as in the tests. Ambient noise was measured for no-flow condition and water-flow condition but without any leak. The standard deviation of the ambient noise was measured to be 0.0038. The amplitude of the sound is very low compared with leak noise (Figure 5-33(a)). Sound wave amplitude is almost same for the both cases. There is no dominant frequency available in the frequency spectrum (Figure 5-33(b)). As the sound amplitude same for both cases, it is assumed that the measured acoustic noise is not affected by inherent noise (i.e. pump noise or noise induced due to flow of water in different size of pipes).



a) Sound wave amplitude



b) Frequency spectrum of ambient noise

Figure 5-33 Sound wave features of ambient noise

5.10 Conclusion

A laboratory test facility is designed to investigate the propagation of acoustic wave through water mains. The developed test facility is used to investigate leak noise attenuation through an in-air and a buried pipe. The buried pipe is backfilled with crushed stone. The laboratory study indicates that the leak noise attenuates during propagation of acoustic wave. The attenuation is higher for the high frequency waves. The attenuation also increases with the increase of flow rate through pipe. Between the in-air pipe and the pipe buried in crushed stone, the attenuation is higher for the buried pipe. For a distance of 1.2 m, the ratio (A1/A0) is 0.987 for in-air pipe and 0.93 for pipe buried in crushed stone at a frequency 2000 Hz and inflow rate of 6.7 gallons per minute (25.36 litres per minute). The change in amplitude ratio is calculated to be 4.13e-3 per gallons per min (1.1e-3 per litres per min) of inflow rate and for buried pipe the change in amplitude ratio is calculated to be 15.92e-3 per gallons per min (4.2e-3 per litres per min) of inflow rate. An attenuation parameter (α) is calculated to be 0.032 dB/m for in-air pipe and 0.12 dB/m for buried pipe at the inflow rate of 6.7 gallons per minute (25.36 litres per minute).

5.11 Reference

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Chapter 6. Finite Element Modelling

6.1 Introduction

Acoustic is often used for inspecting, testing, evaluating material and elements for discontinuities in continuum. Acoustic emission method is one of the popular methods used for detecting leak in water mains. In this technique, acoustic noise from leak is propagated through pipe that is received at two access points to the pipe. Successful leak detection using this method depends on the propagation characteristics of the acoustic noise. Noise can be attenuated while propagating through the pipeline. Thus, if the sensors are not located close enough, the leaks may remain undetected. Understanding the propagation behaviour of acoustic wave is therefore very important for determining the distance over which the method would be successful. In this regard, development of analytical and numerical tools are required for the assessment of acoustic wave propagation. Finite element method is a versatile method that could be used for modelling of acoustic wave propagation. However, FE modelling technique for AE is not well developed. Chatoorgoon and zhou (1995) used a finite element software "ABAQUS" to simulate a benchmark experiment conducted by D'Souza and Oldenburger (1964). In the experiments, D'Souza and Oldenburgen (1964) used a water filled straight pipe of 12.268 m long and 12.57 mm diameter. The inlet of the pipe had a fixed input mount for an inflow rate. The other end of the pipe was reduced to an orifice. Water from the orifice discharged to a tank which was open to atmosphere. There were pressure and velocity transducers at the inlet and outlet of the pipeline. During experiments the Reynolds number was 650. Chatoorgaoon and zhou (1995) have used this simple test setup for the simulation. They proposed a prototype volumetric drag formula for turbulent flow for the modelling. Using the modelling approach the resonant frequency was successfully simulated and the normalized pressure change with frequency of that benchmark laboratory test.

This chapter describes a finite element investigation of acoustic wave propagation through water filled pipeline. Laboratory investigations conducted (discussed in previous chapters) are used for evaluation of the FE model. A commercially available finite element package software "ABAQUS" was used. Attenuation of leak noise is modelled using volumetric drag feature in ABAQUS. The effect of volumetric drag coefficient of pipe and water are studied. Finite element model is then extended to study the behaviour of leak noise propagation and attenuation characteristics in a long pipe.

6.2 Theoretical Background of Acoustic Wave

An introduction of acoustic wave formulation is given in this section. The branch of science which deals with all kind of mechanical waves i.e. vibration, sound, ultrasound and infrasound, are designated as acoustics. Acoustic waves are longitudinal waves which propagate by means of adiabatic compression and decompression. In ABAQUS, acoustic medium can be used to model the sound propagation problems (Analysis user's manual, ABAQUS 6.11). Generally, acoustic medium is assumed as elastic medium, generally like as fluid. In acoustic medium, stresses are purely hydrostatic. The pressure is proportional to volumetric strain. The volumetric drag coefficient have effect on the equilibrium equation of acoustic medium. The equilibrium equation for small motions of a compressible, adiabatic fluid is taken to be

$$\frac{\delta p}{\delta x} + \gamma(x, \theta_i)\dot{u^f} + \rho_f(x, \theta_i)\ddot{u^f} = 0 \qquad [1]$$

Here,

p = the excess pressure in the fluid

X = the spatial position of the fluid particle

$\dot{u_f}$ = the fluid particle velocity

$\ddot{u_f}$ = the fluid particle acceleration

ρ_f = the density of fluid

γ= the volumetric drag

θ_i= i dependent field variables such as temperature, humidity of air or salinity of water

The constitutive behaviour of the acoustic medium (usually a fluid) described in ABAQUS as

$$p = K_f(x, \theta_i)\frac{\delta}{\delta x}u^f \qquad [2]$$

Here, K_f is the bulk modulus of the fluid.

A total wave formulation is used for a nonlinear acoustic medium.

6.3 Modelling of Test Pipe In-Air

Numerical simulation of leak noise propagation through the pipe wall is essentially performed by simulation of wave propagation through fluid filled pipeline as an acoustic medium. An incident wave is considered on one end and propagation of this wave through the conduit is analyzed at some reference points.

Axisymmetric finite element analysis is used to simulate the propagation of axisymmetric acoustic wave-modes in the fluid-filled pipe in the air. Damping behaviour of ductile iron and water are considered in this simulation. The effect of the air is not considered for simplification of the model.

ABAQUS/Explicit (version 6.11) is used in the analysis with default viscosity parameters in the software. The default viscosity parameters include linear bulk viscosity parameter of 0.06 and quadratic bulk viscosity parameter of 1.2. Pipe and water are modeled using AC3D8R element from ABAQUS library. AC3D8R is an 8-node linear brick element with reduced integration and hourglass control.

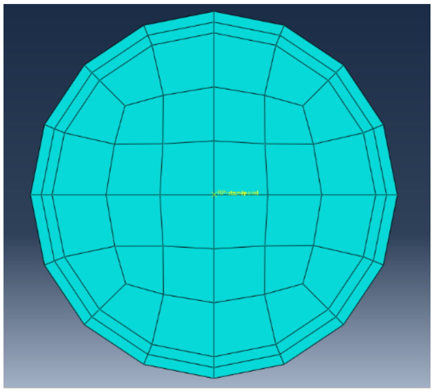
The sound wave speed of 1200 m/s is used based on the results of field investigation discussed in Chapter 3. The incident wave frequency of 3000 Hz is considered. Based on the speed and the frequency, the wavelength is calculated to be 0.4 m. Element length is thus chosen as 0.04 m, which means there are 10 elements in one wavelength. The dilatational wave velocity speed is calculated as, $Cd = \sqrt{(K/p)} = 4145$ m/s. The stable time increment is taken as 5E-7 second which is less than the value of characteristic length divided by dilatational wave velocity (ABAQUS/Explicit note, 2005). Time step is chosen long enough to separate the transient and stable wave propagation. The chosen time step is 0.01 sec.

A mesh sensitivity analysis was performed to identify the optimum mesh size. The variation of attenuation over mesh size are shown in Table 6-1. FE mesh of the model is shown in Figure 6-1.

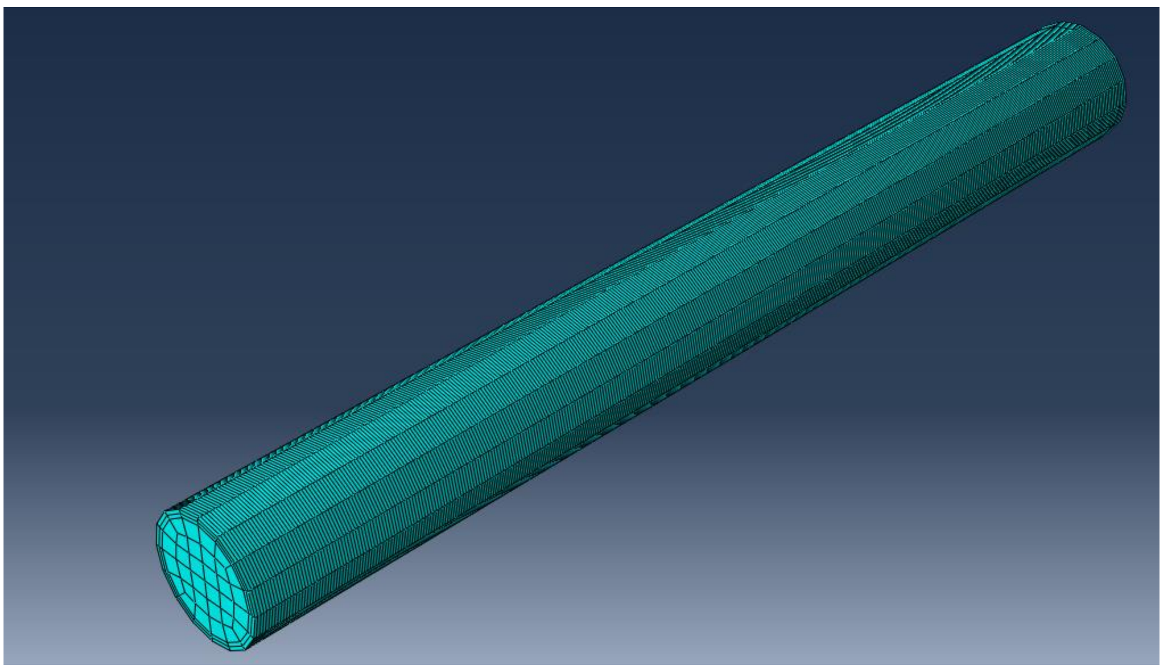
Table 6-1 Mesh sensitivity test

Element size (m)	Number of element in one wavelength	Amplitude ratio (A1/A0)	Percent change
0.04	10	0.9486	
0.004	100	0.9911	4.4%
0.0015	250	0.9983	0.7%

From Table 6-1, it is clear that element number increase from 100 to 250 have changed the amplitude ratio by only 0.7%. Therefore 100 element in one wavelength is chosen for the analysis. The corresponding mesh size is 0.004 m. A pipe with 0.15 m diameter and 1.5 m of length is considered. Total number of element for the model was 24000.



(a) Cross-sectional view



(b) Three dimensional view

Figure 6-1 Mesh of the model

The pipe and water was modelled as acoustic medium. The material parameters used in this simulation for pipe and water are given in Table 6-2.

Table 6-2 Material Parameter

	Density (Kg/m^3)	Bulk Modulus (Pa)
Water	1000	2.15e9
Pipe	7100	122e9

Finite element modelling of acoustic wave propagation in water pipeline is generally performed by incident plane wave. Graf et al., (2014) described that at low frequencies the fundamental mode of wave is plane wave. For the particular problem considered here, plane wave is applied at one end of the pipeline. The plane incident wave was applied at the pipe cross section with varying frequency ranging from 500 to 3000 Hz to simulate the attenuation behaviour. In Figure 6-2, the incident plane is shown by purple color. The opposite surface of the incident surface is assigned as non-reflecting boundary. The amplitude of incident wave of 0.04 is used as recorded in the laboratory experiments.

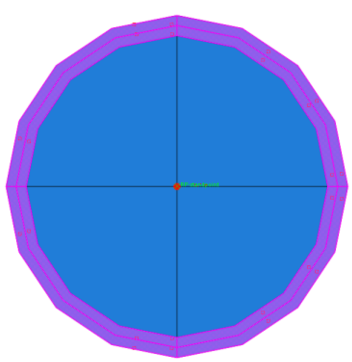


Figure 6-2 Surface of incident wave application (purple color)

6.4 Effect of Volumetric Drag

Water filled pipe is modeled as acoustic medium to simulate the leak noise propagation. The material parameters required for water and pipe (as acoustic medium) are density and bulk modulus. Typical values of these parameters for water and ductile iron are used. Modeling of attenuation of wave requires “volumetric drag coefficient”. However, no value of this parameter is currently available in the literature. Study have been conducted to identify suitable parameters applicable for the test condition analysed.

Frequency independent volumetric drag coefficient have been used in this model. Chatoorgoon and Zhou (1995) have used volumetric drag coefficient in ABAQUS to model wave propagation in water filled pipe. They used a volumetric drag of 13200 Ns/m^4 for water. Based on this value, the volumetric drag for water is chosen as 13200 Ns/m^4. To study the effect of the volumetric drag of pipe, two different values are first chosen in two case for this parametric study. In case a, the volumetric drag for pipe is chosen as 0 (as Chatoorgoon and Zhou, 1995). In case b, volumetric drag of pipe is chosen as half of the volumetric drag of water (i.e. 6600 Ns/m^4). Volumetric drag for steel is expected to be less than the volumetric drag of water. The values are presented in Table 6-3.

Table 6-3 Volumetric drag selection

	Case a	Case b
Water	13200.0 Ns/m^4	13200.0 Ns/m^4
Pipe	0.0	6600.0 Ns/m^4

The acoustic pressure was recorded at two reference points, which are 60 cm and 120 cm from the incident plane (similar to those measured during the laboratory test). The two recorded signals have time lag due to travel time required for the acoustic wave to travel from one point to the other. The recorded signals are then analysed using MATLAB code. The time lag was obvious in the recorded signals, as the signal amplitudes initiated at two different times at these points. The time-lag was then calculated as the difference of the time for signal initiations. Both signals are then initialized to start at t=0 sec, for the frequency spectrum analysis. Fourier analysis have been performed to obtain the frequency spectrum. The amplitudes are obtained from FFT analysis and used to calculate the amplitude ratio for those two reference points. These results are compared with those from the experiment. Figure 6-3 compares the amplitude ratio from FE analysis and those from the experiment. At 500 Hz frequency, the amplitude ratio is 0.998 from the FE simulation and 0.986 from the experiment. At 3000 Hz frequency, the amplitude ratio is 0.991 from the FE simulation and 0.986 from the experiment. The inflow rate was 8.8 gallons per min (33.3 litres per min) and the outflow was 4.8 gallons per min (18.2 litres per min) and the leak rate was 4 gallons per min (15.1 litres per min) during the experiment considered here.

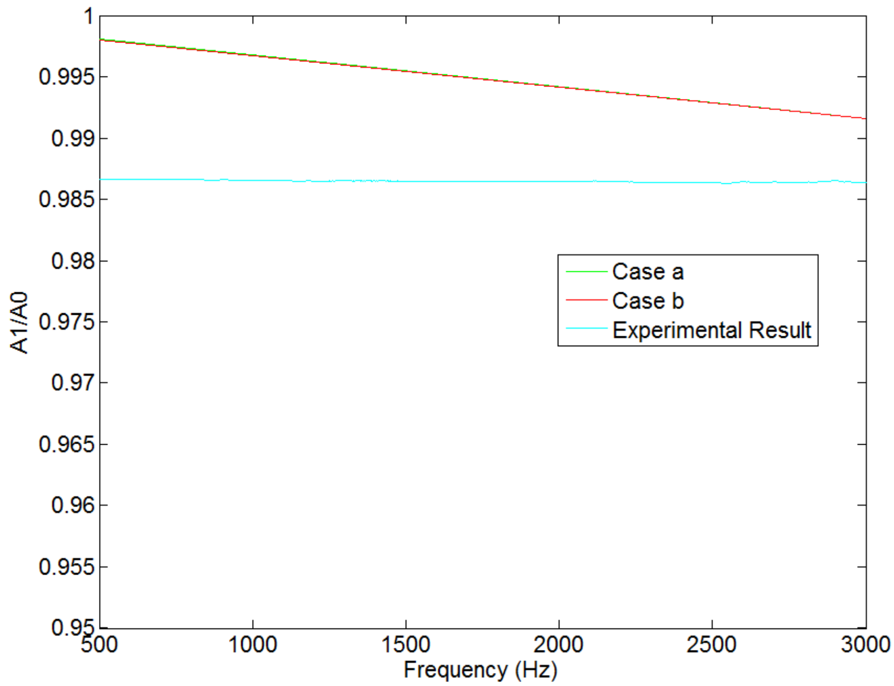


Figure 6-3 Amplitude ratio for comparison with assumed volumetric drag

In Figure 6-3, the amplitude ratios from FE analysis are much higher than those from experiment. To simulate the experimental results, the volumetric drag value should be increased. The volumetric drag value is then doubled to 26400 Ns/m^4 for the water. The volumetric drag for the pipe value is taken as 0 for case a and half of the value of volumetric drag of water as 13200 Ns/m^4 for case b, as before. The values of first revision of volumetric drag are tabulated in Table 6-4.

Table 6-4 First revision of volumetric drag

	Case a	Case b
Water	26400.0 Ns/m^4	26400.0 Ns/m^4
Pipe	0.0	13200.0 Ns/m^4

Figure 6-5 illustrates the results after increasing the volumetric drag value of water and pipe (first revision). At 500 Hz frequency in Figure 6-5, the amplitude ratio is 0.992 from FE simulation whereas the ratio is 0.986 from the experiment. At 3000 Hz frequency, the amplitude ratio is 0.988 from the FE simulation and 0.986 from the experiment. The FE and experimental amplitude ratios approaches closer with a higher volumetric drag of water. Further increase in the volumetric drag is recommended to improve the performance of the FE simulation.

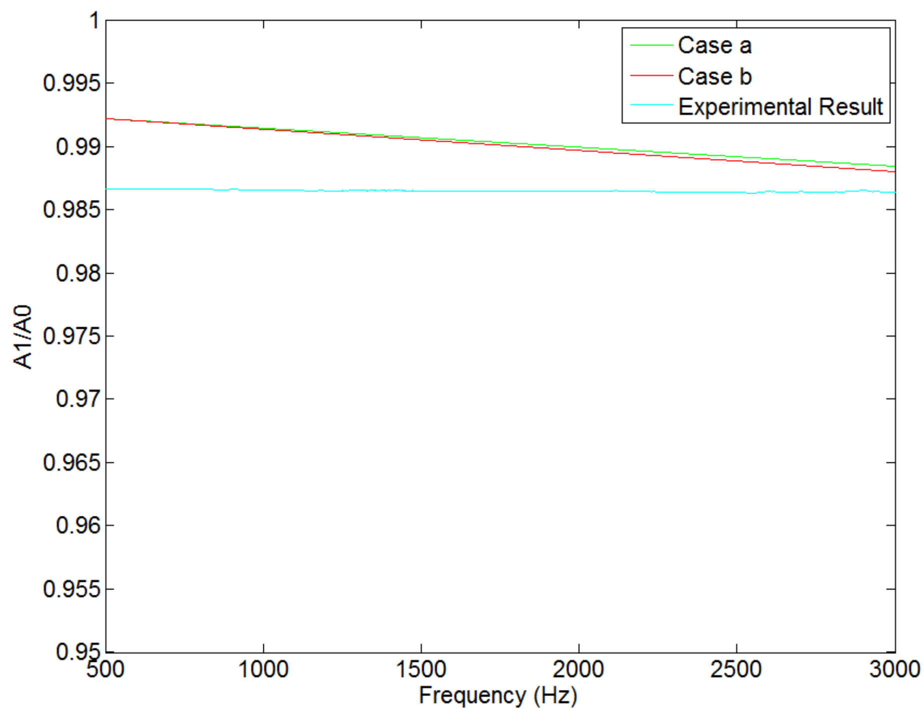


Figure 6-4 Amplitude ratio with first revision of volumetric drag

The volumetric drag value of water is then increased to three times of the value of 13200 Ns/m^4 (used in Chatoorgoon and Zhou, 1995). The value of volumetric drag for water is chosen to be 39600 Ns/m^4. The volumetric drag for the pipe are used as in the previous cases. The value of volumetric drag for water and pipe are shown in Table 6-5.

Table 6-5 Second revision of volumetric drag

	Case a	Case b
Water	39600.0 Ns/m^4	39600.0 Ns/m^4
Pipe	0.0	20000.0 Ns/m^4

Figure 6-6 illustrated the results after increasing the volumetric drag value for water. At 500 Hz frequency, the amplitude ratio is 0.986 from FE simulation, which is the same as the value obtained from the experiment (i.e. 0.986). At 3000 Hz frequency, the amplitude ratio is 0.985 from FE simulation and 0.986 from experiment, which are very close to each other.

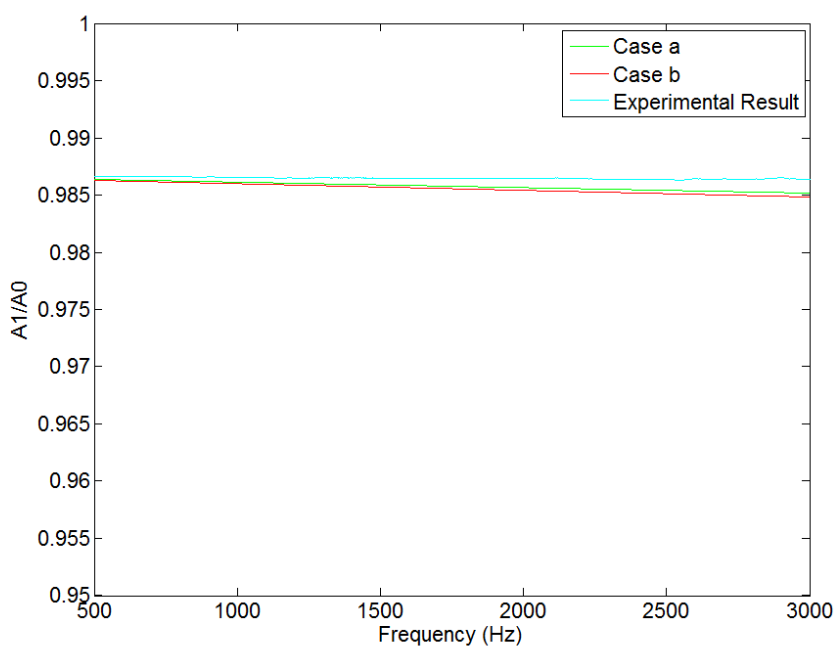


Figure 6-5 Amplitude ratio with second revision of volumetric drag

In the three different studies above, the volumetric drag value for the pipe is taken as zero and half of the value of water in different case. Figure 6-4, 6-5 and 6-6, reveal that the volumetric drag of pipe has relatively small effect on the amplitude ratio while volumetric drag of water significantly control the acoustic wave propagation. Based on these results, the volumetric drag of water is chosen as 40000 Ns/m^4 and 20000 Ns/m^4 for ductile iron pipe.

6.5 Effective Distance

Due to attenuation of leak noise, acoustic method may not be effective if the sensors are located at far from the source (leak). A study is carried out using FEM for the determination of the distance up to which the method can successfully be used. Material parameters discussed above are used. A long pipe of 250 m was modelled to simulate acoustic wave attenuation over the length. Volumetric drag values are used as 40000 Ns/m^4 for water and 20000 Ns/m^4 for ductile iron pipe. A frequency of 500 Hz is considered.

Due to meshing constrain of this large model, 10 element per wave length was chosen. The element length along the length is 0.25 m. The element in radial direction is same as before. The time step of 0.2 second is used, and time increment is calculated using similar procedure, discussed above.

The magnitude of leak noise at source have effect on the effective distance. During laboratory test, the magnitude of acoustic wave was measured to be 0.04. A set of noise source magnitude value was used to identify the effect of source magnitude on effective distance. The noise source magnitudes of 0.04, 0.06 and 0.12 are considered.

Figure 6-6 shows the attenuation of acoustic wave with distance. The ambient noise level is shown in the figure in red line denoting the level under or at which the sensor cannot identify leak noise signals. This level represents the cut-off level. When the magnitude of noise source (potentially leak noise) is 0.04, the noise can be identified up to 140 m from the source. When the magnitude of the noise source is increased to 1.5 times (0.06), the noise can be identified up to 170 m. For leak noise with magnitude of 0.12, noise magnitude remain above the ambient noise up to a distance of 210 m. Thus, the acoustic method can be effectively used up to a sensor distance of 140 m, 170 m and 210 m for leak noise with magnitudes of 0.04, 0.06 and 0.12, respectively.

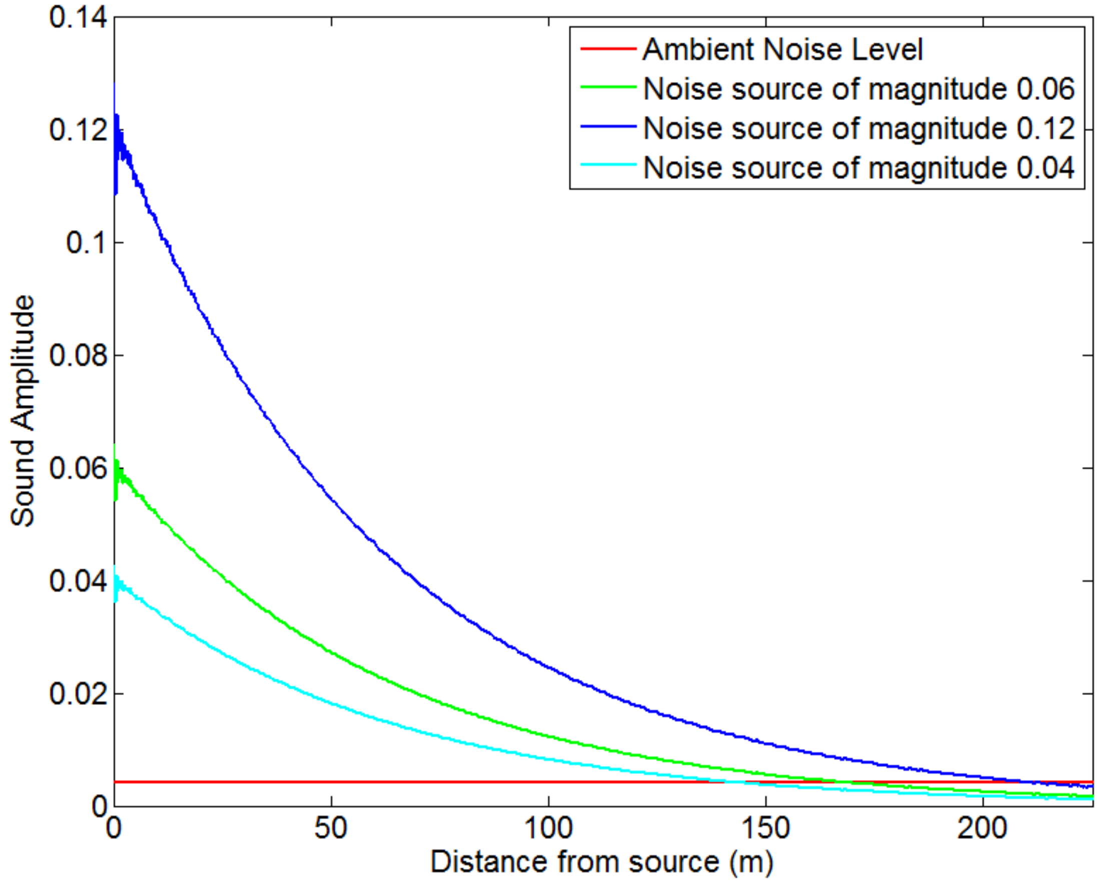


Figure 6-6 Sound wave attenuation over length for different noise source magnitude

6.6 Conclusion

A finite element study is presented in this chapter for a better understanding of acoustic leak noise propagation in pipe segment. Typical material property of soil and pipe is used to model the in-air pipe. Effect of volumetric drag on attenuation is presented. The similar trend of amplitude ratio of laboratory test results was achieved by using volumetric drag of 39000 Ns/m^4 for water. The volumetric drag of pipe has less significant effect on acoustic wave propagation. The acoustic method can be effectively used up to a sensor distance of 140 m, 170 m and 210 m for leak noise with magnitudes of 0.04, 0.06 and 0.12, respectively.

6.7 Reference

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Chapter 7. Discussion and Conclusion

7.1 Introduction

Municipal water distribution system suffers 20-30% water loss due to leaky pipes. The water loss could be minimized through leak detection and repair of the leaks. Acoustic emission with cross-correlation leak detection is one of the most popular methods for leak detection in water mains. Appropriate interpretation of recorded data is an important issue for successful leak location detection using AE method. Conventionally, coherence analysis is conducted for identification of the presence of leak noise in recorded signal and cross-correlation analysis is conducted for leak location determination. Research attention is required to identify coherence and cross-correlation values for different field conditions. Attenuation behaviour is also important factor to determine maximum sensor to sensor distance for successful leak detection.

This research investigates the application of acoustic emission method for different field conditions and identify the typical value range for frequency analysis, coherence analysis and cross-correlation analysis. Laboratory investigation was also conducted to identify leak noise source for low leak rate and attenuation behaviour for different water flowrate. Three dimensional finite element analysis was employed to simulate acoustic leak noise propagation in a pipe placed in open air.

7.2 Conclusions

7.2.1 Field Implementation of Acoustic Emission Leak Detection Method

In the case studies presented in Chapter 3, the acoustic emission method was successfully used for leak detections in water mains in the City of Mount Pearl. Methodologies undertaken for successful leak detection on a lateral and on a water main are presented. The coherence values and noise frequencies corresponding to the leak noise and the wave propagation velocities based on real-time data are described. The buried depths of the pipes were generally 2.43 m to 3.0 m. Pipe backfill material was sandy crushed rock/gravel. Water pressure in the city water mains varied from 480 kPa to 620 kPa. The average leak rate was estimated to be 4200 m^3 per month or 1.6 litres per second.

For the above conditions, wave propagation velocities for ductile iron pipes with diameters of 152 mm, 203 mm, and 254 mm in. were 1290 m/s, 1263 m/s and 1224 m/s that provided leak locations with reasonable accuracy for the sites considered. The propagation velocity in the 19 mm diameter copper pipe was 1164 m/s. Frequency bands corresponding to the leak noise was found to vary up to 2000 Hz. The average of the lower bound and upper bound of frequencies were around 220 Hz and 1400 Hz, respectively. A coherence magnitude higher than 0.5 was found to represent a correlation for leak noises between the sensors for the cases presented. The coherence magnitudes were higher within the frequency bands corresponding to the leak noises (i.e., average 220 Hz to 1400 Hz).

7.2.2 **Characteristics of Leak Noise**

The results of preliminary laboratory tests conducted to develop a better understanding of the leak noise in a ductile iron water main using acoustic emission method reveals that the leak noise is governed significantly by the surrounding obstacles when the leak rate is low. A new instrument setup was configured and necessary programming code was developed to conduct the test. No device was attached during this test to measure leak rate. No detectable noise was encountered when no obstacle was placed in front of the leak hole. However, the leak noise was detected when obstacles such as wooden block and river stone was placed in front of the leak hole.

For the leaks with a surrounding obstacle, frequency of the leak noise ranges from 2000 Hz to 10000 Hz. The frequency band appears to vary depending upon the type of obstacle. A coherence magnitude higher than 0.75 was found to represent a correlation for leak noises between the sensors. The coherence magnitudes were higher within the frequency bands corresponding to the leak noises. Cross-correlation function for leak location determination was also consistently higher.

7.2.3 **Attenuation Behaviour of Leak Noise**

A new laboratory facility was developed to study the attenuation behaviour of leak noise. Tests were conducted to study the acoustic wave attenuation for an in-air and a buried pipe.

Significantly different attenuation behaviour is observed for the pipe placed in air and the pipe placed in buried condition. When pipe is placed in air, the amplitude ratio was between 0.993-0.981 for flowrate 6.8-9.7 gallons per minute (25.74-36.72 litres per minute). There was a general trend of higher attenuation or lower amplitude ratio for higher frequency. For the buried pipe, the attenuation was higher. In general, higher attenuation or lower amplitude ratio are observed at higher frequencies. The amplitude ratio was between 0.973-0.93 for the flowrate 6.7-9.4 gallons per minute (25.36-35.58 litres per minute) in the buried pipe. The attenuation was found to depend on the inflow-rate. The amplitude ratio decrease for the in-air pipe was 4.13e-3 per gallons-per-minute of inflow rate and the amplitude ratio decrease for the buried pipe was 15.92e-3 per gallons-per-minute of inflow rate, which is higher than in-air pipe. For buried pipe, the attenuation parameter (α) is calculated to be 0.12 dB/m and for in-air pipe, the attenuation is calculated to be 0.032 dB/m at the inflow rate of 6.7 gallons per minute (25.36 litres per minute).

7.2.4 Modelling acoustic wave attenuation

A finite element (FE) modelling technique has been developed for acoustic wave propagation through an in-air water main. FE model was validated using laboratory test results. The laboratory test condition could be successfully simulated using a volumetric drag for water as 39000 Ns/m^4 and for pipe a 20000 Ns/m^4. These parameters were used to simulate a long pipe. From this simulation, it was found that acoustic wave from leak noise can be detected from a distance from the source that depends on the magnitude of the leak noise. For leak noise magnitude of 0.04, 0.06 and 0.12, the leak noise can be detected from a distance of 140 m, 170 m and 210 m, respectively.

7.3 Recommendations for Future Study

In this research, experimental and numerical investigation are carried out to characterize acoustic noise from water main leaks. It is recommended to extend this research further for successful leak detection in water mains. The following presents some specific recommendations for future research.

- Investigation of the effect of leak rate on the acoustic wave propagation using the developed laboratory facility.
- Investigation of the attenuation of leak noise at field conditions.
- Investigation of the effect of flow-rate on attenuation for field condition.
- Investigation of the effect of water pressure on attenuation of leak noise in laboratory and field conditions.
- Investigation of the effect of soil in attenuation in finite element simulation.
- Investigation of the effect of frequency dependent volumetric drag in finite element simulation.
- Integration of the effect of water flow in the pipe and the pressure at both end in the finite element simulation.