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Feasibility Evaluation of a Vibration-Based Leak Detection Technique for Sustainable Water Distribution Pipeline System Monitoring

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FEASIBILITY EVALUATION OF A VIBRATION-BASED LEAK DETECTION TECHNIQUE FOR SUSTAINABLE WATER DISTRIBUTION PIPELINE SYSTEM MONITORING

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ABSTRACT

Conventional water pipeline leak-detection surveys employ labor-intensive acoustic techniques, which are usually expensive and less useful for continuous monitoring of distribution pipelines. Based on a comprehensive review of literature and available commercial products, it has been recognized that despite previous studies and products attempting to address the limitations of the conventional surveys by proposing and evaluating a myriad of leak-detection techniques (LDTs), they lacked extensive validation on complex looped systems. Additionally, they offer limited compatibility with some pipe materials such as those made of plastic and may even fail to distinguish leaks from other system disturbances. A novel LDT that addresses some of these limitations is developed and evaluated in the current study using an experimental set-up that is representative of a real-world pipeline system and made of Polyvinyl Chloride (PVC) pipe. The studied LDT requires continuous monitoring of the change in the cross spectral density of surface vibration measured at discrete locations along the pipeline. This vibration-based LDT was hypothesized to be capable of not only detecting the onset of leakage, but also determining its relative severity in complex pipeline systems. Findings based on a two-phase, controlled experimental testing revealed that the proposed LDT is capable of detecting leakages and estimating their relative severities in a real-size, multi-looped pipeline system that is comprised of multiple joints, bends and pipes of multiple sizes. Furthermore, the sustainability merits of the proposed LDT for a representative application scenario are estimated. Specifically, life cycle costs and energy consumption for monitoring the large diameter pipelines in the water distribution system of the Charleston peninsula region in South Carolina are estimated by developing conceptual prototypes of the sensing, communication and computation schemes for practically employing the proposed LDT. The prototype designs are informed by the knowledge derived from the two-phase experimental testing campaign. Overall, the proposed study contributes to the body of knowledge on water pipeline leak detection, specifically to non-intrusive vibration-based monitoring, applications on plastic pipelines, and smart and sustainable network-wide continuous monitoring schemes.

DEDICATION

I would like to dedicate this dissertation to:

My inspiring mother and generous father: You have been the continuous light in my life

&

My husband and best friend, Hassan: Your love and support throughout this endeavor were invaluable for me and I cannot wait to see where life takes us.

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CHAPTER ONE

INTRODUCTION

1.1 Motivation for the Dissertation

Over the last few decades, water stress has been rising due to decreasing freshwater resources and increasing growth in demand, owing mainly to increasing population and rapid urbanization (Rodriguez et al., 2012). Making this supply-demand imbalance worse, drinking water pipeline infrastructure in the U.S. has severely deteriorated resulting in an increasing number of main breaks and leakage (ASCE report card, 2013). In the U.S., approximately 20% of all treated water, which amounts to about 26.5 million m^3 per day, is estimated to be lost through pipeline leakage; these losses are estimated to exceed 50% in some developing and underdeveloped countries (Mutikanga et al., 2012). In addition to the loss of treated water, ancillary losses include embedded energy and the energy required to compensate the pressure losses due to leakages. It is estimated that the energy consumed for treating and distributing water in U.S. is estimated to be 900 kWh per 1000 m^3 (Copeland, 2014). Furthermore, leaks can potentially compromise the drinking water quality due to contaminant infiltration into water distribution systems. Given the lack of financial resources to adequately rehabilitate pipelines that continue to operate past their intended design life, leakage is expected to only increase in the coming years (Costello et al., 2007). Therefore, Leak Detection Technique (LDTs) that work efficiently on a wide range of pipe materials and sizes can greatly enhance the ability of water utilities to detect leakages and possibly intervene at an optimal time. Although it may not be feasible to eliminate all existing leakage in water infrastructure, reducing it by even half could save an estimated $2.9 billion annually for water utilities (Kingdom et al., 2006).

A variety of non-destructive inspection techniques for pipeline leak detection, such as ground penetrating radar (Hyun et al., 2003), tracer gas (Hunaidi et al., 2000), infrared thermography (Zhang, 1997) and acoustic techniques (Hunaidi et al., 2004), exist. Nevertheless, research needs and technology gaps still remain for the successful application of these techniques on a wide range of pipe materials and sizes. For example, acoustics-based techniques, which are the most widely used, have proven to be less reliable on plastic pipe material which is increasingly becoming the popular choice for water distribution system pipelines (Liu et al., 2012). Currently, there are very few LDTs that are suitable for plastic pipeline applications. Although plastic pipelines that are currently in use are not so aged that the utility owners are highly concerned about leakages and other defects in them, it will soon emerge as an area of concern and a suitable technique makes significant contributions in this specific regard.

Another major limitation of existing LDTs is their intended applications to only depict the snapshot status of the system. Moreover, water utilities would employ these LDTs only after the leakages have grown significant enough to be recognized through some form of an indirect inference, thereby making the whole monitoring approach reactionary and less sustainable. Due to the advent of wireless sensor networks, it is indeed possible and desirable to have a proactive LDT enabled by smart and sustainable sensor networks that will support continuous near real-time leakage monitoring of water distribution systems.

1.2 Research Objective and Scope of this Study

The idea of deploying sensor networks that are embedded in water pipelines for the detection of leakage and other defects has received some attention in the past decade (Puust et al., 2010). Surface vibration-based monitoring of water pipelines is seen as a promising alternative for defect detection (Cheraghi et al., 2005, Stoianov et al., 2007). The distinctive advantage of sensor networks that are non-intrusively embedded in water pipelines is the ability to continuously monitor for rapid detection and locating of leaks. City-wide near real-time monitoring of pipelines and timely intervention can ultimately reduce water losses, save energy, minimize cost of pipeline failures, and safeguard public health. While the computing aspects, especially energy-efficient sensing (Tackett et al., 2011), data sampling (Bajwa et al., 2006) and data transmission (Akyildiz et al., 2009) received great attention, the engineering problem of leveraging monitoring data to appropriately detect leak presence and determine its severity has not been demonstrated on complex pipeline systems.

This dissertation contributes to the field of leak detection in water pipeline systems by recognizing the effect of leakage on the structural behavior of the pipeline in terms of its vibrational characteristics. This study starts with the premise that the dynamic behavior of a pipeline is influenced by the variation in the enclosed flow characteristics as a result of a leak and accordingly develops a leak detection approach. The developed approach is hypothesized to be independent of priori system-related knowledge and it is expected to work in the presence of typical system disturbances, and be applicable to a wide range of pipe materials and sizes.

Accordingly, the ***objective*** of this dissertation is to evaluate the merits of a proposed non-intrusive, vibration-based LDT that is suitable even for plastic pipeline applications and subsequently estimate the life cycle cost and energy requirements for network-wide monitoring using the proposed LDT. The proposed technique is validated using a multi-looped experimental set-up made of Polyvinyl Chloride (PVC) pipe and which is representative of a real-world pipeline system in terms of system disturbances and complexities. Life cycle cost and energy needs for network-wide monitoring using the proposed LDT are estimated using the distribution infrastructure data from the peninsula region of Charleston, SC.

The importance of successful development of such study stems from the fact that it enables early detection of leakages and timely intervention by water utility departments, as opposed to the conventional LDTs which have: (a) only been successful in detecting leakages in suspected sections of water supply networks, (b) expensive, intrusive, and operator-dependent, and (c) only depicted the snapshot status of the system at the time of monitoring.

1.3 Dissertation Organization

This dissertation is organized into six chapters as described in the following paragraphs[1].

Chapter two presents a review of state-of-the-art knowledge and state-of-the-art practice on the leak detection techniques, highlighting the advantages, limitations and

[1] Chapters 2-5 of the dissertation serve as stand-alone journal publications; therefore, some level of conceptual overlap is required.

suitability to various application scenarios. Specifically, six popular commercial acoustic LDTs are evaluated based on four typical criteria. Guidance on choosing an appropriate commercial LDT for a given application scenario is also presented in this chapter. This review work is submitted as a technical manuscript to the *Journal of Management of Environmental Quality* and it is currently under review.

Chapter three discusses the conceptual development of the proposed leak detection index which is sensitive to the onset of leaks and insensitive to ambient noises. The proposed index is a distance-based damage indicator that relies on the variation in structural behavior of the pipeline system in response to variation in leakage-induced flow characteristics. Specifically, the Cross Spectral Density of pipeline surface vibration data, collected along the length of pipeline is monitored for detecting leakage using the proposed LDT. This chapter also describes the preliminary experimental campaign carried out to validate the proposed LDT using a single stretch of a real-size (3 inches or 76mm in diameter) PVC pipeline. This chapter has been published as a peer-reviewed manuscript in the *Journal of Structure and Infrastructure Engineering.*

Chapter four extends the validation campaign of the proposed LDT using a two-looped pipeline test bed that exhibits several complexities observed in a real-world pipeline system, such as valves, T-joints, multiple pipe sizes, and multiple leaks. Detailed description of the experimental settings, scenarios investigated, and the resulting findings are described in this chapter. This chapter has been published as a peer-reviewed manuscript in the *Journal of Structure and Infrastructure Engineering.*

Chapter five describes the investigation of the life cycle cost and energy needs of the proposed LDT for network-wide leakage-monitoring. Various sensor and communication hardware characteristics are discussed to identify optimally feasible alternatives. The distribution infrastructure data for the peninsula region of Charleston, SC is used to estimate the life cycle cost and energy consumption needs and to also evaluate the sensitivity of both life cycle cost and energy consumption to numerous uncertainties associated with the sensing and communication schemes. This chapter has been submitted as a technical manuscript for publication in the *Journal of Resources, Conservation and Recycling* and it is currently under review.

Chapter six summarizes the contributions of this dissertation study, highlights its limitations, and presents directions for future work in the important area of water pipeline leakage detection.

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CHAPTER TWO

OPTIMAL SELECTION OF ACOSUTIC-BASED LEAK DETECTION TECHNIQUES FOR WATER PIPELINES USING MULTI-CRITERIA DECISION ANALYSIS[1]

There has been a sustained interest over the past couple of decades in developing sophisticated leak detection techniques that are economical and reliable. A majority of current commercial leak detection techniques are acoustics-based and they are not equally suitable to all pipe materials and sizes. There is also limited knowledge on the comparative merits of such acoustics-based leak detection techniques (ALDTs). This paper reviews six commercial ALDTs based on four criteria and subsequently proposes guidance for the selection of an optimal leak detection technique. The techniques include listening devices, noise loggers, leak-noise correlators, free swimming acoustic, tethered acoustic, and acoustic emissions. The evaluation criteria include cost, reliability, access requirements, and the ability to quantify leakage severity. Numerous publications and field demonstration reports are reviewed for evaluating the performance of ALDTs in this study. The proposed guidance for the selection of an optimal ALDT is driven by the Monte-Carlo Analytical Hierarchy Process (AHP) whose results are evaluated using interviews with water utility experts. The findings of this study would benefit water utility owners in choosing an ALDT that optimally suits their needs.

2.1 Introduction

Domestic and industrial demand for water is increasing rapidly around the world, while the freshwater resources are becoming increasingly scarce. Currently, the water distribution infrastructure is critically deteriorated leading to significant leakage of treated water, making this supply-demand imbalance worse. It is estimated that roughly 7

[1] Yazdekhasti, S., Piratla, K. R., Matthews, J.C., Khan, A. and Atamturktur, S. (2017, Under Review). A Review of Acoustic-based Leak Detection Techniques for Water Pipelines, Journal of Management of Environmental Quality.

billion gallons (≈ 15-25%) of treated water is lost per day in the U.S. (ASCE, 2013), and this problem is worse in some developing and under-developed countries (Thornton et al., 2008). Leakages of such magnitude are not sustainable as water supply (i.e., collection, treatment and distribution of water) is energy-intensive and expensive undertaking (Hendrickson and Horvath, 2014). Leaks can also potentially compromise water quality, resulting in contaminant infiltration, leading to health issues (Martini et al., 2015). In an attempt to address this serious problem, numerous leak detection techniques (LDTs), ranging from simple visual inspection to sophisticated acoustics-based ones, have been investigated hitherto.

Previous studies reviewed various LDTs and highlighted their specific advantages, limitations and suitability to different application scenarios. While a majority of these studies focused on LDTs in general (Costello et al., 2007; Colombo et al., 2009; Thomson and Wang, 2009; Puust et al., 2010; Liu et al., 2012; Liu and Kleiner, 2012 and 2013, Xu et al., 2014), some focused specifically on the acoustics-based techniques (Nestleroth et al., 2012; Hunaidi, 2012; Anguiano et al., 2016). The acoustics-based LDTs (hereafter referred as ALDTs), which are widely used in practice, rely on the premise that a leak induces noise or a vibration signal that travels through the pipe wall or the water column and that this signal can be detected using appropriate sensing equipment. Although ALDTs have worked well in the cases of small to medium-diameter (< 300 mm) metallic pipelines, their suitability to plastic and large-diameter metallic pipelines has been uncertain, owing mainly to the possibility of high signal attenuation rate in these types of pipelines (Hunaidi, 2012).

Innovative advancements in the recent past reportedly improved the suitability of ALDTs to plastic and large-diameter metallic pipelines through the passage of sensors inside the pipeline via a tether or by freely swimming (Nestleroth et al., 2012). Taking into account such developments, this paper reviews several ALDTs and compares them based on the following criteria: cost (C_C), reliability (C_R), ability to determine leak severity (C_Q), and pipe access requirements (C_A). The comparative evaluation of ALDTs is then leveraged for determining their relative suitability to typical application scenarios using Monte-Carlo Analytical Hierarchy Process (MCAHP). Overall, this paper offers guidance to water utility owners in selecting ALDTs for optimal leakage surveys.

2.2 Review of ALDT Options for Water Pipelines

Leakage detection methods cover a wide spectrum of techniques that leverage various scientific principles. Table 2-1- Classification of water pipeline inspection techniques categorizes several popular pipeline inspection techniques into acoustic and non-acoustic classes based on whether or not acoustic principles are employed in their operations. Non-acoustic techniques are further classified into direct (Amirrato and Zayicek, 1999; Shin et al., 2009; Tse and Wang, 2009; Agarwal, 2010; Hao et al., 2012; Liu and Kleiner, 2013; Khader, 2016) and indirect methods (Sadiq et al., 2004; Colombo et al., 2009) based on whether or not they directly indicate leakage presence without needing to further interpret the results through inferential indicators (Liu and Kleiner, 2013).

The acoustic techniques, as shown in Table 2-1, are also categorized in two groups based on their capabilities. The first group of techniques, which comprises listening devices, noise loggers, and leak-noise correlators, are capable of only leak detection and/or locating. The second group of techniques, which comprises free swimming or tethered sensors and acoustic emissions, are capable of assessing the structural condition of the pipeline in addition to leak detection and/or locating. The acoustic techniques are briefly described in this section.

Table 2-1- Classification of water pipeline inspection techniques

Non-acoustic	Direct	- Visual inspection: Closed-circuit television (CCTV) inspection, Laser Scan (LS) - Electromagnetic methods: Magnetic flux leakage (MFL), remote field eddy current (RFEC), broadband electromagnetic (BEM), pulsed eddy current (PEC) testing, ground penetrating radar (GPR), ultra-wideband (UWB) pulsed radar system - Ultrasound methods: Guided wave ultrasound (GWU), Discrete Ultrasonic Measurement (DUM), Phased array technology (PA) - Radiographic methods (RM): Gamma or X-ray - Thermography (TM) - Fiber-optic sensors (FOS)
	Indirect	- Soil characterization analysis (SCA): Such as moisture content of the soil, PH value and soil resistivity - Hydraulic-based methods (HBM): Inverse transient analysis, Free vibration analysis, Time domain reflectometry techniques, Pressure analysis, computational pipeline monitoring (real-time transient model), Volume balance
Acoustic	Leak detection only	Listening devices, leak noise correlator, noise loggers
	Leak detection and structural condition inspection	Free swimming, tethered, acoustic emission

2.2.1 Listening Devices (LD)

Listening technique is a commercial leak-detection method that has been used since 1850s (Pilcher, 2003). This technique, which is depicted in Figure 2-1a, enables detecting leaks through fire hydrants or valves using inexpensive listening rods and hydrophones by listening to the sound of water emitting from the leak. LD is not highly reliable for detecting small leaks unless further inspection is carried out to ensure leak-induced signals are not masked by ambient noises. Piezoelectric materials, adjustable amplifiers, and noise filters are used along with the listening rods and hydrophones for filtering the ambient noises depending on the frequency range of interest (Hunaidi et al., 2000). Sound-based transducers, such as ground microphones, are also capable of detecting leak-induced sound at ground level in addition to monitoring valves or fire hydrants.

The accuracy of results from the LD technique reportedly decrease with increased cover depth, increased distance between the leak and monitoring location, decreased conductivity of soil, decreased pressure of fluid in the pipe, and increased temperature (Hunaidi et al., 2000). The accuracy of LD technique is also uncertain in large diameter metallic and plastic pipelines, for they exhibit higher acoustic attenuation rate (Hunaidi, 2012); for example, the acoustic attenuation rate in plastic pipelines is five times greater than that in metallic pipelines (Hunaidi et al., 2000). The set-up time of LD equipment to be attached to a hydrant or valve is estimated to be about five minutes, whereas its average on-station time is estimated to be in the range of two to five minutes depending on the operator’s familiarity with leakage-induced sounds in pipeline systems (EPA, 2010). The applications, advantages, and limitations of LD technique are highlighted in Table 2-2.

2.2.2 Noise Loggers (NL)

Noise logger is an ALDT that has been commercially available since 1990s. Noise loggers, as depicted in Figure 2-1b, can be embedded in a pipeline system permanently or temporarily (at least for two consecutive nights typically), and are programmed to listen for leaks. Statistical analysis of the recorded data, especially the noise intensity and consistency, over a period enables the detection of the likely presence of a leak. As soon as a suspected leak is detected, an alarm state is initiated through a radio signal to indicate the presence of a leak. Unlike manual techniques such as LD, which can be used only in an ad-hoc manner, NL can be installed for permanent use. Furthermore, it is a suitable option for busily crowded areas where manual surveys might be difficult to carry out. The suggested distance of loggers from each other in NL technique is 100 m for metallic (of diameter ≤ 400 mm) and 50 m for plastic pipelines (Covas et al., 2006). The set-up time for NL technique is estimated to be in the range of 20 to 30 minutes per logger with limited training required for the technician. On the other hand, additional time of a trained professional is required for analyzing the gathered data after a reasonable period of monitoring time (EPA, 2010). The applications, advantages, and limitations of NL technique are further highlighted in Table 2-2.

2.2.3 Leak Noise Correlator (LNC)

LNCs are commercial ALDTs that have been in use since 1978 primarily for pinpointing leaks upon the determination of their presence and approximate vicinity. LNC technique entails using either accelerometers or hydrophones attached at two contact points on the pipeline surrounding the leak, as depicted in Figure 2-1c. The correlation between signals at the two contact points is leveraged to estimate the location of a potential leak. Hydrophones are preferred for locating small leaks, when placed closely to the leak (< 4.5 m) (Hunaidi, 1999), and they are also generally more suitable for plastic pipelines (Thomson and Wang, 2009). With the use of hydrophones spaced at 100 m from each other, LNC technique is reportedly estimated to inspect 3 km of pipeline per day with a two-person crew (Hunaidi, 2012). On the other hand, accelerometers are preferred for metallic pipes, especially small diameter ones (< 300 mm) when employing LNC technique (Nestleroth et al., 2012; Hunaidi, 2012). With the use of accelerometers spaced at 200 m, LNC technique is reportedly estimated to inspect 9 km of pipeline per day with a two-person crew (Hunaidi, 2012). The background noise issues in plastic pipelines make it necessary to use appropriate digital filters to enhance accuracy with the LNC technique (Gao et al., 2004 and 2005; Brennan et al., 2008).

The set-up time for LNC technique is estimated to be in the range of 10 to 20 minutes per station, whereas the average on-station time is estimated to be in the range of 30-60 minutes or more depending on the time of the day (EPA, 2010). Further applications, advantages, and limitations of LNC technique are highlighted in in Table 2-2.

2.2.4 Free Swimming Acoustic (FSA)

FSA is an ALDT that is commercially available since 2004. The FSA technique, depicted in Figure 2-1d, is mainly comprised of a free-swimming foam ball with an instrumented-filled aluminum alloy core and it is suitable for pipelines of diameter 250 mm or larger. This technique works through the passage of the free-swimming ball directly adjacent to the source of noise (Liu et al., 2012) and consequently, it is more suitable for highly attenuating pipelines such as those made of plastic in comparison to the previously described ALDTs. FSA technique is also used for structural pipeline inspections in some applications. The core of the foam ball is approximately 60 mm in diameter and houses acoustic acquisition device, data storage equipment, and a power supply (Puust et al., 2010). The foam shell around the aluminum core, which helps in reducing the ambient noises in the pipeline environment, can vary in diameter depending on the project parameters including but not limited to pipe diameter, pressure, and configuration; and the shell's spherical design allows for more flexibility in passing through small radius bends and obstacles. The FSA technique is deployed into the flow of a pipeline from a valve with clearance of at least 100 mm diameter, which then freely swims to a downstream extraction point. The frequency content of the recorded pipeline acoustic activity is evaluated to inform leakage detection. Specifically, the acoustic frequency and power can indicate the presence and severity of leaks by comparing the recorded data with leak calibration curves in the post-processing analysis. The accuracy of leak calibration curves will increase as more data points are added, since the leak indicator is a function of various field criteria such as pressure, pipe diameter, and pipeline configuration (Fletcher and Chandrasekaran, 2008). The FSA technique has detected leaks as small as 0.11 lit/min under ideal conditions and in pipelines with operational pressure more than 10 psi (Nestleroth et al., 2012). The device is also capable of sending out ultrasonic pulses every 3 seconds to track the position of the ball during the survey; or it can be tracked through GPS, which allows the location of leak to be determined with ±1 m precision (Fletcher and Chandrasekaran, 2008). The specific applications, advantages and limitations of FSA technique are highlighted in Table 2-2. It should be noted that the FSA technique struggles to discern leaks in clusters that are less than 0.8 m apart (Nestleroth et al., 2012); this limitation is however applicable to other ALDTs as well. The set-up time and on-station time of the FSA technique varies widely depending on the access and length of the pipeline to be inspected; the average set-up time is estimated to be about an hour (EPA, 2010).

2.2.5 Tethered Acoustics (TA)

TA is a commercially available technique that has been in use in the leak detection industry since the mid-1990s. This technique uses a hydrophone sensor, as depicted in Figure 2-1e, which is mounted at the end of a tether and travels inside a water main to record leak noises and in some cases conduct visual and structural inspections. TA technique, similar to FSA, takes advantage of passing directly adjacent to the leak and subsequently offers improved suitability for leak detection in plastic and large diameter metallic pipelines, compared to the external ALDTs. The TA system is deployed into the pipeline flow from any existing tap point that is at least 50 mm in diameter and connected to a pipeline of diameter larger than 250 mm. As the system passes a water leak, the sound is detected. The sensor is tethered to the ground level and an operator tracks the sensor from above ground in order to locate the position of detected leaks. The sensitivity of TA to leaks as small as 0.015 lit/min and its accuracy in locating leaks with less than ±1 m precision have been proven in field trials (Nestleroth et al., 2012). In the later versions of TA, a camera has been added to reveal more information on the pipeline condition; similarly, an assessment sensor for the pipe wall can be added for the inspection of metallic pipeline wall thickness. In addition to revealing average wall thicknesses at set intervals of a pipeline (every 9 m) based on the speed of sound (Liu and Kleiner, 2013), the TA system is capable of detecting internal corrosion, illegal taps, unknown laterals, and loss or damage to internal lining (Youngpyo and Boon, 2012).

The average set-up time for TA technique is estimated be one hour; although it should be noted that this is highly dependent on the water main access. Furthermore, the average on-station time for TA technique is estimated to be in the range of one to three hours depending on the size and condition of the pipeline; the on-station time is expected to be more for older water mains, for it takes longer to map and characterize numerous leaks (EPA report, 2010). Further applications, advantages, and limitations of the TA technique are highlighted in Table 2-2.

2.2.6 Acoustic Emission (AE)

AE technique is a commercial technique for near real-time leak detection (Xu et al., 2012) and integrity inspection of concrete pipelines, especially large diameter ones (Liu et al, 2012). The two phenomena that guide AE technique are: (a) sensors can detect the energy waves which are produced by the pressurized fluid flowing from the leak, as depicted in Figure 2-1f; and (b) growth of local cracks, cavitation at the leak, and movement of soil and temporary entrapment of solid particles at the pipe opening due to the leak can be the other sources of generated acoustic waves which propagate through the pipeline material or the fluid (Pollock and Hsu, 1982). Different sensors such as hydrophones, piezoelectric, fiber optics and micro-electromechanical can be used with the AE technique using appropriate monitoring frequencies ranging between 10 KHz to 40 KHz (Liu et al, 2012). The maximum spacing of sensors with this technique is suggested to be 100 m to achieve sufficient resolution of recorded data (Anastasopoulos et al., 2009). Filtration of noises, such as those resulting from passing traffic, pumps, and ground movement, is necessary before the recorded data using this technique can be analyzed. The higher average of signal amplitude at sensors closer to the leak narrows down the potential leak location to a smaller area.

The estimated average set-up time for AE technique excluding the time required for excavation is about one hour, while its average on-station time is in the range of two or three hours (Karr et al., 2003). The applications of AE technique along with specific advantages and limitations are highlighted in Table 2-2.

2.3 Comparative Evaluation of ALDTs

The ALDTs are comparatively evaluated for their suitability to four typical application scenarios based on four criteria. This section describes the typical application scenarios, presents an overview of the four evaluation criteria, and summarizes the performance of ALDTs.

Table 2-2. Advantages and limitations of various acoustic-based leak detection techniques

Technique	Advantages	Limitations
Listening Devices	- Suitable for asbestos cement and metallic pipes (diameter < 300 mm) - Inexpensive - No system interruption - No further analysis	-Unsuitable for non-metallic pipes (except asbestos cement) or large diameter pipelines unless the devices are placed in a close proximity of the leak's location (Hunaidi, 2012) -Not suitable for locating leaks or quantifying their severities -Operator's skill-dependent and extensive operator training is required
Noise Loggers	- No system interruption - Suitable for low-pressure pipelines inspection - Low cost battery and maintenance expenses	-Not suitable for locating leaks or quantifying their severities -High rate of false alarms and its hardware reliability is questionable (Van der Kleij and Stephenson, 2002; Hunaidi, 2012) -Temporary leakage survey using NL (very commonly employed) is less cost effective and it is estimated to be three times more expensive than LD (Pilcher, 2003; Hunaidi et al., 2004; Hamilton, 2009; Hunaidi, 2012)
Leak Noise Correlator	- No system interruption - A beneficial option for leak locating om small diameter metallic pipes	- Less productive and more costly in case of plastic and large diameter metallic pipes - Great chances of missing small leaks due to the possibility of their signals masked by ambient noises and large leaks due to the presence of softeners[1] in the pipe which may interfere with leak signals (Hunaidi, 2012) - Extensive operator training is required - Incapable of quantifying leak severity (Nestleroth et al., 2012)
Free Swimming Acoustic	- No system interruption - Pushes the practical limits of inspecting long pipeline sections with a single launch	- High cost - Unsuitable for highly complex pipeline configurations - Unsuitable for high pressure systems (>400 psi) - A chance of losing the ball during inspection when unknown conditions are encountered.
Tethered Acoustics	- No system interruption - Suitable options for leak detection/location of any material - Suitable for shorter lengths or more lateral connections (Nestleroth et al., 2012)	- It can be expensive - Incapable of discerning separate leaks in a cluster, similar to other methods - FSA and TA are both comparable in terms of equipment cost, however TA inspection tends to be more expensive as its hardware needs to be housed in a large vehicle during inspection.
Acoustic Emission	- Low maintenance requirements	- Developing standards to easily calibrate the equipment and preparing a library of acoustic signatures of known events still remain incomplete - Interruption of service during installation of sensors is required, which is typically accompanied with the cost and customer satisfaction issues. - Incapable of quantifying leakage severity (Anastasopoulos et al., 2009) - Suffers from high rate of false alarms (Xu et al., 2012)

1) A chemical additive used to reduce mineral content of the water

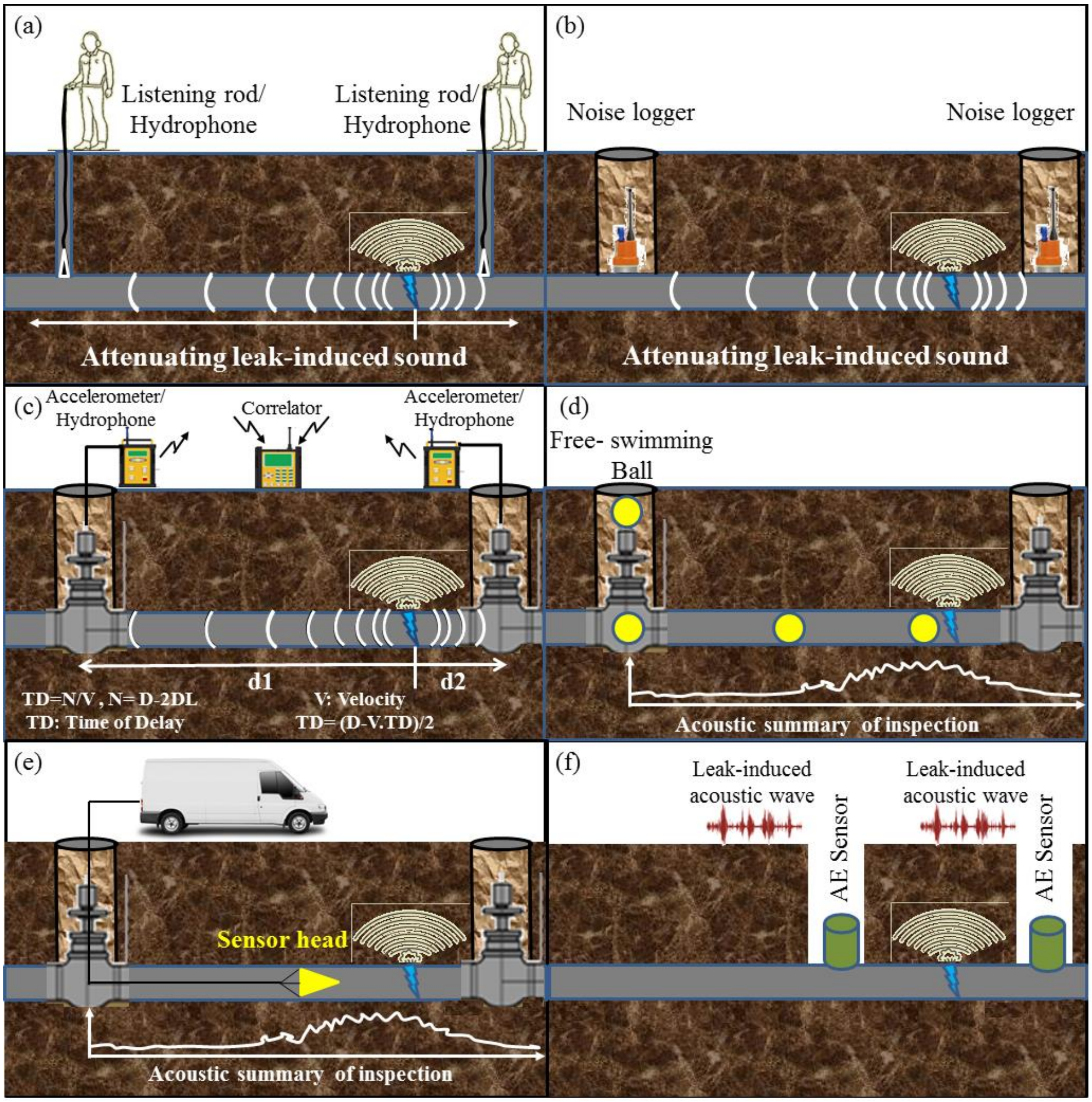

Figure 2-1- The principles of various acoustic-based leak detection methods: (a) LD; (b) NL; (c) LNC; (d) FSA; (e) TA; and (f) AE

2.3.1 Application Scenarios

The four broad application scenarios considered in this study are identified in Table 2-3. Scenarios one (SC1) and two (SC2) represents small diameter (< 300 mm) and large diameter (≥ 300 mm) metallic pipelines, respectively. A majority of water pipelines that are currently in service fall under either SC1 or SC2 scenarios. Scenario three (SC3) represents small diameter plastic pipelines (< 300 mm) which are becoming increasingly popular for water applications (Liu et al, 2012). Scenario four (SC4) represents large diameter concrete pipelines (> 600 mm) which are often used in transmission applications. Table 2-3 also identifies the set of ALDTs that are generally reported to be suitable for each application scenario.

Table 2-3. Application scenarios for ALDTs

Scenarios	Description	Suitable ALDTs
SC1	Metallic; <300 mm dia.	LD, NL, LNC, FSA TA[(1)], $\forall$ 250mm $\leq$ diameter < 300mm
SC2	Metallic; ≥300 mm dia.	FSA, TA, LNC
SC3	Plastic; <300 mm dia.	TA[(2)], FSA[(2)], LNC
SC4	Concrete; >600 mm dia.	TA, FSA, AE

[(1)] TA is suitable for SC1 but not commonly used for financial reasons
[(2)] Employing TA or FSA may be too expensive for small diameter plastic pipes which are currently not highly concerning to many water utilities

2.3.2 Performance Evaluation

The four evaluation criteria chosen for the comparative analysis of ALDTs are described in this section.

Reliability (C_R): Reliability in this context signifies the trustworthiness of the inspection results and it can be interpreted as the probability of detecting a leak and differentiating it from the ambient noises in a water pipeline system without any false-positives or false-negatives. This criterion is considered dependent on the sources of possible errors and likelihood of false positive/negative alarms with the use of any ALDT. The sources of errors with each ALDT have been highlighted in section 2. In order to estimate the likelihood of false alarms, the past performance of ALDTs has been synthesized from various field demonstration reports and other documents published by water utilities and researchers (Hunaidi et al., 2000, 2004, and 2012; Dingus et al., 2002; Van der Kleij and Stephenson, 2002; Colla et al., 2003; Hunaidi et al., 2004, Hunaidi, 2012; Hunaidi and Wang, 2006; Gao et al., 2004; Chastain-Howley, 2005; Mergelas and Henrich, 2005; Sánchez et al., 2005; Suzuki et al., 2005; Covas et al., 2006; Stringer et al., 2007; Fletcher and Chandrasekaran, 2008; Misiunas, 2008; Anastasopoulos et al., 2009; Thomson and Wang, 2009; Hamilton, 2009; Nestleroth et al., 2012; Nuss et al., 2012; Xu et al., 2012; Davis et al., 2013; Hamilton and Charalambous, 2013; Anguiano et al., 2016). Based on the synthesis of past performance of various ALDTs, they are categorized qualitatively into low, moderate and high reliability classes for each application scenario, as shown in Tables 2-4 and 2-5. Table 2-4 presents quantitative performance scores of ALDTs for various criteria as a translation of the qualitative performances as reported in the literature. Table 2-5 presents adjusted performance scores for various application scenarios depending on the suitability of ALDTs. Techniques that fall into the low reliability category, with a score of 1 (see Table 2-4) have been reported to generate high rates of false alarms in the field demonstrations. In contrast, techniques that fall in the high-reliability category, with score of 3, usually produced accurate results in the field demonstrations. Techniques that lacked consistency in performance but have been reported to be more satisfactory than the techniques in the low-reliability category are grouped into the moderate-reliability category with a score of 2. The ALDT performance scores presented in Table 2-4 and Table 2-5 are derived assuming that the ALDTs are used in an ad-hoc (or temporary) manner and not in a permanent deployment manner. It should also be noted that the scores of ALDTs vary depending on the application scenario because some ALDTs are more suitable to certain types of pipelines than others are. For example, the score of LNC for C_R criterion is greater in SC1 than SC2 and SC3, because of its better suitability to small diameter metallic pipelines (SC1). The latest improvements in LNC technique enabled by the enhanced correlation function, which improves the detection of peaks in case of narrow-band leak-induced signals, make it a more reliable ALDT for small diameter metallic pipes than other pipeline categories. The performance scores in Table 2-5 reflect the adjustments such as these made to the scores in Table 2-4.

Ability to Quantify Leak Severity (C_Q): ALDTs vary in their respective capabilities to quantify leak severity information that is vital for intervention planning by utility operators. Techniques that are incapable of quantifying leak severity are grouped into the "Incapable" category with score of 1 as shown in Table 2-4, while the capable techniques are grouped into the "Capable" category with score of 3. ALDTs that either provide less accurate leak severity information or need additional calibration for greater accuracy are grouped into the "Somewhat capable" category with a score of 2. The adjusted performance scores of various suitable ALDTs based on C_Q criterion for the four application scenarios are presented in Table 2-5. It can be observed from Table 2-5 that only FSA and TA are rated as "Somewhat capable" of determining leakage severity due to the possibility of comparing the recorded data from leakage surveys with the leak calibration curves. Most state-of-the-art ALDTs are incapable of accurately determining severity information, except for the ones that are typically employed for a more comprehensive pipeline condition assessment (e.g., Impact Echo). Such condition assessment techniques are excluded from this study as it is solely focused on leak detection methods.

Pipeline Access Requirements (C_A): Different ALDTs have varying pipeline access requirements, as discussed in section 2, and they are accordingly grouped into three categories as shown in Table 2-4 and appropriately rated for the four application scenarios as shown in Table 2-5. ALDTs that require access to the surface of the buried pipeline, which could be inconvenient to the utility operator and therefore less preferred, are grouped into the “Pipeline surface” category with a score of 1. As can be seen from Table 2-5, AE technique, which requires access to the pipeline surface all along the length of inspection, is given a score of 1. On the other hand, ALDTs that can conveniently tap into above ground fixtures such as fire hydrants are grouped into the “Above ground” category with a score of 3. As can be seen from Table 2-5, LD, NL and LNC techniques, which tap into aboveground fixtures, are given a score of 3. The inline ALDTs that work through the movement of transducers inside the pipeline require two access points, one for their insertion and another for extraction, and these ALDTs are grouped into the “Insertion and extraction only” category with score of 2. A few ALDTs can be classified into more than one category but with varying reliabilities; for example, LNC can work through “Pipeline surface” as well as “Above ground,” but tapping the fire hydrants (Above ground) was reportedly more accurate (Hunaidi, 2012). Similarly, LD can work through “Above ground” as well as through manual inspection, but “Above ground” category was reportedly more accurate (Hunaidi et al., 2000).

<u>Cost (C_C):</u> Based on the total cost incurred in inspecting a unit length of pipeline, ALDTs are categorized into three groups namely, high, moderate, and low with corresponding performance scores of 1, 2 and 3, respectively as shown in Table 2-4. The total cost, which is subjectively compared for various ALDTs, comprises of costs associated with labor, equipment, data analysis, and the societal inconvenience resulting from their use. The cost information used for the comparison of ALDT performance is obtained from the published literature.

The equipment cost is a function of the hardware and software needs of an ALDT. For the reasons highlighted in section 2, LD works with hardware that is cheaper than that of FSA, TA, and AE. Similarly, hardware costs of correlator-based techniques such as LNC are high except for those that can work with personal computers instead of existing expensive commercial correlators (Hunaidi et al., 2004). Labor costs, on the other hand, are dependent on the set-up requirements of each ALDT and the time it takes to inspect a unit length of a pipeline. Labor costs for setting-up tend to be higher if access to the external surface of the pipeline is desired. Consequently, labor costs for AE, which requires external pipeline surface access, would be more than other techniques. Other techniques including LD, NL, and LNC cost less in terms of labor. LD technique, which tends to take more time for inspection due to its less sensitive sensors compared to NL and LNC, would therefore require shorter sensor-to-sensor spacing, which in turn results in higher inspection-related labor costs followed by NL and LNC. On the other hand, FSA and TA techniques, which require only two access points (as insertion and extraction), would be least expensive for longer lengths of inspection due to minimal inspection time per unit length of the pipeline. The cost of analyzing the inspection data depends on the ease of analysis in terms of expertise required to translate the data into a more comprehensible format for interpretation. Data analysis for LNC, FSA, and AE techniques would be relatively more expensive due to the complexity involved in interpreting the inspection data.

In summary, scores of ALDTs in terms of C_C are based on their combined performance for all the afore-described cost categories coupled with limited quantitative and qualitative data available in the literature (Karr et al., 2003; Chastain-Howley 2005; Stringer et al., 2007; Thomson and Wang, 2009; EPA, 2010; Nestleroth et al., 2012 and Xu et al., 2012). The ALDTs are subsequently rated based on cost for the four application scenarios as shown in Table 2-5. It is found that LD is the only technique that can be grouped into the ”low” category for C_C, for it has cheaper needs in majority of cost categories and it does not result in any societal inconvenience. All other ALDTs are grouped into either “moderate” or “high” categories for C_C, as can be seen in Table 2-5. It should also be noted that the score of FSA for C_C criterion is lower in small diameter pipelines (i.e., SC1 and SC3) than large ones (i.e., in SC2 and SC4), as FSA is relatively more expensive for smaller diameter pipes due to the additional effort required to gain internal access.

Table 2-4. Criteria scoring for evaluating ALDTs

Criterion	Rating Type	Evaluation Ratings		
		Scores [1= least preferred; 3 = highest preferred]		
C_R	Qualitative	Low	Moderate	High
	Quantitative	1	2	3
C_Q	Qualitative	Incapable	Somewhat capable	Capable
	Quantitative	1	2	3
C_A	Qualitative	Pipeline surface	Insertion and extraction only	Above ground
	Quantitative	1	2	3
C_C	Qualitative	High	Moderate	Low
	Quantitative	1	2	3

Table 2-5. Evaluation of ALDT candidates for the four application scenarios

Criteria	SC1				SC2			SC3			SC4		
	LD	NL	LNC	FSA	FSA	TA	LNC	FSA	TA	LNC	FSA	TA	AE
C_C[(1)]	3	2	2	1	2	1	2	1	1	2	2	1	1
C_R	2	2	2	3	3	3	1	3	3	1	3	3	2
C_Q	1	1	1	2	2	2	1	2	2	1	2	2	1
C_A	3	3	3	2	2	2	3	2	2	3	2	2	1

[(1)]NL for temporary mode requires patroller unit for transmitting data with unit cost of $8,000/each and Permalog loggers for data collection which costs about $450/each (Stringer et al., 2007). The unit cost excluding preparation cost, traffic control and other logistical support is reported to be $16/m for FSA on average, while it is $7/m for longer inspections and $13/m for shorter runs in the case of TA (Nestleroth et al., 2012). The unit cost of the LNC technique with improved correlation function is reported to be $7/m (excluding costs of preparation, traffic control and logistical support) (Nestleroth et al., 2012). Furthermore, the preparation cost of the enhanced LNC is less than FSA and TA (Nestleroth et al., 2012).

2.4 Decision-Guidance for Optimal ALDT Selection

Monte-Carlo Analytical Hierarchy Process (MCAHP)-based guidance is proposed for determining selection preferences of ALDTs for the typical application scenarios. This section presents an overview of the MCAHP framework and the results of selection preferences.

2.4.1 Decision-making Framework

In order to identify an optimal ALDT for a given set of user-defined criteria preferences, a MATLAB code is written to integrate Monte Carlo analysis with the Analytical Hierarchy Process. Typical AHP procedure breaks down a decision problem, with precisely identified percentage weightings for the various influential criteria, to a hierarchical form. Subsequently, the set of choices are ranked for each criterion using pair wise comparisons while the decision criteria themselves are prioritized using similar pair wise comparisons (Saaty, 1987). In a traditional AHP procedure, the user (i.e., the decision maker) compares the influential criteria in a pair wise manner to inform the development of relative criteria weightings. Due to the wide ranges of application scenarios and individual preferences, it is challenging to derive a set of representative criteria weightings. Successful performance of Monte Carlo-AHP have been reported in various probabilistic judgments applications (Banuelas and Antony, 2004; Vaidya et al., 2006; Jing et al., 2012; Vien and Toussaint, 2015) In such probabilistic decision making applications, Monte Carlo (MC) simulation has been integrated with the AHP process for successful outcomes in the past (Banuelas and Antony, 2004; Vaidya et al., 2006; Jing et al., 2012; Vien and Toussaint, 2015). In the MC-AHP procedure, the criteria percentage weightings will be randomly generated so that they add up to 100%, and the decision problem is solved numerous times (i.e., simulations) using various sets of random criteria weightings (Banuelas and Antony, 2004).

Furthermore, the MCAHP procedure is adjusted to reflect the prevalent biases in the water utility decision-making. Among the four criteria considered in this study, cost, access requirements, and reliability are given specific preferences compared to the ability to quantify severity, for they are believed to be more critical in real-world decision making. Twenty seven "what-if" cases have been defined for each of the application scenarios (i.e., SC1-SC4), based on the systematic variation of percentage weightings for the four criteria, as shown in Figures 2-2, 2-3, 2-4 and 2-5. As can be observed from these figures, each "what-if" case is defined by the mean percentage weightings assigned to cost, reliability and access requirements criteria. The percentage criteria preferences are simulated using Monte-Carlo method, and in each simulation, optimal ALDT is determined using the traditional AHP method (Yaraghi et al., 2015). For example, the mean percentage weighting for the cost criterion varies from 90% in case 1 (which represents an application scenario with significant importance given to cost criterion) to 30% in case 27 (which represents an application scenario with less importance given to cost criterion). The actual weightings of these criteria are randomly generated in a ±5% range of the defined mean weightings (e.g. in range of 25-35% for cost in case # 27 and 85-95% in case #1). Accordingly, the percentage weighting of C_Q is determined such that sum of the weightings for the four criteria add up to 100% in each “what-if” case. The MCAHP code is run for 1,000 simulations for each “what-if” case and for each application scenario. The percentages of 1,000 simulations in which each ALDT is chosen as the optimal technique for each what-if case in application scenarios SC1, SC2, SC3, and SC4 are presented in Figures 2-2, 2-3, 2-4 and 2-5, respectively.

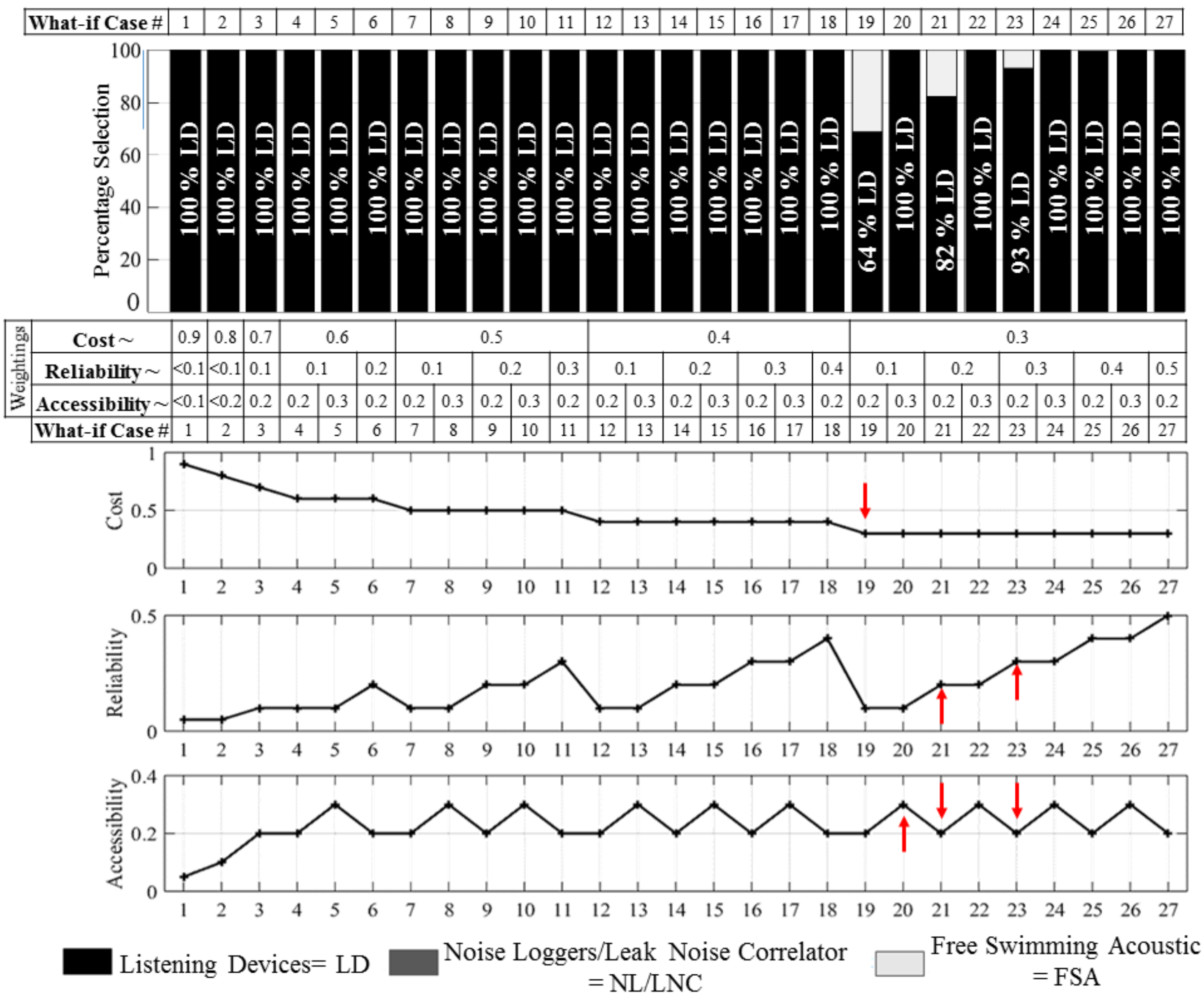

Figure 2-2. ALDT selection preferences scenario SC1 (the numbers at the bottom table are criteria weightings in absolute values, not in percentages)

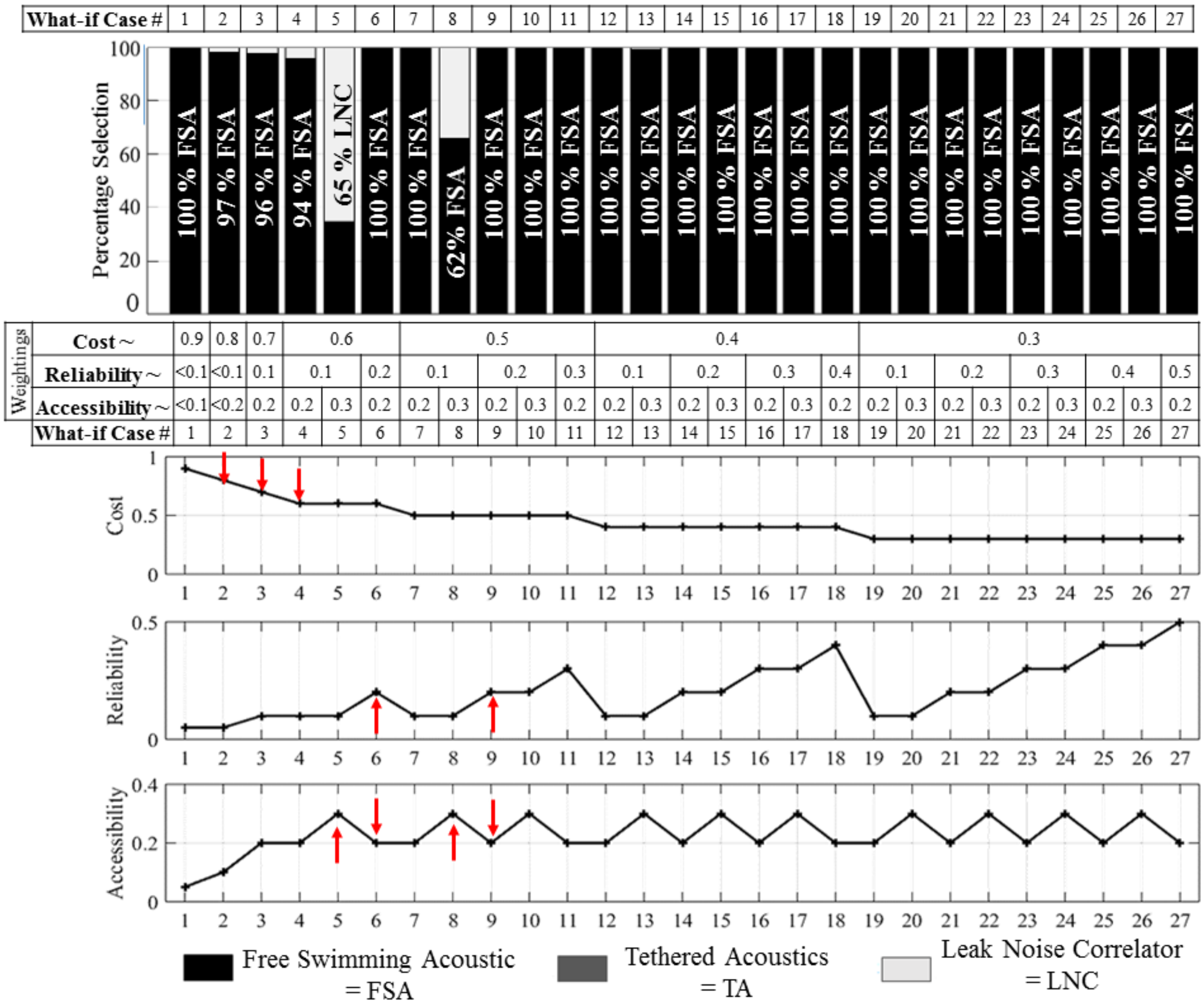

Figure 2-3. ALDT selection preferences scenario SC2 (the numbers at the bottom table are criteria weightings in absolute values, not in percentages)

2.4.2 Results and Discussion

The selection preferences of ALDTs for scenario SC1 are presented in Figure 2-2. For each of the 27 “what-if” cases, Figure 2-2 shows the distribution of most preferred ALDTs as a percentage of 1,000 simulations. It can be observed from Figure 2-2 that LD is found to be a highly preferred technique in all the 27 what-if cases of SC1. NL/LNC are not found to be preferable for SC1. It can also be observed from Figure 2-2 that FSA is found to be highly preferable in few of the 1,000 simulations for cases 19, 21, and 23, where combined preference weightings of reliability and quantification of damage severity are comparable to the combined weightings of cost and pipeline access requirement. The observed trends of LD's superior preference with higher cost weighting is mainly due to its cheaper cost, as can be seen from Table 2-5. The general percentage selection of LD decreased by reducing the cost weighting to 0.3 in case 19 while that of FSA increased; however, by increasing the accessibility weighting in case 20, LD becomes the only preferred option as it is more convenient for use compared to FSA. Similarly in 21st and 23rd cases, increase in reliability weighting and decrease in accessibility weighting (as highlighted in Figure 2-2) at low cost, supported the selection of FSA. While the trends presented in Figure 2-2 are generic in nature, it should be noted that NL is usually more preferred than LD for applications in noisy urban areas, e.g., high traffic zones, for it can pick up leak-induced sounds that are neither audible to the human ear nor to typical listening rods that are employed in LD (Hunaidi, 2012). Additionally, NL is a particularly suitable option for leak detection in low-pressure pipelines (Hamilton, 2009). LNC, on the other hand, is usually employed for pinpointing a leak in suspected regions, especially in case of pipelines that exhibit lower signal attenuation. Furthermore, the combined NL and LNC system is reportedly efficient for near real-time detection and pinpointing of leaks (Hunaidi, 2012).

As can be observed from Figure 2-3 , FSA is found to be the only preferred technique for SC2 in as many as 22 what-if cases and most preferred in four more cases. It can also be inferred from Figure 2-3 that the percentage preference of LNC is considerable when reliability (≤ 0.1) and quantification of damage severity (≤ 0.1) weightings are low, while access requirement (≥ 0.3) weighting is moderate and cost (≥ 0.5) weighting is high, simultaneously, as highlighted in Figure 2-3.

It can be seen from the first 11 what-if cases in Figure 2-4 that LNC is found to be the only preferred technique among the three suitable ALDT candidates for SC3 when cost is the main criterion of concern. When the cost preference weighting is moderate (= 0.4), the percentage selection of TA and FSA, which have similar performance scores for all criteria, are found to be increasing, specifically when the reliability weighting is increased and access requirement weighting is decreased, i.e. states 14, 16, and 18. In majority of cases 19-27 where cost is not the highest priority, TA and FSA are found to be the preferable options. Furthermore, percentage selection of LNC significantly decreased when reliability weighting has increased and access requirement weighting has decreased, i.e. states 21, 23, and 25.

For SC2 and SC3 application scenarios, it should be noted that FSA and TA are complementary techniques with FSA being more suitable for inspecting longer pipeline lengths with each insertion, while TA is more suitable for shorter distances or in cases where large numbers of lateral connections exist. Although FSA is found to be highly preferred in several what-if cases in Figure 2-3, it may not be always convenient to employ FSA technique because it needs access to the inside of the pipeline which may be inconvenient to utility owners. Furthermore, employing TA and FSA may be too expensive for small diameter plastic pipes (SC3) which are currently not as concerning to water utilities as the deteriorating metallic pipelines. LNC, on the other hand, as an external ALDT may be suitable for locating leaks in SC2 and SC3 scenarios, albeit less likely mainly due to the high signal attenuation rate in these scenarios and the resulting difficulty associated with sensing leak-induced changes through external transducers. Considering the difficulties and the economic considerations associated with the application of internal ALDTs for small diameter pipelines, there is a need for a technique that is economical and suitable for this class of pipelines.

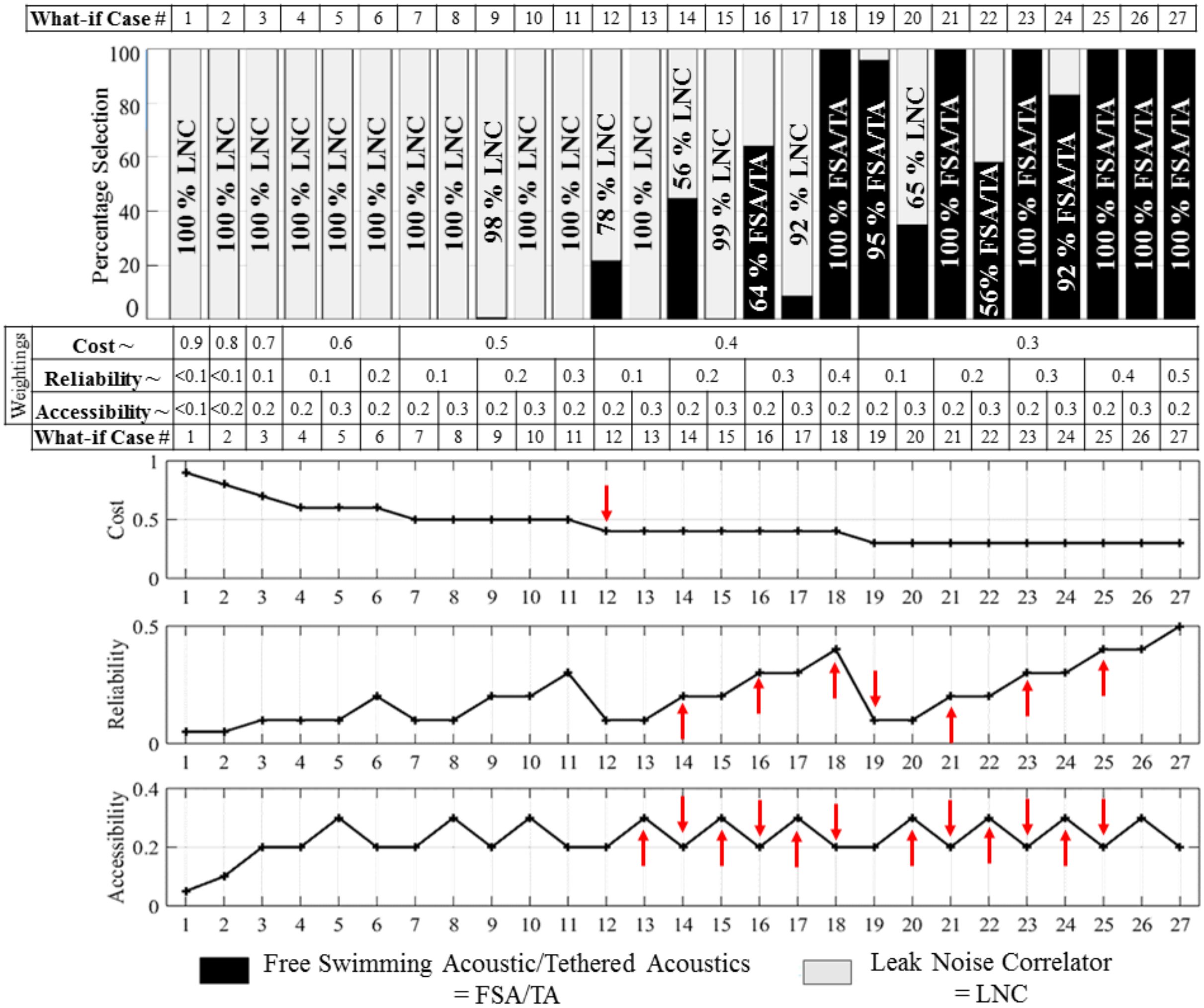

Figure 2-4. ALDT selection preferences scenario SC3 (the numbers at the bottom table are criteria weightings in absolute values, not in percentages)

It can be observed from Figure 2-5 that FSA is found to be the only preferred technique among the three suitable ALDT candidates for SC4. However, as pointed out previously in this paper, FSA is more suitable for inspecting longer pipelines, while TA is more suitable for shorter lengths. It is worth noting that AE, which is a suitable ALDT for SC4, offers additional insights on the pipeline condition such as remaining wall thickness and defect depth, thereby making it more suitable for a comprehensive pipeline inspection and not just leakage surveys.

It should be noted that the results presented in this paper are based on the ALDT scores derived from the literature after reasonable interpretations are made for meaningful comparisons where limited quantitative data is available. Consequently, the selection preferences of ALDTs, as presented in this paper, should be interpreted only as primitive as they may vary depending on the availability of more accurate data on ALDTs' performance.

Furthermore, in order to validate the performance evaluation presented in this paper, brief interviews of eight water utility professionals have been conducted. These experts represented water utilities and consulting companies. The lower expert participation reflects the fact that there are fewer experts that are knowledgeable about all the ALDTs reviewed in this paper; it should however be noted the expert inputs were largely congruent. In an attempt to minimize possible bias of one expert from unduly influencing the validation outcomes, the Delphi technique is used, as a popular tool for validating surveys (Okoli and Pawlowski, 2004; Kauko and Palmroos, 2014; Tricco et al., 2016). During multiple interactions with the respondent group, the responses from preliminary interactions are summarized and recirculated to identify and redress areas of disagreements (Hsu and Sandford, 2007). The experts were asked to choose suitable candidates for the four application scenarios based on the four decision criteria using their experiential knowledge. It was understood from their responses that cost and access requirements are the typical criteria of concern in the case of small diameter pipelines (SC1 and SC3), whereas reliability is a highly concerning criteria in the case of large diameter pipelines (SC2 and SC4). Summarizing the collective responses of the interviews, it was found to be customary for SC1 application scenario to adopt a straightforward leak survey procedure in which leakage presence is detected followed by the pinpointing of leaks with the combined total cost ranging between $125-$250 per km. Consistent with the findings of this paper for SC1, LD as one of the oldest and straightforward ALDTs is often employed in practice for small diameter metallic pipelines where reliability may not be a great concern. It was opined by the respondents that LD might be rarely successful in crowded areas where leak-induced noises are difficult to hear by the operator and consequently NL is meritorious and becomes preferable in such scenarios. Once the leak is detected and the potential leaky area is narrowed down to a smaller region, leak locating is typically carried out using LNC technique. FSA is beneficial for SC1 scenario only if reliability is of great concern and higher costs can be justified. Similarly, expert responses were found to be consistent with the findings presented in this paper for other application scenarios too. Figure 2-6 presents the summary of conclusions from this study, which should be further corroborated and extended in the future as the reviewed ALDTs continue to evolve into techniques that are more sophisticated.

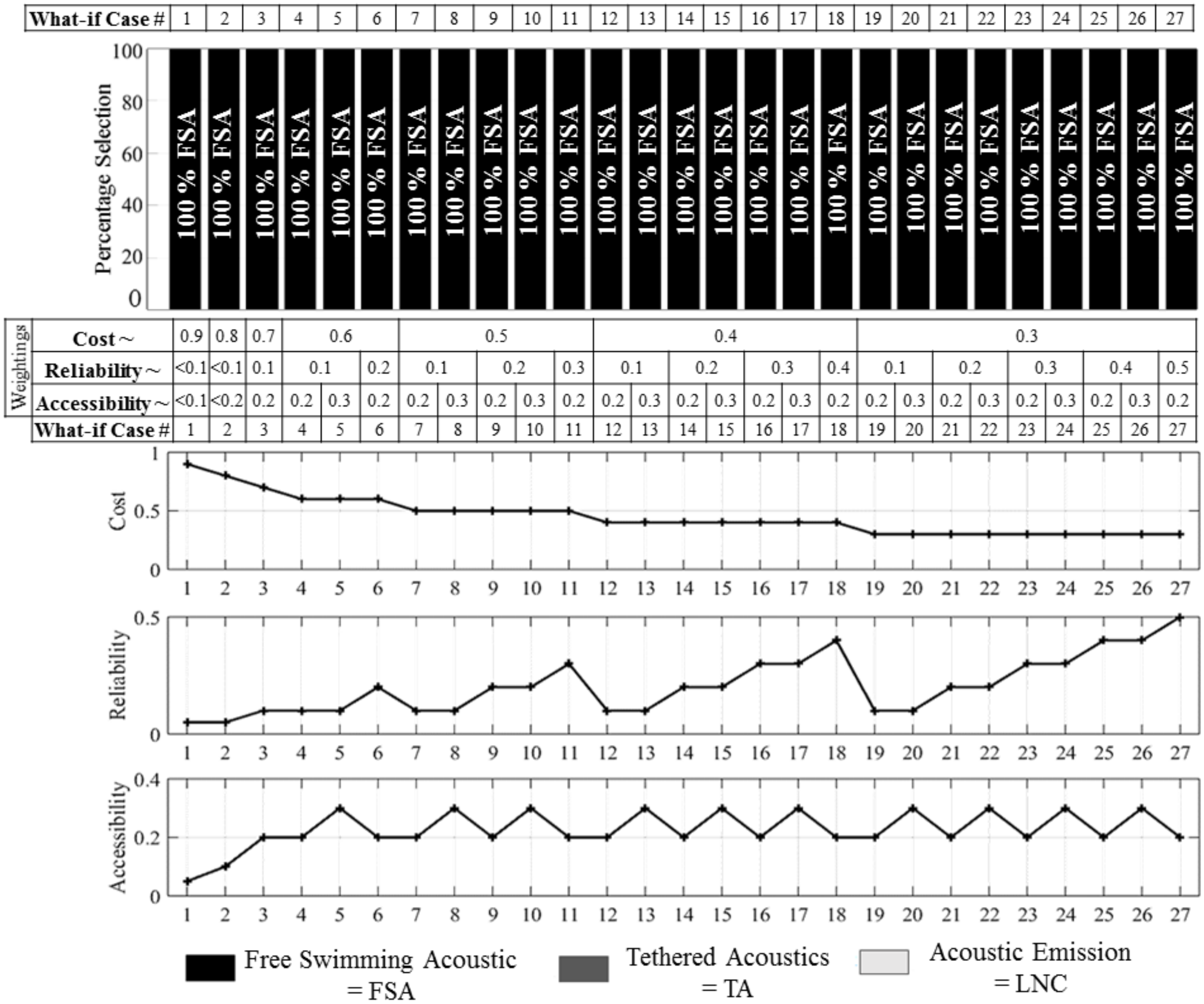

Figure 2-5. ALDT selection preferences scenario SC4 (the numbers at the bottom table are criteria weightings in absolute values, not in percentages)

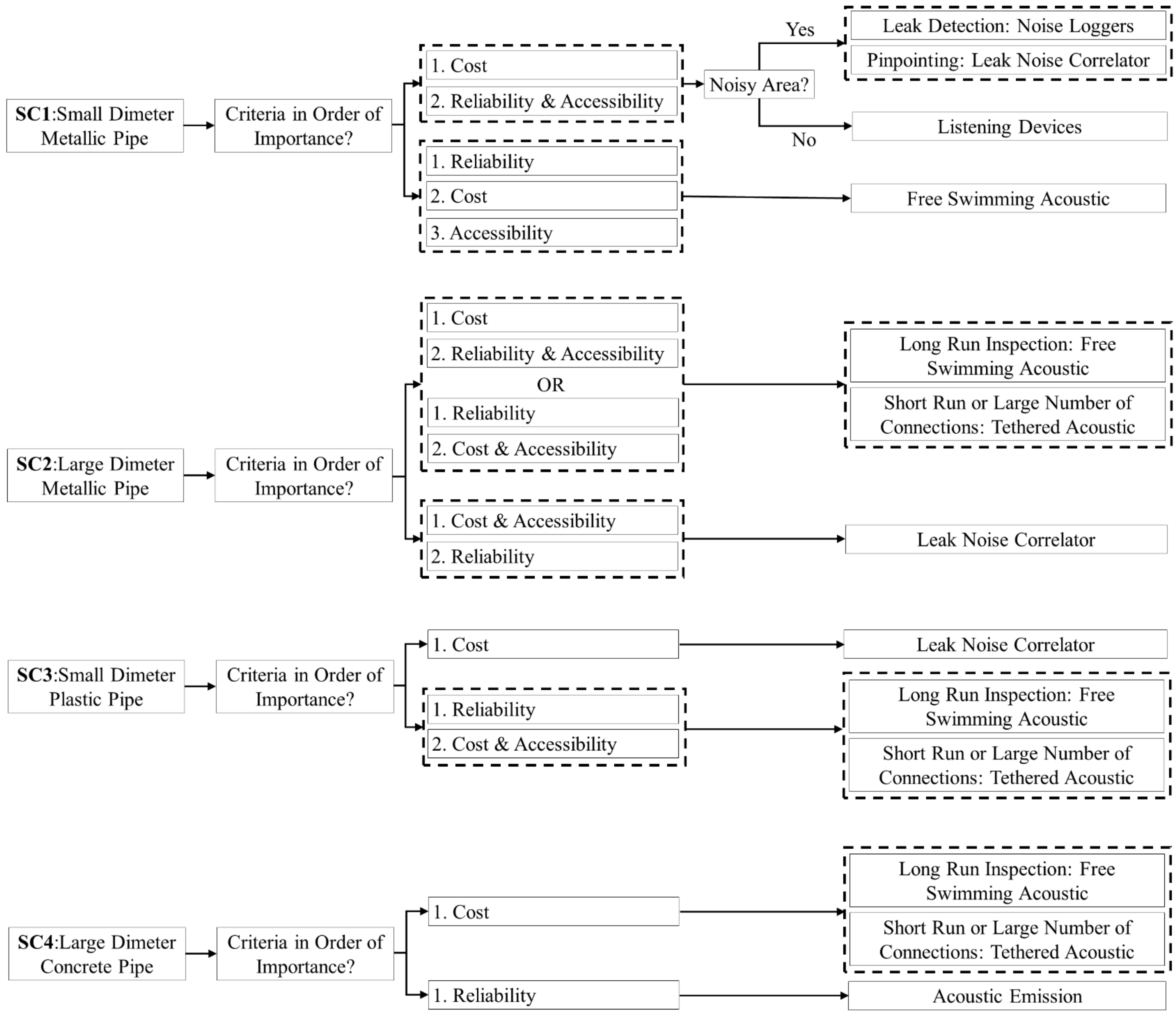

Figure 2-6. Flowchart of selection of acoustic-based leak detection methods over different conditions

2.5 Conclusions and Recommendations

Leakage of treated water in distribution system pipelines is one of the most concerning issues water utility owners currently face in the U.S. With the pipeline infrastructure deteriorating and the funding gap widening over the past few years, the technological needs for pipeline monitoring and rehabilitation have grown. There is shortage of guidance for choosing an appropriate leak detection technique from the many possible options that are currently available. Given the popularity of acoustics-based leak detection techniques (ALDTs), this paper systematically reviewed six commercial ALDTs and made recommendations for appropriate techniques for various typical application scenarios. The techniques evaluated include listening devices, noise loggers, leak noise correlators, free-swimming acoustic, tethered acoustics, and acoustic emissions. The criteria based on which these six techniques are evaluated in this study include cost, reliability, ability to quantify leakage severity, and pipeline access requirements. The performance evaluation presented in this paper is primarily based on the published literature in the form of research articles and reports summarizing several practical demonstrations. While the analytical hierarchy process (AHP) is employed for the evaluation of six ALDTs based on the four criteria, Monte-Carlo approach is used in conjunction with AHP to develop recommendations for appropriate ALDTs for various typical scenarios.

According to findings of this study, listening devices and leak noise correlators are found to be appropriately suitable for detecting and locating leakage of small diameter metallic pipelines. Monitoring of large diameter metallic and small diameter plastic pipelines is however reported to be problematic with conventional techniques such as listening devices and leak noise correlators, due to the greater attenuation of acoustic noises. In these cases, free-swimming acoustic and tethered acoustic techniques are found to be appropriately suitable. Additionally, free-swimming acoustic and tethered acoustic techniques are found to be suitable for detecting leakage in large diameter concrete transmission mains, as well. It should be noted that the findings of this study are consistent with the findings of brief interviews conducted with eight water utility experts. It is worth mentioning that a few of the ALDTs evaluated in this study are expected to be improved based on on-going R&D and consequently, their suitability and performance scores need to be updated periodically. Furthermore, the results should be interpreted cautiously as the application scenarios are average representations of typical industry needs and may not hold true under unique constraints and specific requirements. The study approach can be adapted in the future to develop selection guidance for other types of defect detection technologies; for example, technologies for evaluating pipe wall condition. The limitations of this study include: (a) the use of a rather simple scale for performance evaluation of ALDTs; and (b) the lack of sufficient quantitative performance data of various ALDTs and the subsequent interpretation of the available qualitative knowledge for developing ALDT scores.

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CHAPTER THREE

NOVEL VIBRATION-BASED TECHNIQUES FOR DETECTING WATER PIPELINE LEAKAGE[1]

Exacerbating the imbalance between demand for freshwater and available water resources is the sub-optimal performance of water distribution systems, which are plagued with leaks that cause significant losses of treated fresh water. This work presents an approach for leak detection that involves continuous monitoring of the changes in the correlation between surface acceleration measured at discrete locations along the pipeline length. A metric called Leak Detection Index (LDI) is formulated based on cross spectral density of measured pipe surface accelerations for detecting the onset and assessing the severity of leaks. The proposed non-invasive approach requires minimal human intervention and works under normal operating conditions of the pipeline system without causing any operational disturbances. The approach is demonstrated on a 76mm- diameter Polyvinyl Chloride (PVC) pipeline test system considering varying leak severities. The preliminary results presented in this work seem promising and lead to several interesting questions that will require further research.

3.1 Introduction

In the U.S., approximately 20% of all treated water, which amounts to about 26.5 million m^3 per day, is lost through pipeline leakage, and the losses exceed 50% in some developing and underdeveloped countries (Mutikanga et al., 2012). In addition to the loss of treated water, ancillary losses include embedded energy and the energy required to compensate the pressure losses due to leakage. Furthermore, leaks can potentially compromise the drinking water quality due to contaminant infiltration into Water

[1] Yazdekhasti, S., Piratla, K. R., Atamturktur, S., & Khan, A. A. (2017). Novel vibration-based technique for detecting water pipeline leakage. *Structure and Infrastructure Engineering*, *13*(6), 731-742.

Distribution Systems (WDSs). Given the lack of financial resources to adequately rehabilitate pipelines that continue to operate past their intended design life, leakage is expected to increase in the coming years (Costello et al., 2007).

A variety of non-destructive inspection techniques for pipeline leak detection, such as ground penetrating radar (Hyun et al., 2003), tracer gas (Hunaidi et al., 2000), infrared thermography (Zhang, 1997) and acoustic techniques (Hunaidi et al., 2004), exist. However, research needs and technology gaps still remain for the successful application of these techniques on a wide range of pipe materials and sizes. For example, acoustics-based techniques, which are the most widely used, have proven to be less reliable on plastic pipe material which is increasingly becoming the attractive choice for WDS pipelines (Liu et al., 2012). Additionally, current methods are labor-intensive, dependent on the operator’s expertise, and less useful for continuous real-time monitoring of WDSs. Due to their higher costs, inspection using current non-destructive techniques is justified only in the case of large diameter transmission pipelines which when fail will result in significant consequences (Nestleroth et al., 2012). In an attempt to address some of these limitations, this paper presents a vibration-based monitoring approach for detecting the occurrence, locating the vicinity, and quantifying the relative severity of leaks in WDS pipelines. The proposed technique employs the principles of structural health monitoring and entails the use of accelerometers installed along the length of the pipeline to continuously (or quasi-continuously) monitor the system dynamic behavior. The approach has been successfully demonstrated through a series of tests conducted on an experimental pipeline test bed that is made of 76 mm diameter, Polyvinyl Chloride

(PVC) pipe. The results obtained from the preliminary experimental campaign are highly encouraging; although, further validation on more complex pipeline configurations and testing conditions is required to determine the true extent of the merits and limitations.

3.2 Background Perspectives

The behavior of a damaged water pipeline depends on its structural characteristics, hydraulic behavior of the fluid flowing within, and the fluid-pipe interaction. Several studies previously employed these principles both individually and collectively to formulate defect detection and location mechanisms.

Damage detection studies based on pipeline structural behavior relied on the premise that vibration response characteristics (i.e., natural frequencies, mode shapes, modal damping, and time history acceleration response) and their derivatives (i.e., mode shape curvature and statistical properties) are functions of the physical properties of the pipeline structure (i.e., mass, stiffness, and damping) and that change in these properties due to a defect may alter the vibration response (Murigendrapp et al., 2004a,b; Cheraghi et al., 2005; Farrar and Worden, 2007; Naniwadekar et al. 2008; He et al., 2009; Dilena et al., 2011; Sharma, 2013; Atamturktur et al. 2013; Martini et al., 2014). Vibration response characteristics of a pipeline are however global features that may be similar for several defect types, positions and severities, making it challenging to determine a unique defect signature (Farrar and Worden, 2007; Atamturktur et al., 2011). Addressing this limitation, several other studies focused on integrating physics-based models, such as the finite element models, with measurements to better understand the variation of vibration responses (Murigendrappa et al., 2004a; Murigendrappa et al., 2004b; Naniwadekar et al., 2008; Dilena et al., 2011). The development of finite element models will however require a large amount of accurate system information which may not be available or difficult to measure.

On the other hand, a majority of leak detection studies based on flow characteristics internal to the pipelines exploited the transient conditions in water pipelines triggered by sudden changes in system boundaries, typically resulting from rapid closure of valves or pump shutoffs (Jönsson and Larson, 1992; Wang et al., 2002; Covas et al., 2005; Lee et al., 2005, 2006). Such rapid changes prompt a pressure wave that travels along the pipe length at the speed of sound in water, and this transient pressure wave gets reflected at pipe fittings, storage tanks, leaks, or demand nodes with varying consumption rates (Colombo et al., 2009). Despite the successful performance of this class of methods on stand-alone pipelines in laboratory environments, their application on complex looped systems are limited (Colombo et al., 2009) due to the difficulty in differentiating reflected pressure waves from pipe fittings and demand changes from that of leaks (Vitkovsky et al., 2003). Transient pressure waves are also dampened by valves, bends, flanges and other appurtenances used in looped systems (Wu et al., 2010), making it difficult to detect leaks using this class of methods. Furthermore, this approach could disturb the regular service of a pipeline system due to the use of invasive pressure transducers (Ben-Mansour et al., 2012).

The third class of leak detection studies is based on pipe-flow interactions. Usually, the temporal pressure gradient of water tends to be larger at locations closer to the source of transient, such as a pipe rupture (Stoianov et al., 2007), and it decays in both pipeline directions (Gao et al., 2004; Shinozuka et al., 2010a). This sharp change in the water pressure is accompanied by a sharp change in the amplitude of vibration response of the pipeline surface (Shinozuka and Dong, 2005). Studies based on pipe-flow interaction monitored the changes in the pipeline surface vibration to interpret changes in water pressure due to a leak (Hunaidi and Chu, 1999; Stoianov et al., 2007; Shinozuka et al., 2010 a, b; and Yoon et al., 2012). This class of techniques suffers from some of the limitations of the flow-based techniques such as the difficulty in distinguishing pressure changes from other transient sources and those due to a leak.

Besides these three classes of leak detection studies, there are several commercially available acoustics-based techniques for locating leaks and these are based on the cross-correlation of collected acoustic signals from different points along the pipeline (Brennan et al., 2008, Hunaidi, 2012). These cross-correlation-based techniques have proven to be reasonably effective on metal pipelines but less on plastic pipes (Liu et al., 2012).

While the leak detection approach proposed in this paper is fundamentally different to several previously proposed approaches in the way it measures the effect of a leak on the system characteristics, it is built upon the principles of pipeline structural behavior and fluid flow characteristics. The proposed approach uses the flow internal to the pipeline as the excitation force to determine the change in cross spectral density (CSD) of vibration data measured at discrete locations on the pipeline between the baseline (i.e., before leak developed) and leaky (i.e., after leak developed) states of the system. The proposed method leverages the change in frequency content of enclosed flow due to the onset of a leak, whereas other cross-correlation based techniques use the cross-correlation function to pin-point the location of suspected leak by estimating the exact distance between two mounted sensors, difference in arrival times of leak-induced signals at those two locations, and the leak noise propagation speed in the pipeline (Hunaidi, 2012).

3.3 Vibration-Based Leak Detection Concept

The leak detection approach proposed in this paper relies on the continuous monitoring of pipeline vibration characteristics to extract an index that is sensitive to the onset of leaks and insensitive to ambient noises.

3.3.1 Conceptual Framework

The presence of a leak within the pipeline introduces pressure variations, which are correlated with the flow-induced pipeline vibration (Sreejith et al., 2004) caused by the fluid-pipeline interaction. This interaction is a result of the transfer of momentum and forces between the pipeline and the internal flow. Three coupling mechanisms compose this fluid-pipeline interaction as illustrated in Figure 3-1, namely Poisson coupling, friction coupling, and junction coupling. Poisson coupling relates the circumferential stress perturbation produced by pressure transients in the fluid to the axial stress perturbations by virtue of Poisson ratio coefficient (Wiggert et al., 1987). Friction coupling, which is usually insignificant, is produced by the shear stresses of the fluid acting on the pipe wall (Tijsseling, 1996). Junction coupling, the most relevant to this study, occurs at unsupported discrete points of the pipeline system through the unbalanced pressure forces and variation in the momentum of flow due for instance to leaks (Wang & Eat Tan, 1997).

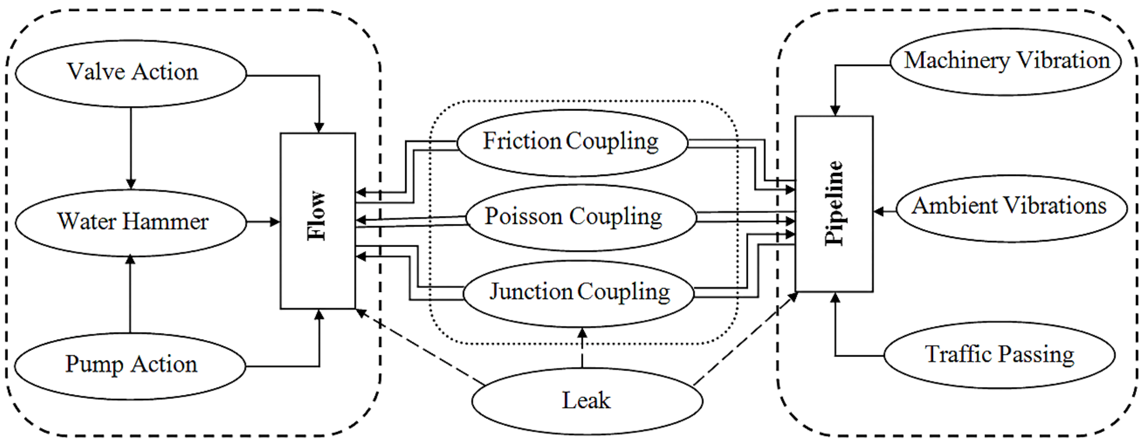

Figure 3-1-Sources of excitations and interaction between fluid and pipeline

When a leak occurs, the transient change in water pressure propagates through the pipeline, resulting in pipeline vibration because of junction coupling. The pipeline vibration is proportional to the pressure fluctuations, which can be described through Reynold's decomposition of total internal pressure of pipeline, p, into the mean component of internal pressure of flow, $\overline{p}$, and the pressure fluctuating component, p', as shown in Eq. 1.

$$p = \overline{p} + p' \tag{1}$$

The pressure fluctuations can then be related to the pipe surface acceleration, $d^2(y)/\, dt^2$ using the differential equation of motion for transverse vibration of a beam, given by Eq. 2 (Seto, 1964):

$$\frac{d^2y}{dt^2} = -\frac{g}{A\gamma} EI \frac{d^4y}{dx^4} = -Cp'(x) \tag{2}$$

where, C is equal to g/A, A is cross sectional area of the beam, γ is the specific weight of the beam, g is the acceleration of gravity, and EI is flexural rigidity.

This study relies on the premise that the onset of a leak causes expulsion of water, which results in a change in the pressure fluctuation and subsequent vibration fluctuation of the pipeline. As a result, the leak is expected to change the measured Power Spectrum Density (PSD) (see Figure 3-2). The PSD operator describes the power distribution of the supplied time signal over different frequencies. PSD can be interpreted as the relative power carried in a sine wave of a given frequency (Stoica & Moses, 1997; Hunaidi & Chu, 1999). As can be observed in Figure 3-2, the PSD of a leak-free pipeline vibration response under operational conditions (i.e. flow excitation) is distinctly different than that of a leaky pipeline, particularly in higher frequencies. A challenge here is in distinguishing changes in the PSD due to leaks from those that are due to random noises.

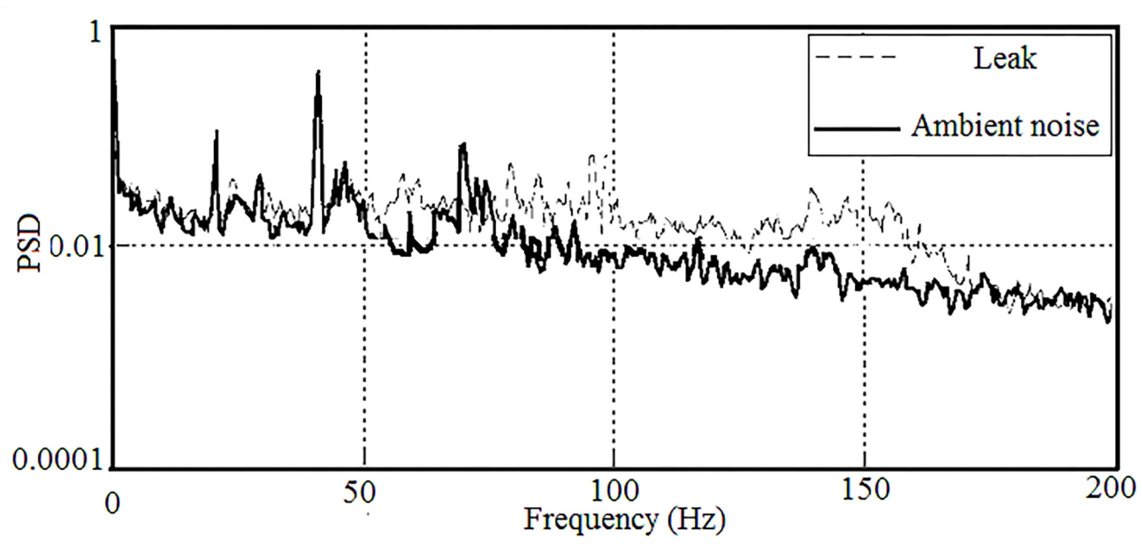

Figure 3-2-Comparison of the PSD of the leak and ambient noise measured by two accelerometers (adapted from Hunaidi and Chu, 1999).

One approach for addressing this challenge is the use of cross-correlation between acceleration data measured at two distinct locations. The effect of spatially- uncorrelated out-of-control noises are filtered by the cross-correlation function (Tokmouline, 2006) which results in the manifestation of leak-induced peaks, which are the only correlated components in the vibration signal. The propagation of the generated transient wave along the pipe in both directions away from the leak (Gao et al., 2004) makes it possible to detect leak by comparing data collected from two accelerometers mounted on the pipeline surface on both sides of the leak.

The leak-borne signals collected in the presence of ambient noise can be represented as:

$$x_1(t) = l_1(t) + n_1(t) \tag{3}$$

$$x_2(t) = l_2(t) + n_2(t) \tag{4}$$

where, $l_1(t)$ and $l_2(t)$ are leak-induced disturbance signals collected from accelerometers 1 and 2, respectively; $n_1(t)$ and $n_2(t)$ are ambient noise signals at the two locations.

The cross-correlation function of the signals $x_1(t)$ and $x_2(t)$ is calculated by Eq-5:

$$\begin{aligned} C_{12}(\tau) &= E[x_1(t)x_2(t+\tau)] \\ &= E[l_1(t)l_2(t+\tau)] + E[l_1(t)n_2(t+\tau)] + E[n_1(t)l_2(t+\tau)] + E[n_1(t)n_2(t+\tau)] \end{aligned} \tag{5}$$

where, τ is the lag of time, and E [.] is the expectation operator.

In the absence of ambient noise, the second, third and fourth terms in Eq-5 vanish leading to a single peak in the cross-correlation function that is due to the leak. However, in practice, the ambient noise contaminates the collected signal. A common noise reduction technique used in signal processing is the filtering approach, which sharpens the peaks in the cross-correlation functions. Previous studies have also suggested that the pipe itself acts as a low pass filter, attenuating high frequency, hard-to-control noises (Tokmouline, 2006).

3.3.2 Leak Detection Index (LDI)

As shown in Eq-5, the presence of a leak alters the cross-correlation function of the acceleration response measured at multiple points along the pipeline. The Cross Spectral Density (CSD), which is the Fourier transform of the cross-correlation of two discrete-time signals, represents the power that is shared by two signals at any frequency. CSD captures changes in both the cross-correlation and PSD functions due to the presence of a leak. The higher the value of CSD, the greater the correlation between the data from the two measurement locations.

In this study, LDI is devised as a distance-based damage indicator relying on the quantification of differences in the physical system based on changes in CSD due to a leak. Similar distance-based indices have been successfully used in several structural health monitoring studies (Ramaswamy et al., 2000; Niu et al., 2011). LDI involves the difference between the CSD functions of leaky and baseline pipeline states normalized with respect to the baseline state:

$$LDI = \frac{\int \left| x^i(t) - x^d(t) \right|}{\int \left| x^i(t) \right|} \tag{6}$$

where, $x^i(t)$ is the CSD of the baseline system and $x^d(t)$ is the CSD of the damaged one. The LDI-based leak detection approach developed in this study is presented in Figure 3-3.

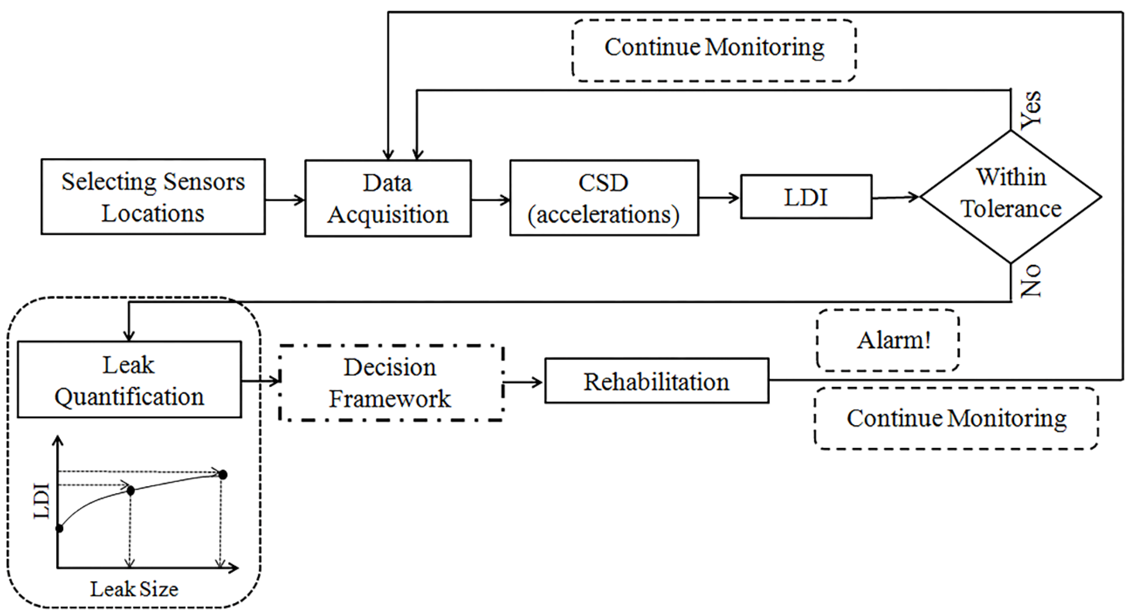

Figure 3-3-Proposed approach for pipeline leak detection.

3.4 Research Methodology and Experimental Campaign

3.4.1 Experimental Set-up

The test bed used in this study for demonstrating the proposed leak detection approach is a closed loop, PVC pipeline system with an integrated leak simulator, as shown in Figure 3-4. The system consists of 16m long, 76mm diameter PVC pipe, installed at a depth of about 0.6m, connected to a Dayton model of 3KV80A pump and a 210-liter reservoir. The pipeline flow rate is determined to be 1,100 lit/min which is calculated based on the pump curve. As illustrated in Figure 3-4, a 0.3m long interchangeable section is placed in the middle of the PVC pipe to simulate leaks of multiple severities by opening the attached 25.4 mm ball valve in a step-wise manner. In addition, as shown in Figure 3-4, one 45^0 bend and two 90^0 bends at different elevations are used at upstream and downstream of the leak, respectively, to form a loop of pipeline connected to pump and reservoir.

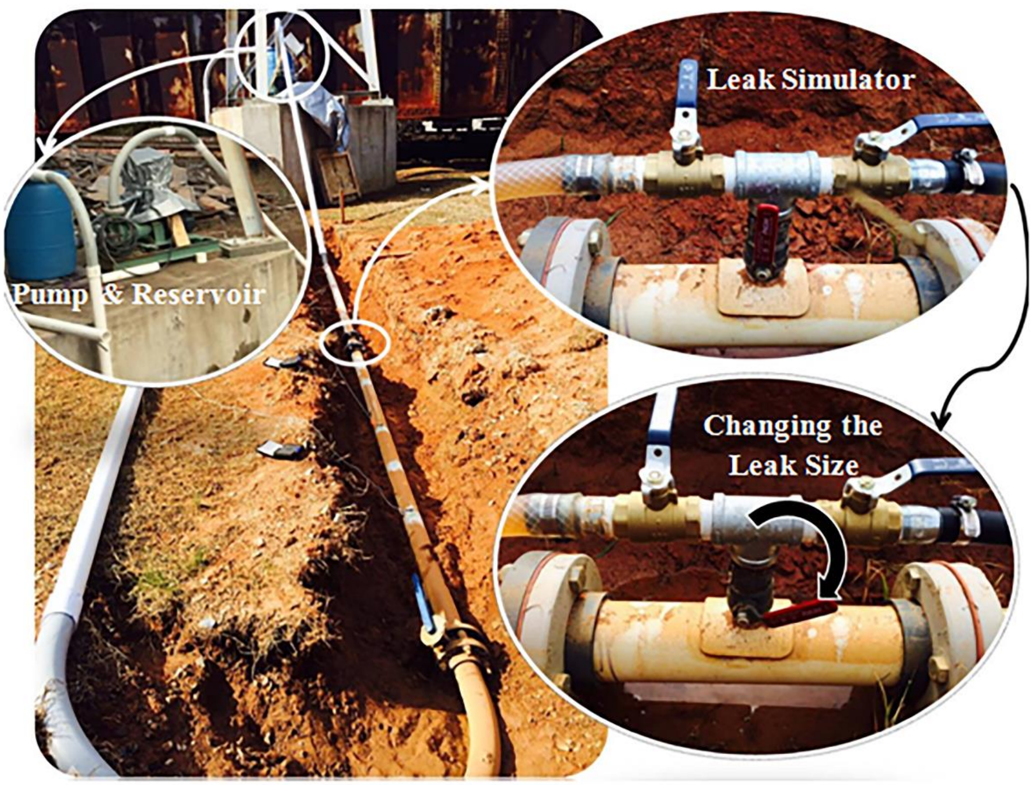

Figure 3-4-Experimental pipeline test bed.

3.4.2 Experimental Campaign

Six accelerometers are mounted on the pipeline at three monitoring points along pipeline length, referred to as points A, B, and C, as illustrated in Figure 3-5. At each monitoring point, one accelerometer is placed in the same azimuthal position as the leak, while another accelerometer is placed at a 90 degree angle from the azimuthal position of the leak. Bruel and Kjaer 4507 B type of accelerometers with nominal sensitivity of 50 mV/N are employed in this study. The interchangeable leak simulator is placed at an equal-distance between monitoring points B and C and the monitoring point A is placed same distance away from B. The accelerometer placement is selected such that the variation in vibration response can be studied along the length of the pipeline both upstream and downstream of the leak.

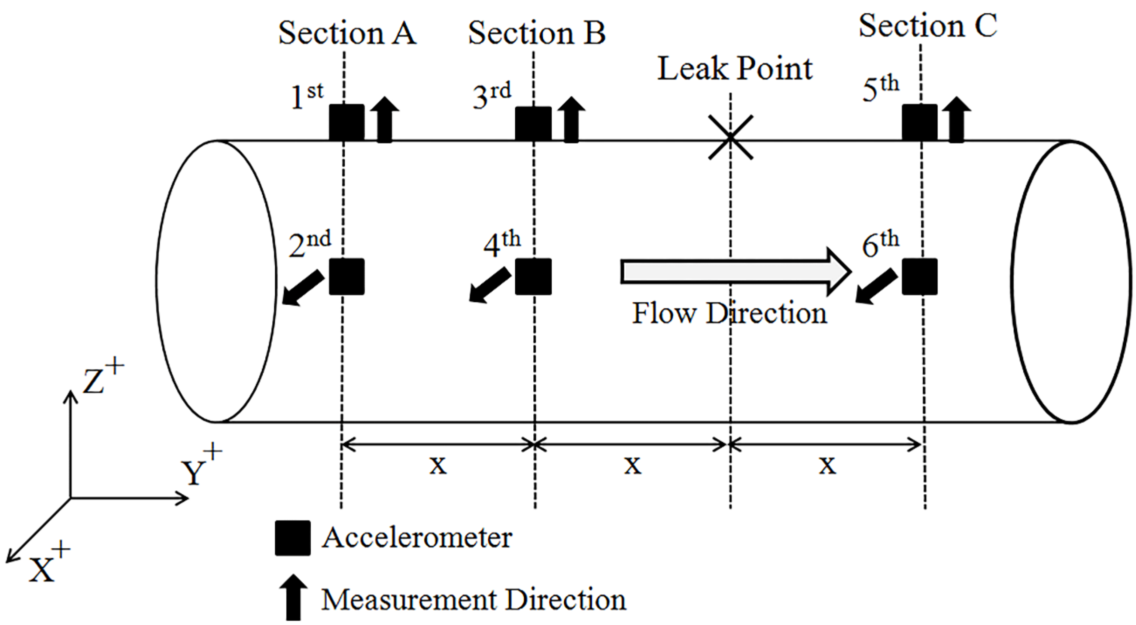

Figure 3-5-Schematic of the experimental configuration (Y-axis is along the flow direction).

The PSD of the flow at any given radial position is a function of Reynolds number, which is a dimensionless quantity used to characterize the flow as laminar or turbulent (Sattarzade, 2011). Based on the PSD graphs presented by Sattarzade (2011) related to energy distribution of flow for different Reynolds numbers and radial positions, the pipeline considered in this study is determined to be excited by the internal flow to the pipeline at frequencies lower than 1000 Hz.

Time-domain acceleration data is collected with a lowest frequency component of 10 Hz and a span of 1600 Hz, leading to a frequency resolution of 11.5 mHz, time resolution of 2.5e-4 seconds with 33-sec data samples. The upper frequency limit is selected based on the frequency span of the energy distribution from the flow excitation (1000 Hz) which needs to be covered, and the lower frequency limit is selected in order to filter noises at frequencies below the first vibration mode of the pipe. A commercial data-acquisition system of the Bruel and Kjaer multi-purpose 4- and 6-channel input LAN-XI type modules with frequency range of 0-51.2 KHz are used to record and digitize acceleration signals. Since the pipeline inherently acts as a low pass filter, the effect of high frequency, hard-to-control noise is expected to be suppressed during data acquisition. This expectation is verified in this study as the use of a Butterworth filter, to filter out high frequency response resulted in no significant difference in the measured ASD.

In this study, five scenarios shown in Table 3-1 are evaluated for detecting the presence and severity of leaks. Different valve configurations, as shown in Table 3-2, are used to simulate the five damage severities evaluated in scenarios 4 and 5. Damage Severity-1 (DS1) represents the baseline state and it is simulated by fully closing the leak simulator's ball valve, whereas DS5 represents a system with maximum damage severity simulated by fully opening the ball valve.

Table 3-1-Experimental scenarios tested in this study.

Scenario	Description	Objective
1	Intact system under three pump rotational frequencies (using all six accelerometers)	Study the effect of pump's rotational frequency on the pipeline dynamic response
2	Intact system without flow (using all six accelerometers)	Study the effect of pressurized flow in the system
3	Intact system filled with pressurized water (using all six accelerometers)	
4	Leaky system with five damage severities (using 1st, 3rd and 5th accelerometers*)	Study the ability of accelerometers that are placed in the same clock position as the leak in detecting and determining damage severity
5	Leaky system with five damage severities (using 2nd, 4th and 6th accelerometers*)	Study the ability of accelerometers that are placed at 90 degree angle with respect to the clock position of the leak in detecting and determining damage severity

Table 3-2- Valve configurations used for simulating different damage severities.

Severity Level	Valve Configuration	Leak Discharge (lpm)
DS1	Fully Closed	0
DS2	One Quarter Opened	8.93
DS3	Half Opened	26.87
DS4	Three Quarters Opened	61.50
DS5	Fully Opened	89.10

3.5 Results and Findings

3.5.1 Preliminary Investigations

Preliminary investigations have been carried out to evaluate the general influences of pump and water flow on the dynamic response of the pipeline system. The intent is to highlight the characteristics of the internal flow as the excitation force on the pipeline and derive a general result that is applicable to other systems as well, without requiring to repeat the hammer impact test on each system.

3.5.1.1 Effect of Pump on the Dynamic Response of the Pipeline System

The operating pump generates noise, and thus it is necessary to evaluate the effect of this noise on the dynamic response of the pipeline system. The effect of the operating pump is evaluated for rotational frequencies of 0 (i.e., pump shutoff), 30, and 45 Hz. Hammer impact excitation is used to induce forced vibration into the system, to ensure the system is adequately excited for consistently testing the effect of the three pump rotational frequencies. Using internal pipeline flow alone as the excitation force would have been inadequate when pump rotational frequency is zero and that is why a hammer test is employed. An 8207 model sledge-hammer, manufactured by Bruel and Kjaer, capable of exciting the system above the maximum pump noise level is used. For each pump rotational frequency, the baseline system is excited at monitoring point A (see Figure 3-5) using the sledge-hammer with an approximate force of 490 N. Average pipeline frequency-domain responses for five repetitive tests are calculated to evaluate the influence of pump rotational frequency.

In the frequency domain, the measured pipeline response normalized with respect to the corresponding hammer impulse leads to Frequency Response Functions (FRF). FRFs are obtained for all six accelerometers. Figure 3-6a shows the representative FRFs from the 5th accelerometer for three different pump rotational frequencies. It can be observed from Figure 3-6a that the FRF of the system for pump rotational frequency of 0 Hz is well-correlated with those for pump frequencies of 30 Hz and 45 Hz, and therefore the pump operation is considered to be an insignificant factor in this study. A similar trend is observed for all other accelerometers which indicated that there is no need for repeating the hammer impact test on each system in the future applications of the proposed technique.

3.5.1.2 Effect of Water Flow on the Dynamic Response of the System

Coherence function measures the degree of linear dependency of output signals to the measured input signals and is representative of the quality of measurements. Coherence assumes a value between 0 and 1, with a value of 1 representing ideal conditions and a value less than 1 indicating noise or non-linearity within the system. As part of Scenarios 2 and 3 (recall Table 3-1), coherence plots for the three pump rotational frequencies considered in Section 5.1.1, i.e. 10, 30 and 45 Hz, are compared to evaluate how the flow excites the pipeline system. Higher pump rotational frequency results in increased flow pressure, improving the coherence specifically in higher frequencies (>800 Hz) as demonstrated in Figure 3-6b for the 1st accelerometer. Similar trend is observed in all six accelerometers, which indicates the benefits associated with the presence of pressurized flow in the pipeline.

3.5.2 Leak Detection

The simulated leak is located at the topmost point of the pipeline (i.e., 0 degrees azimuth) as depicted in Figure 3-5. In this study, vibration profiles gathered from monitoring locations oriented in two different azimuthal positions are evaluated (as part of Scenarios 4 and 5 in Table 3-1, respectively) for their ability in detecting the onset and severity of the leak. The 1st, 3rd and 5th accelerometers, which are aligned with the azimuthal position of the leak, constitute the first set; whereas the 2nd, 4th and 6th accelerometers placed with a 90 degree angle from the azimuthal position of the leak constitute the second set. Results for each set of accelerometers are separately discussed in the following sub-sections.

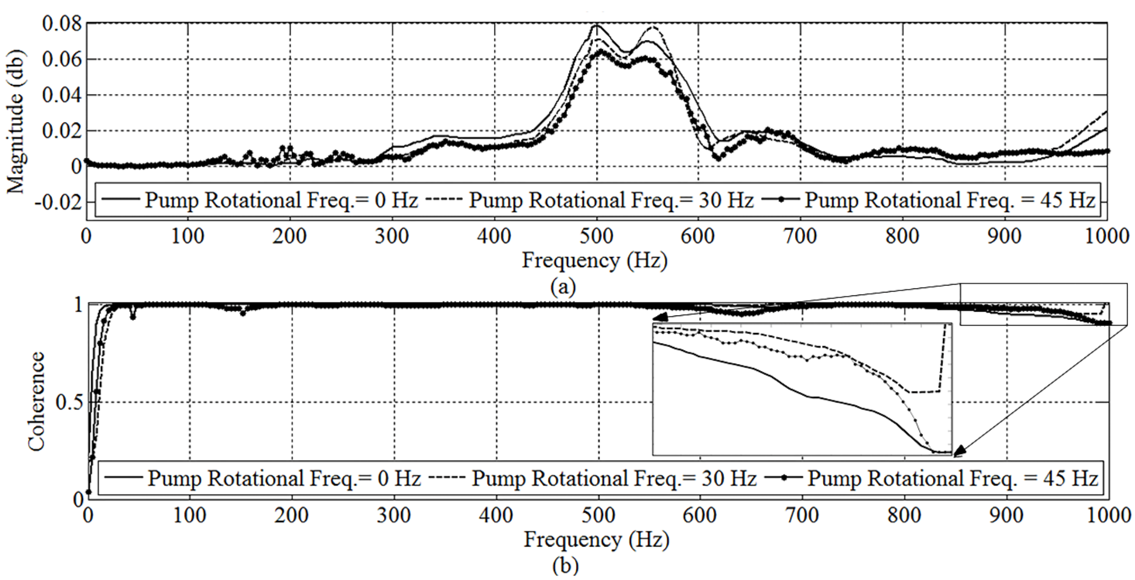

Figure 3-6- (a) Average FRFs of the 5th accelerometer in the hammer impact tests for the three pump rotational frequencies. (b) Coherence of 1st accelerometer in the hammer impact test.

3.5.2.1 Accelerometers and Leak Exist in the Same Azimuthal Position

One hundred tests are performed for each damage severity level (see Table 3-2) to achieve statistical significance of the obtained acceleration data and eliminate the influence of sporadic outliers. Acceleration responses under ambient excitation due to turbulent water flow are recorded. The CSD functions of each pair of accelerometers, i.e., 1^{st}-3^{rd}, 1^{st}-5^{th} and 3^{rd}-5^{th}, are observed to be negative in all three cases implying that the measured acceleration amplitude of one accelerometer decreases when that of other accelerometer increases. Figure 3-7a presents the CSD plots of the 3^{rd} and 5^{th} accelerometers based on 100 data sets for the baseline (DS1) scenario. It can be seen from Figure 3-7a that the observed frequency range matches the predefined range of interest (i.e., 0-1000 Hz). A similar trend is observed for other pairs of accelerometers.

Figure 3-7b presents the mean CSD plots of the 3^{rd} and 5^{th} accelerometers based on 100 data sets for the five damage severity levels defined in Table 3-2. As highlighted in Figure 3-7b, an upward shift of CSD plots for leaky cases is observed in much of the frequency range of interest. This observed shift towards lower absolute values of CSD signifies the reduced correlation of acceleration between the 3^{rd} and 5^{th} accelerometers with increased damage severity. It can be inferred from this result that leak-induced disturbance reduces the correlation between the measured system responses at different locations along the pipeline.

Figure 3-8 presents the comparison of lower and upper bounds of CSD functions of the 3^{rd} and 5^{th} accelerometers for different damage severity levels. As can be observed from Figure 3-7b and Figure 3-8a, the mean and upper bounds of CSD in baseline state (DS1) in much of the frequency range has the greatest absolute values, followed by damage severity (DS) levels 2, 3, 4 and 5. It can also be observed from Figure 3-7b and Figure 3-8a that the CSD plots in the lower frequencies (less than 100 Hz) do not clearly reflect the system's sensitivity to damage severity. The lower bound CSD plots presented in Figure 3-8b do not reflect the system's sensitivity to damage severity in much of the frequency range, which is consistent with the expectation (Moens and Vandepitte, 2007) that lower bounds of CSD are highly sensitive to the signal-noise ratio. Figure 3-8c presents the lower and upper bounds of CSD of the 3^{rd} and 5^{th} accelerometers for DS1 and DS4 cases to highlight the ability of upper bound trend to inform leak detection process, due to its greater value for DS1 than DS4 in much of the frequency range, compared to the highly inconsistent lower bound trend.

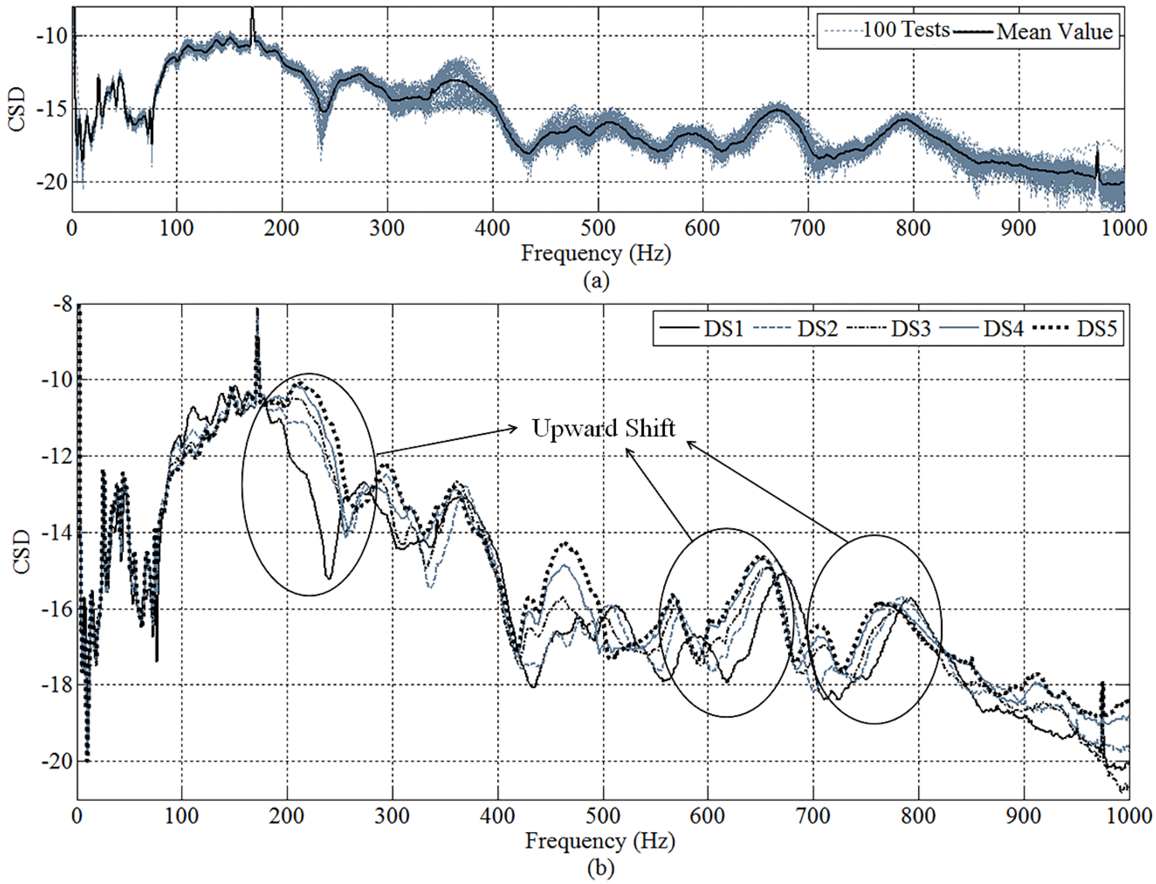

Figure 3-7-CSD of 3rd and 5th accelerometers for: (a) The intact system (DS1). (b) The different damage severities.

Figure 3-9 illustrates the mean value of LDI from 100 tests for the five damage severities. It can be observed from Figure 3-9 that LDI increases monotonically with damage severity. While the ideal value of LDI is zero for the baseline (DS1) scenario, PSD is not constant over the 100 tests due to the variability inherent in measurements. To account for such realistic behavior, LDI in the baseline state is calculated based on the mean values of two sets of data each comprising 50 tests.

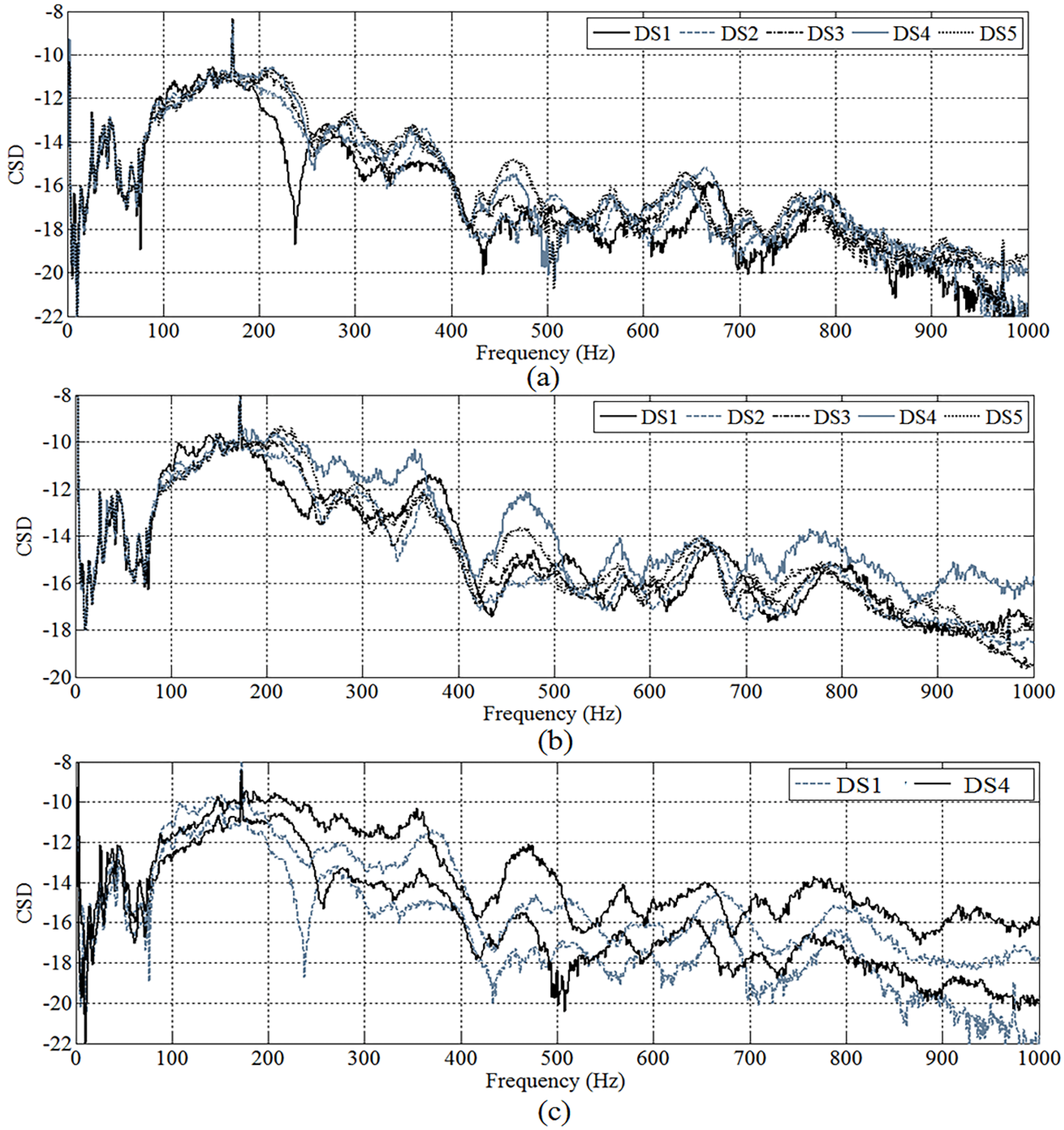

Figure 3-8-Comparison of CSDs for 3rd and 5th accelerometers with focus on: (a) Upper bounds. (b) Lower bounds. (c) Lower and upper bounds for DS1 and DS4.

3.5.2.2 Accelerometers Placed Normal to the Azimuthal Position of Leak

Only a limited number of studies have previously evaluated proposed damage indices considering various azimuthal positions of the accelerometers other than those of the defect (Naniwadekar et al., 2008). The accelerometer pairs 2nd-4th, 2nd-6th and 4th-6th

are considered in this study to evaluate the ability in detecting the onset and severity of the leak. Figure 3-10 illustrates the relationship between the LDI and damage severity based on the data collected from the accelerometers that are positioned with a 90 degree azimuth angle from the leak. As shown in Figure 3-10, LDI consistently increases with damage severity, which shows promise in detecting and quantifying pipe damage in a different azimuthal position than the monitoring points. However, comparing LDI values of 2^{nd}-4^{th}, 2^{nd}-6^{th} and 4^{th}-6^{th} pairs with 1^{st}-3^{rd}, 1^{st}-5^{th}, and 3^{rd}-5^{th} pairs reveal that LDI values are greater for accelerometers that are aligned with the leak (i.e. 1^{st}-3^{rd}, 3^{rd}-5^{th} and 1^{st}-5^{th}). This trend can be explained by the fact that the leak-induced signal propagates in all directions and its intensity and energy decreases with distance from the leak. Therefore, the signal can be sensed with higher intensity through accelerometers which are aligned with the leak.

3.6 Sensitivity of the Proposed Leak Detection Approach

The sensitivity of the proposed leak detection approach is evaluated for: (a) very small leak size, (b) variation in relative distances of the leak from the two monitoring locations on each side, (c) variation in the location of the leak with respect to the monitoring boundaries, and (d) variation in environmental noise.

3.6.1 Effect of very small leak size on LDI

The smallest leak size (i.e., in DS2) in this study is imposed by the size of the valve used as the leak simulator. In order to evaluate the proposed approach for detecting even smaller leak sizes, a $3/8^{th}$ inch (or 9.525mm) ball valve is inserted into the pipeline at 0.2 m from the 1 inch (or 25.4 mm) valve. The 3/8th inch (or 9.525mm) valve resulted in a leak flow of 2.46 lit/min. While the LDI value of this smaller leak could not be compared with other damage scenarios due to inconsistent baseline states, it has been observed that LDI has increased by 198% compared to the baseline scenario, thereby showing promise in the proposed approach for detecting smaller leaks.

3.6.2 Effect of Monitoring Location Distances from the Leak

The farther leak-induced vibration characteristics propagate, the greater the attenuation in frequency response changes. Given that the proposed leak detection technique is based on the differences of CSD of acceleration data gathered from different locations, it is important to understand the effect of different distances of monitoring locations from the leak, for they could exhibit differently attenuated frequency response behaviors and result in lower cross-correlation (and LDI) values. To validate this theory, 1st-5th, 3rd-5th, 2nd-6th, and 4th-6th pairs of accelerometers are considered. The distance between monitoring point A (which houses 1st and 2nd accelerometers) and the leak is twice of that between the monitoring point C (5th and 6th accelerometers) and the leak. The distance between monitoring point B (which houses 3rd and 4th accelerometers) and the leak is equal to the distance between monitoring points C and the leak. Based on the theory that leak-induced changes attenuate with distance, it is expected that LDI values corresponding to 1st-5th and 2nd-6th be less than those corresponding to 3rd-5th and 4th-6th, respectively. In Figure 3-9 and Figure 3-10, the expected trend is indeed observed.

Additionally, it is worth mentioning that different types of bends are placed at upstream (a large diameter 45° bend) and downstream (two large diameter 90° bends at different elevations each) of the leak, as can be observed from Figure 3-4, thereby inducing non-linear system behavior. These bends can generate additional fluid reflections that could influence the flow excitation and consequently the capability of LDI to detect leaks. However, studying the effect of complexities-induced disturbances would be only possible if detailed information on the nature (e.g. unique frequency function) of the source of disturbance (e.g. bend) is available, which is difficult for real world systems that encompass wide range and types of unique complexities (Norton and Karczub, 2003). Based on conducted experiments and the resulting observations, it however seems possible to detect leakage based on LDI values from different pairs of accelerometers even in the presence of bends. LDI approach overcomes the limitation of system complexities by comparing the baseline and leaky system states, both of which entail the same set of complexities, and consequently nullify their effect. It will however require extensive testing on several pipeline configurations and accelerometer placements to further validate this claim.

3.6.3 Effect of Leak Location on LDI

In some cases, it may be necessary to detect pipeline leaks that exist beyond the section that is bound by monitoring locations. Therefore, the sensitivity of LDI for out-of-bounds leaks is evaluated using 1^{st}-3^{rd} and 2^{nd}-4^{th} pairs of accelerometers. It can be seen in Figure 3-9 and Figure 3-10 that these two pairs of accelerometers also result in monotonic increase in LDI with leak severity, which again shows promise in LDI for detecting out-of-bounds leaks, although based on limited experimental testing.

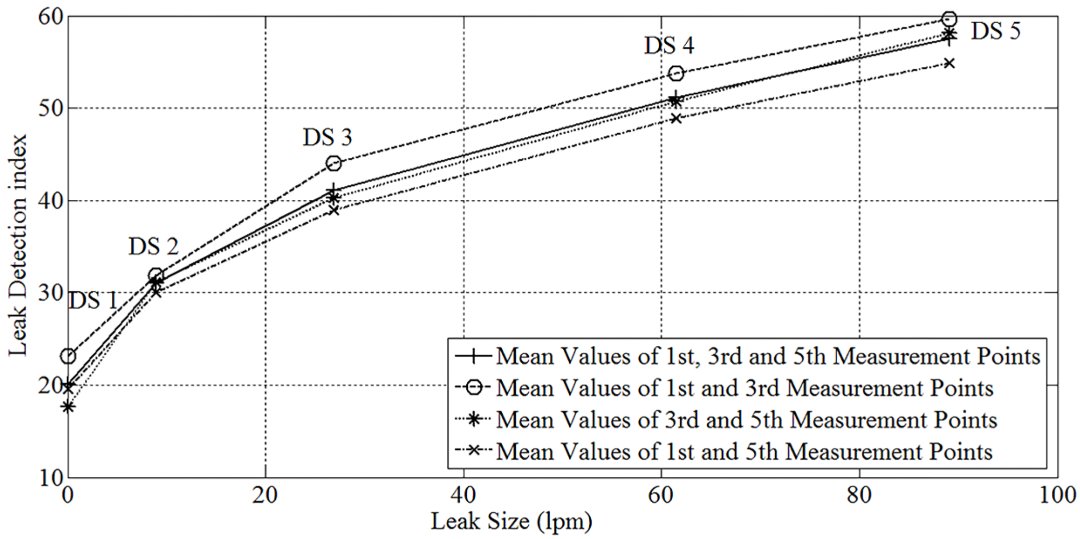

Figure 3-9- LDI for all damage severities considering different accelerometers which are oriented in the same direction of the leak.

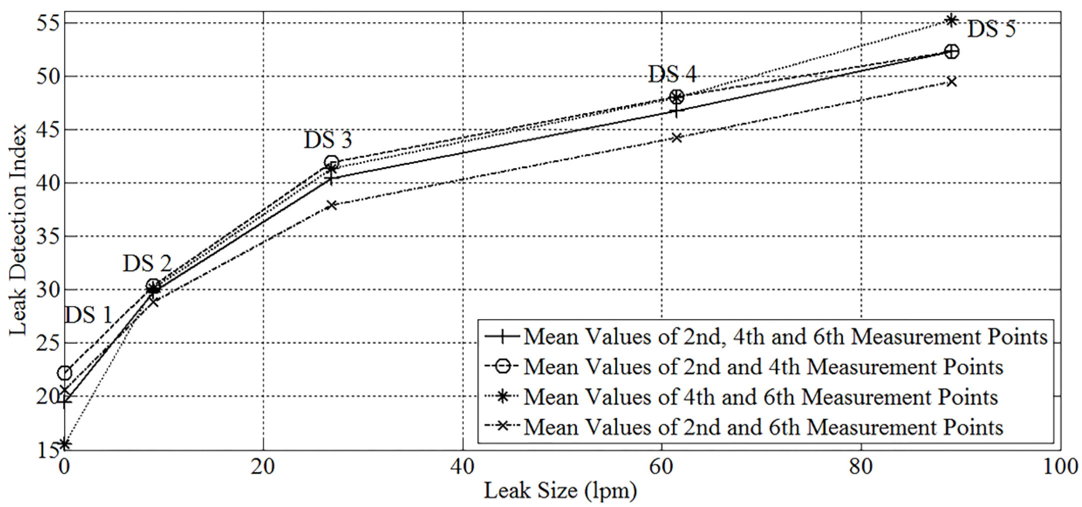

Figure 3-10- LDI for all damage severities considering different accelerometers which are oriented in the perpendicular direction to the leak.

3.6.4 Effect of Noise on LDI

To test the sensitivity of the proposed leak detection approach to random noises at monitoring locations, a numerical simulation is performed by introducing random noise on the CSD of the acceleration data. The random noise from a specific source under actual operating conditions can be expected to be correlated along the length of the pipeline. Representing a worst case scenario, three levels of intended noise with mean values of zero and standard deviations (σ) of ±1%, ±5% and ±10% of CSD are induced independently at each monitoring point. Figure 3-11 presents the Auto Spectral Density (ASD) of the responses from the 1st accelerometer for different noise levels.

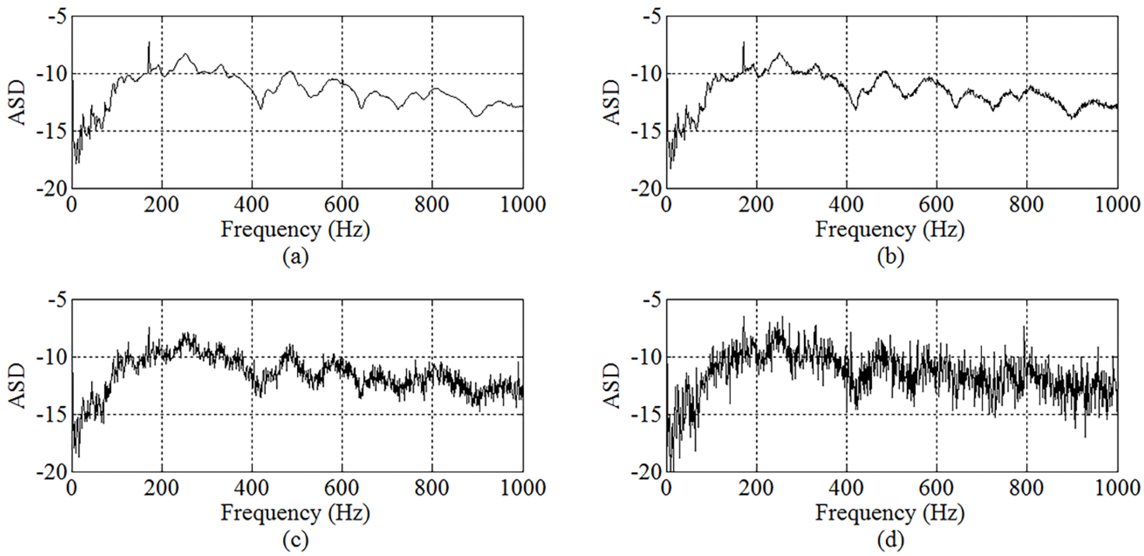

Figure 3-11- ASD of 1st accelerometer for: (a) No noise case. (b) Noise with mean value = 0 and σ = 1%. (c) Noise with mean value = 0 and σ = 5%. (d) Noise with mean value = 0 and σ = 10%.

The effect of randomly induced noise on mean values of LDI obtained from all pairs of accelerometers for the five damage severities is summarized in Table 3-3, which suggests that noise levels with higher standard deviation result in greater values of LDI that tend to become less differentiable. The closer values of LDI at higher noise levels indicate that LDI could be less sensitive to damage severity at high levels of noise. However, the general trend of increase in the LDI value with damage severity supports the claim that the proposed approach has the potential to work in the noisy environments of buried pipelines; however, extensive future studies are required to further validate this claim on more complex systems.

Table 3-3- Mean values of LDI obtained from all pairs of accelerometers for different noise variations.

Damage Severity	LDI			
	(Noiseless)	Noise with σ =1%	Noise with σ =5%	Noise with σ =10%
DS1	0	0	0	0
DS2	31.0	33.0	66.9	119.8
DS3	42.1	43.5	69.9	120.1
DS4	51.3	52.3	75.8	125.7
DS5	57.8	58.4	79.1	125.7

3.7 Concluding Remarks

Given the high percentage of water leakage through distribution pipelines, it is imperative to detect, locate, and prevent the onset of water pipeline leakage. The existing leak detection techniques are labor-intensive and practical only when the suspected location of leak is narrowed down to a smaller area of the pipeline system. In an attempt to address some of the current limitations, this paper presented a vibration-based leak detection technique that is suitable for continuous monitoring of the pipeline system and explored its merits by validating it through experimental testing conducted on a small-scale, 76mm- diameter PVC pipeline test bed.

A damage index, LDI, which is based on the differences of cross spectral density functions of acceleration data collected from baseline and leaky pipeline systems, is proposed to effectively detect the onset and severity of leaks. The merit of LDI lies in its sensitivity to leak-induced signals and insensitivity to the out-of-control environmental noises. The results of the study revealed good correlation between LDI and leak severity, thereby showing promise in the proposed approach. Additionally, LDI was found to be greater when acceleration data obtained from locations that are oriented in the same direction of the leak were considered compared to a perpendicular orientation. The results from the sensitivity analyses based on limited number of tests suggest that: (a) LDI is likely able to detect leaks as small as $3/8^{th}$ inches (or 9.525 mm) in diameter, (b) LDI will likely decrease when one monitoring point is farther from the leak than the other, (c) it is possible that severity of leaks that exist outside the monitoring boundaries can be detected using LDI values, and (d) LDI may be able to detect leaks in noisy environments, but it is less sensitive to damage severity at high noise levels.

While the results from the preliminary experimental campaign presented in this paper are promising, further validation is required to gain confidence in the proposed approach and develop it for a possible real-world pipeline monitoring exercise. In the future, the proposed approach needs to be tested on different pipeline materials, diameters and their combinations with various pipeline configurations, as well as in in situ conditions. To fully realize the capabilities of the approach, its sensitivity to WDS complexities such as loss in pipeline thicknesses through corrosion, wave propagation along bends and etc., needs to be further investigated. This requirement stems from the fact that these complexities can generate additional transient fluid reflections that could potentially affect the flow excitation source and consequently LDI. Additionally, the sensitivity of the LDI technique to soil backfill, damping effect, sudden and significant legitimate demands, potential false positives and false negatives need to be evaluated through extensive validation campaign in the future. From a practical feasibility standpoint, optimal number and configuration of sensors, energy needs of the monitoring system, and the cost-benefit analysis of deploying such a monitoring system should also be investigated in the future.

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CHAPTER FOUR

EXPERIMENTAL EVALUATION OF A VIBRATION-BASED LEAK-DETECTION TECHNIQUE FOR WATER PIPELINES[1]

Conventional water pipeline leak-detection surveys employ labor-intensive acoustic techniques, which are usually expensive and not amenable for continuous monitoring of distribution systems. Over the last decade, many previous studies attempted to address these limitations by proposing and evaluating a myriad of continuous, long-term monitoring techniques. However, these techniques have difficulty to identify leaks in the presence of pipeline system complexities (e.g. T-joints), offered limited compatibility with popular pipe materials (e.g. PVC), and were in some cases intrusive in nature. Recently, a non-intrusive pipeline surface vibration-based leak detection technique has been proposed to address some of the limitations of the previous studies. This new technique involves continuous monitoring of the change in the cross-spectral density of surface vibration measured at discrete locations along the pipeline. Previously, the capabilities of this technique have been demonstrated through an experimental campaign carried out on a simple pipeline set-up. This paper presents a follow-up evaluation of the new technique in a real-size experimental looped pipeline system located in a laboratory with complexities, such as junctions, bends and varying pipeline sizes. The results revealed a positive correlation between LDI and leakage severity in the presence of multiple system discontinuities and demonstrates the potential feasibility of the proposed technique for not only detecting and assessing the onset of single or multiple leaks in a complex system, but also to determine the relative leakage severity.

4.1 Introduction

Loss of potable water through pipeline leakage is one of the most serious issues currently threatening water supply security across the world. Drinking water pipeline infrastructure in the U.S. reportedly loses 20% of the supply through leakage (Mutikanga et al., 2012). As freshwater resources are becoming increasingly limited in many populous regions, loss of treated water exacerbates water sustainability challenges and highlights the deteriorated state of buried pipeline infrastructure. While conventional leak detection techniques, such as ground penetrating

[1] Yazdekhasti, S., Piratla, K. R., Atamturktur, S., & Khan, A. (2017). Experimental evaluation of a vibration-based leak detection technique for water pipelines. *Structure and Infrastructure Engineering*, 1-10.

radar (Hyun et al., 2003; EPA report, 2010), tracer gas (Hunaidi et al., 2000), infrared thermography (Zhang, 1997, Khader, 2016) and acoustic techniques (Hunaidi et al., 2004), have been very useful in detecting leakages in suspected sections of water supply networks, they often depict only the snapshot status of the system at the time of inspection and do not support continuous real-time monitoring.

City-wide near real-time monitoring of pipelines and timely intervention can reduce water losses, save energy, minimize cost of pipeline failures, and safeguard public health. The concept of deploying sensor networks to monitor water pipelines for the detection of leakage and other defects has received great attention in the past decade (Puust et al., 2010; Sun et al., 2011; Yoon et al., 2011; Cai et al., 2016). The distinctive advantage of sensor networks that are non-intrusively embedded on the surface of water pipelines is the ability to continuously monitor pipeline behavior to rapidly detect and locate leaks. While aspects related to data collection, especially energy-efficient sensing (Tackett et al., 2011), data sampling (Bajwa et al., 2006) and data transmission (Akyildiz et al., 2009) received great attention, research needs and technology gaps still remain in detection techniques that leverage the monitoring data to appropriately detect leakage and determine its severity. A common approach for leak detection entails partitioning the water distribution system into a number of smaller zones which are referred to as District Meter Areas (DMA) (Brothers, 2003). The mass flow balance of each DMA is assessed to determine the presence of leakage and subsequently the need for further on-site inspection (Li et al., 2011; Romano et al., 2012). Several commercial technologies are available for on-site inspection and many of these are reported to be successful, albeit under certain conditions. Even the acoustic techniques which are most widely used typically fall short in cases of narrow-band signals, such as those emitted by leaks in plastic or large diameter metallic pipelines (Liu et al., 2012; Hunaidi, 2012). Because plastic material (e.g. polyvinyl chloride or PVC) is becoming an increasingly popular choice for water distribution pipelines, especially in small to medium diameter range (Liu et al., 2012), there is a growing need for leak inspection techniques that are equally suitable for plastic pipelines.

In an attempt to address this research gap, Yazdekhasti et al. (2016) presented a leak detection technique where cross spectral density (CSD) of acceleration data, collected at discrete points along the pipeline length, is leveraged for leakage assessment – i.e. detecting the onset of leakage and determining its relative severity – using a leak detection index (LDI). The LDI-based technique is different from the previous acoustics-based techniques in that it uses a correlation function to increase data-fidelity, while variation in the CSD of the pipeline's vibrational response under operational conditions is monitored for detecting and quantifying the leak. While the results of Yazdekhasti et al. (2016) were promising, their demonstration was limited to a simple experimental set-up comprised of a single stretch of pipeline. This paper further evaluates the LDI-based approach using a two-looped pipeline test bed that exhibits several complexities observed in a real-world pipeline system; these include junctions, bends, T-joints and varying pipe diameters. The results presented in this paper highlight the merits and limitations of the LDI-based approach, and raise additional research questions that will need to be answered for LDI-based techniques to be practically feasible.

This paper is presented in five sections. Section 2 presents a review of relevant previous studies including a description of the proposed leak-detection technique. The experimental set-up along with the devised test scenarios are described in section 3. Research results and discussion follow in section 4, and section 5 concludes the paper by highlighting the main contributions along with limitations and recommendations for future research.

4.2 Previous Research

This section presents a brief review of literature on pipeline leak detection and describes the LDI-based approach of leak assessment that is evaluated in this paper.

4.2.1 Review of Pipeline Leak Detection Studies

Leak detection studies in the literature can be broadly categorized into three classes focusing on (a) the structural features of the pipeline; (b) the hydraulic aspects of the enclosed flow; and (c) the pipe-flow interaction. Studies that focused on the structural features exploited the leak-induced changes in the vibration response of the pipeline (Cheraghi et al., 2005; Dilena et al., 2011; Sharma, 2013; and Martini et al., 2014). One of the major limitations of this class of studies is their focus on global vibration response features that could be similar for defects of different types, locations and severities. Thus it becomes difficult to identify a unique solution for the leak detection (Atamturktur et al., 2013). Studies that relied on the variation of the enclosed flow characteristics, majority of which are based on transient-analyses (Jönsson and Larson, 1992; Wang et al., 2002; Covas et al., 2005; Lee et al., 2005, 2006), had difficulties distinguishing leaks from the other flow disturbances that may arise from system complexities, such as loops, valves, bends and etc. (Vitkovsky et al., 2003; Colombo et al., 2009). Studies that relied on the pipe-flow interactions were usually based on the observed changes in the pipeline surface vibration as a result of various disturbances in the system that include leak-induced pressure changes (Shinozuka and Dong, 2005; and Stoianov et al., 2007). This third class of techniques suffered from the same limitation as the second class, i.e. the inability to distinguish leaks from other disturbances.

From a practical standpoint, several commercial non-acoustic and acoustic-based leak detection techniques currently exist (Hunaidi, 2012). They have been reviewed by previous researchers by identifying specific advantages, limitations and suitability to different application scenarios (Colombo et al., 2009; Puust et al., 2010; Liu et al., 2012; Liu and Kleiner, 2013; Anguiano et al., 2016). Acoustic-based techniques are the most widely used approaches and fall into one or more of the three classes discussed in the previous paragraph. These techniques are developed to monitor the propagating leak-induced sound or vibration. The majority of commercial, non-intrusive leak detection techniques such as Listening Devices (e.g. listening rods or geophones) and Noise Loggers (e.g. Permalog and MLOG) are capable of determining the presence of a leak in the system, but provide no information on the damage severity. Although acoustic-based leak detection techniques have worked well in the cases of small to medium-diameter (< 300 mm) metallic pipelines, their suitability to plastic and large-diameter metallic pipelines has been uncertain (Hunaidi, 2012). In addition, these techniques reportedly suffer from high rates of false alarms in non-metallic pipelines (Van der Klejj and Stephenson, 2002). This problem stems from the fact that these techniques work through statistical analysis of high-frequency (>2000 Hz), leak-induced signals. Since high-frequency signals attenuate faster than the lower frequency ones (Forrest, 1994), the suitability of acoustic-based techniques to plastic pipes is doubtful. Furthermore, a few acoustic-based techniques for detecting and locating leaks are intrusive in nature (e.g. free swimming acoustics and tethered acoustics) and these take advantage of sensing tools passing directly adjacent to the leak from the inside of the pipeline (Puust et al., 2010; Youngpyo and Boon, 2012; Liu and Kleiner, 2013). While these intrusive techniques are not capable of determining leakage severity, they are less preferred because it is inconvenient for utility owners to provide access for insertion and removal of inspection tools with these techniques (Bracken and Cain, 2012).

4.2.2 LDI-based Leak Detection Technique

The authors recently proposed a vibration-based leak detection technique based on the premise that monitoring of surface acceleration of pipeline under ambient flow conditions can reveal the presence and relative severity of a leak (Yazdekhasti at al. 2016). The variation in the Cross Spectral Density (CSD) function of acceleration measured at multiple locations along the pipe length, under ambient excitation of the enclosed flow, is exploited for leak assessment. CSD, the Fourier transform of the cross-correlation of two discrete time signals, indicates the power shared by the two signals at a given frequency (Norton and Karczub, 2003), as shown in Eq. 1:

$$f_{x-y}(t) = \lim_{T \to \infty} \frac{1}{T} E\{X^*(\omega) Y(\omega)\} \tag{1}$$

In Eq. 1, $X^*(\omega)$ and $Y(\omega)$ are the finite Fourier transform of signals X(t) and Y(t) at frequency ω, $X^*(\omega)$ is the complex conjugate of $X(\omega)$ and two, and E{.} is the expectation operator. It has been demonstrated that the CSD of acceleration measured at different locations along a pipeline changes due to the onset of a new leak (Hunaidi and Chu, 19991). In an attempt to quantify this change, the leak detection index (LDI) is introduced (see Eq. 2). LDI is a unit-less index that characterizes the normalized difference between the CSD of acceleration data collected at two locations in a baseline system state (i.e. before the onset of a leak) and a leaky state (i.e. after the onset of a leak).

$$LDI(x, y, SC_b, SC_d) = \frac{\int \left| f_{x-y}{}^{d}(t) - f_{x-y}{}^{b}(t) \right|}{\int \left| f_{x-y}{}^{b}(t) \right|} \tag{2}$$

In Eq. 2, x and y are two locations along the pipeline length where the acceleration data is collected, SC_b is the baseline scenario, SC_d is the damaged scenario, $f_{x-y}{}^{b}(t)$ is the CSD of data from *x*-*y* locations in the baseline system state, and $f_{x-y}{}^{d}(t)$ is the CSD of data from *x*-*y* locations in the damaged system.

The LDI-based technique leverages the variation in the frequency content of enclosed flow owing to the additional wall pressure fluctuations (that is in addition to the usual boundary layer pressure fluctuation in the pipe) that result from the onset of a leak. The additional wall pressure fluctuations in turn result in increased vibration of the pipe surface, as can be observed in Figure 4-1, which is the representative of time history data (raw data) collected from a single measurement point under a baseline and leaky states of system. The LDI-based technique employs a cross-correlation function to increase data fidelity, as this function filters the influences of spatially uncorrelated ambient noises (Tokmouline, 2006). Furthermore, effective data acquisition and analysis procedures can be adopted to avoid potential false alarms generated by high levels of environmental noises. For example, multiple cycles of data may be collected during midnight when non-leakage related sporadic noises, such as those induced by traffic or legitimate consumption, are minimal (Martini et al., 2015). Furthermore, only a smaller subset of acquired data samples that correspond to lower LDI values may be shortlisted for analysis so as to eliminate potential outliers. The LDI-based technique has been demonstrated using a series of experiments conducted on a 76 mm PVC pipeline that included a leak simulator made from a 25.4 mm (1 inch) ball valve capable of simulating leaks of various severities. The results were promising with LDI being able to detect the onset of a leak and yield a good correlation with leak severity, as it increases monotonically with damage severity (Yazdekhasti et al., 2016) and the R-squared values for all pairs of samples for different scenarios were more than 0.90. The effect of noise on LDI has been explicitly discussed in the Yazdekhasti et al. (2016), and the results revealed that the sensitivity of LDI to damage severity decreased with increasing noise levels;

however, LDI values continued to increase even at high noise levels which showed promise in the technique to work in potentially noisy environments. The demonstration presented in Yazdekhasti et al. (2016) was however on a simple stretch of a pipeline that is devoid of complexities that are integral to real-world pipeline systems. Pipeline networks are complex, dynamic systems with various uncertainties such as changing demands, changing component statuses, reflections at bends, T-joints and valves, etc. To gain further confidence in the LDI-based approach and further evaluate its merits and limitations, its demonstration on a more complex experimental set-up that comprises bends, T-joints, multiple loops, multiple pipe sizes, and multiple leaks is presented in this paper.

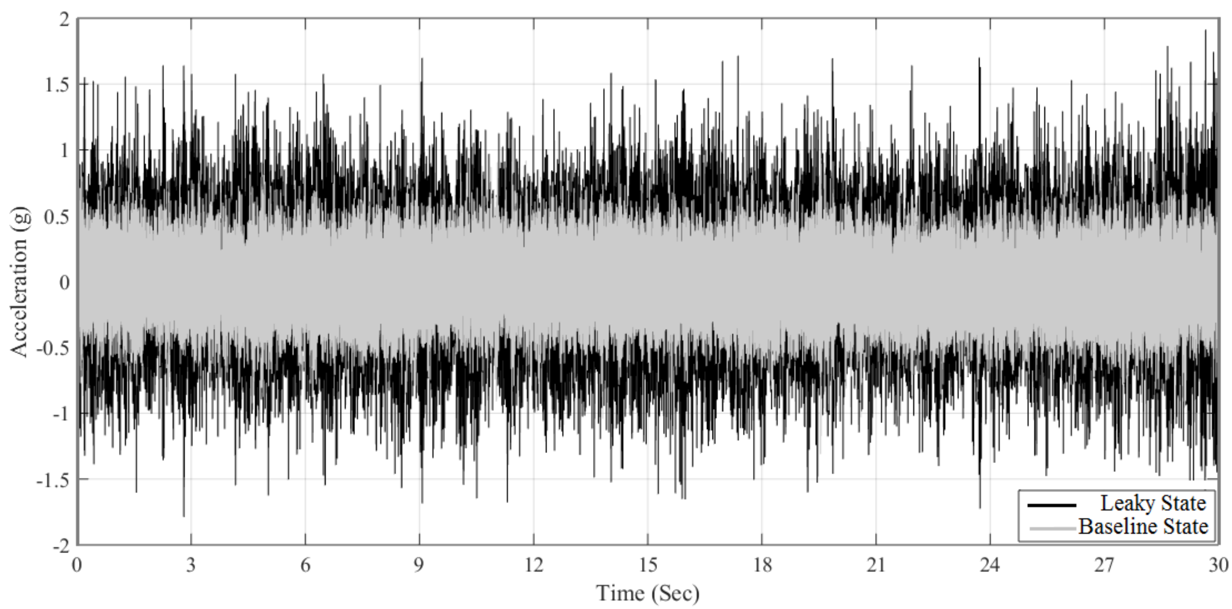

Figure 4-1- Time history data of a single accelerometer, under baseline and leaky states

4.3 Experimental Study

In this study, a two-looped pipeline system, consisting of pipelines of varying diameters, multiple bends, T-joints, and valves, in addition to having elevation changes and the capability of simulating multiple leaks of varying severities, is designed and installed in full scale in the laboratory.

4.3.1 Experimental Set-up

The test bed, depicted in Figure 4-2 and shown in Figure 4-3, is comprised of two closed loops of PVC pipes connected to a pump (Dayton model of 3KV80A) that circulates water from a small reservoir with a capacity of 210 liters. The flow rate induced by the pump is estimated to be 1,100 lit/min based on the pump curve. The longer loop is comprised of 32 m, 76 mm diameter PVC pipe in which two leak simulators of different sizes, 25.4 mm and 9.52 mm, are embedded to simulate a leak (L1). The smaller loop shares the 76 mm PVC pipe with the larger loop on one side, while the remainder of the loop is made of a 102 mm diameter PVC pipeline in which one 25.4 mm leak simulator (L2) is embedded, as depicted in Figure 4-2. Standard ball valves are used as leak simulators to control the leak intensity. Representative flow directions, shown in Figure 4-2, are subject to change depending on valves' configurations, leakage flows, and the energy added by the pump.

Pipelines in the test bed are placed at an average depth of 0.6 m on sand cushion bedding, as illustrated in Figure 4-4. The pipeline system is connected to a pump placed at an elevated location using curved joints, as can be seen in Figure 4-3. The pipeline system is not buried so it is convenient to modify the operational configuration of the test bed for simulating the various scenarios studied. This is anticipated to have little impact on the study outcomes as the literature suggests that burial has an insignificant impact on the leak-induced wave propagation velocity (Muggleton et al., 2002; Brennan et al., 2008, and Pal et al., 2010).

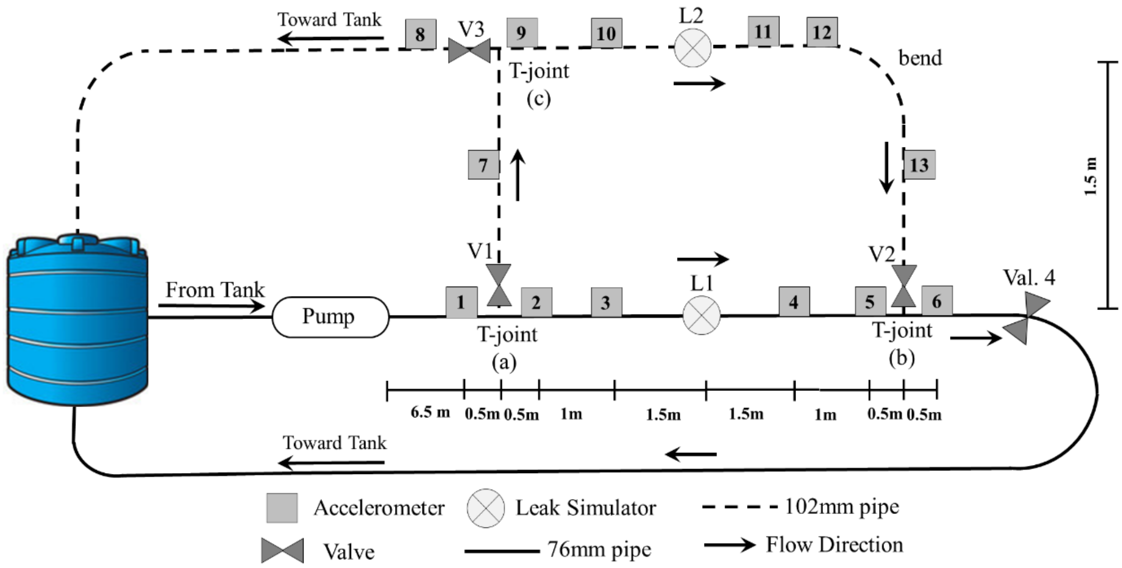

Figure 4-2- Schematic of the experimental set-up

Figure 4-3- Experimental set-up

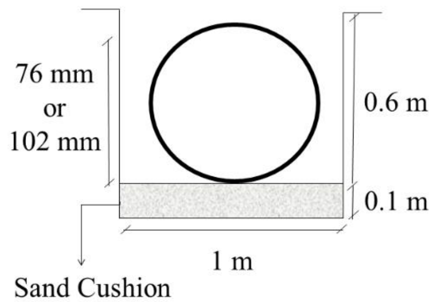

Figure 4-4- Cross-sectional schematic of the pipe in the experimental set-up

4.3.2 Experimental Procedure

To monitor the vibration profile of the two-looped pipeline network, thirteen accelerometers are mounted on the exterior surface of the pipeline along its length, as illustrated in Figure 4-2. The number of sensors and their locations were selected with only the intent of evaluating the proposed leak detection technique in the presence of various typical system complexities. Bruel and Kjaer 4507 B 006 type of accelerometers with nominal sensitivity of 500 mV/g are distributed across the network in a way that allows studying of multiple leaks through the variation in system's vibration response along the pipeline length, across a bend, across a T-joint, upstream and downstream.

A commercial data-acquisition system, Bruel and Kjaer multi-purpose LAN-XI type 3050 modules with frequency range of 0-51.2 KHz, is used to record and digitize the acceleration signals measured in this study. The excitation frequency content of the pipeline under ambient flow conditions is determined to be in the range of 0-1,000 Hz (Sattarzadeh, 2011; Yazdekhasti et al., 2016). Accordingly, time-domain acceleration data is collected in a span of 0.2-1,600 Hz with measurement duration of 33 seconds (corresponding to a frequency resolution of 11.5 mHz and a time resolution of 2.5e-4 seconds). The upper limit for the frequency band is chosen to cover the frequency span of flow energy distribution, while the lower limit (i.e., 0.2 Hz) is chosen to filter out noises at frequencies below the first vibration mode of the pipe.

4.4 Scenario Analyses: Results and Discussion

Several experimental configurations, characterized by the 10 scenarios presented in Table 4-1, have been studied to evaluate the merits of the LDI-based techniques. The proposed scenarios for investigation are chosen to evaluate the merits of LDI technique in the presence of various system complexities. For example, LDI from a pair of accelerometers placed before and after a bend; before and after a joint, etc. Various system states such as no-leakage and leakages of multiple severities are considered as key characteristics of the devised experimental scenarios. Twenty tests have been conducted for each scenario to obtain statistically significant data and in order to mitigate the influence of sporadic outliers. In order to evaluate the confidence level of the repeated experiments, the discrepancies between different tests have been quantified based on the square of the coefficient of correlation (commonly known as R-square) for pairs of data samples (Sarin et al., 2008). R-square can range from 0 to 1, with larger values indicating better fits. The results of such analyses revealed that the R-squared values for all pairs of samples for different scenarios are more than 0.95, which shows greater consistency of data samples and lower margin for errors. In the first two scenarios, LDI values are expected to be close to zero due to the lack of leakage; however, the CSD values do not remain constant over the 20 tests due to the inherent variability in measurements that leads to nonzero LDI values. To mitigate these ambient effects, LDI is calculated based on the mean values of two sets of data each comprising 20 tests. Consequently, 40 tests have been conducted for both the first and second scenario, and the resulting data is categorized into two separate groups each containing data corresponding to 20 tests, i.e. BS1 and BS2 for first scenario and BS3 and BS4 for second scenario. Various hypotheses have been tested using the 10 experimental scenarios to understand the merits and limitations of the LDI-based technique.

Table 4-1- Different Experimental Configurations (valves 3 and 4 are open in all scenarios)

Scenario No.	Scenario ID	Scenario Description	V1	V2	L1 (*l/min*)	L2 (*l/min*)
1	BS1 & BS2	Baseline system without bend and joint effects	✗	✗	✗	✗
2	BS3 & BS4	Baseline system with bend and joint effects	✓	✓	✗	✗
3	LS1	One leak (of varying severities) located on the 76mm pipe section	✓	✓	2.1	✗
4	LS2		✓	✓	12	✗
5	LS3		✓	✓	22.1	✗
6	LS4	One leak (of varying severities) located on the 102mm pipe section	✓	✓	✗	4.8
7	LS5		✓	✓	✗	8.5
8	LS6	One leak (of varying severities) each on 76mm and 102 mm pipe sections simultaneously	✓	✓	12	4.8
9	LS7		✓	✓	22.1	8.5
10	LS8		✓	✓	2.1	8.5

Hypothesis-1: The LDI-based technique has the potential to work across pipeline bends.

A bend in the pipeline system can induce pressure fluctuations and fluid reflections that may be similar to those induced by a leak (Colombo et al., 2009). This similarity makes it difficult for several existing leak detection techniques to distinctly identify the presence of a leak. The additional pressure fluctuations and fluid reflections induced by the bend could affect the flow excitation, and consequently the capability of the LDI-based technique to assess leakage. The correlation between pipeline acceleration measured across a bend may reduce due to the disturbance induced by the bend, and as a result, the LDI values are expected to increase. It is however hypothesized that the leak can still be distinguished using the LDI-based approach because the bend-induced effects are inherent to both baseline and leaky states of the system and will therefore be nullified.

To test this hypothesis, LDI values for two different pairs of accelerometers, i.e. (11, 12) and (12, 13), for different damage severity levels, based on the measured leak flow rates shown in Table 4-1, are compared. Accelerometers 11 and 12 are both located on the upstream side (based on the depicted flow direction in Figure 4-2) of the bend on the 102 mm pipeline (Figure 4-2), while accelerometer 13 is located on the downstream side of the bend. It should be noted that the distance between accelerometers 11 and 12 is approximately the same as that between 12 and 13. Figure 4-5a compares LDI values for accelerometer pairs (11, 12) and (12, 13) for BS4, LS1, LS2, and LS3 scenarios with BS3 as the baseline scenario. Figure 4-5b presents a similar comparison for BS4, LS4, LS5, LS6, and LS7 scenarios with BS3 as the baseline scenario. It can be observed from both the plots in Figure 4-5 that LDI values not only increased with damage severity for both (11, 12) and (12, 13) accelerometer pairs, but also that LDI values of (12, 13) pair are consistently higher than that of (11, 12) pair, as expected.

It can be inferred from these observations that the LDI-based technique has the potential to work across bends in pipeline systems and that LDI values derived from accelerometers placed across the bends are greater than the values derived from those that are placed along a straight section of a pipeline.

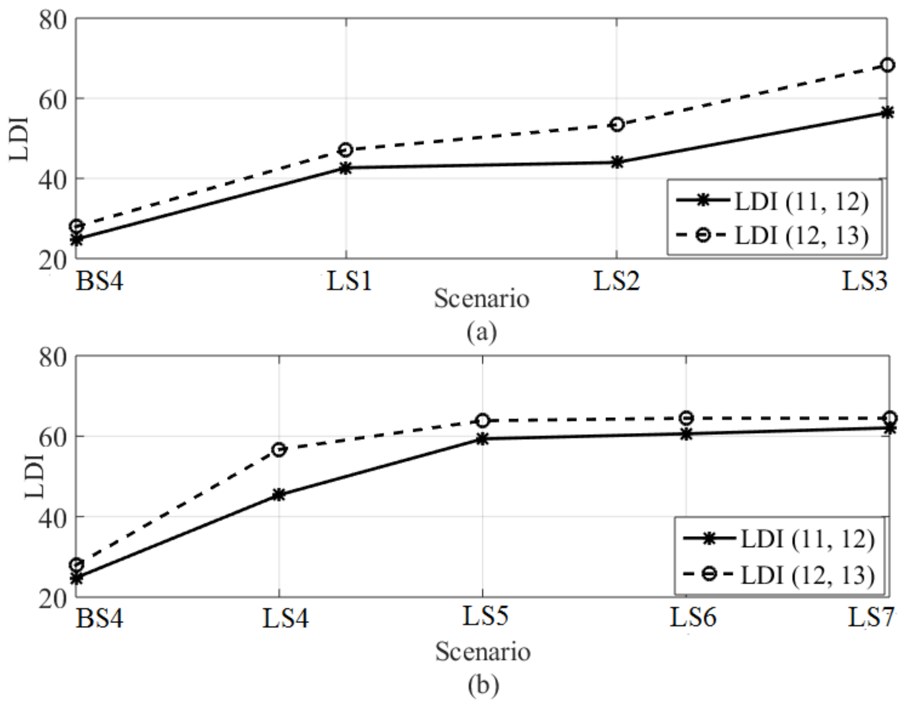

Figure 4-5- Comparison of LDI plots for evaluating the effect of bend with BS3 as the baseline scenario

Hypothesis-2: The LDI-based technique has the potential to work across pipeline joints (T-joints).

T-joints are another source of disturbance in the enclosed flow of a pipeline. Pressure waves get reflected at T-joints appearing similar to leaks, thereby making it difficult to distinguish leaks (Xu et al., 2014). Consequently, leak-detection techniques that are based on the flow characteristics may be less accurate in the presence of T-joints. Although a joint may affect the dynamic response of the pipeline, it is hypothesized that the LDI-based approach is capable of detecting leakage since the joint-induced effect is inherent to both baseline and leaky states of the system, and consequently its effect nullified.

To evaluate this hypothesis, three common types of joints, highlighted in Figure 4-2, with varying pipe diameters and flow directions have been investigated through the use of pairs of accelerometers that bracket one joint and one leak each. The selected pairs include (1, 4) and (4,

7) which bracket joint (a) and L1 (refer to Figure 4-2), (3, 6) and (3, 13) which bracket joint (b) and L1, and (7, 11) which brackets joint (c) and L2. To investigate the effect of a joint in the leak-free scenario, LDI (1, 4, BS1, BS2)[1] (= 26.32) and LDI (1, 4, BS3, BS4) (= 35.91) are compared. The higher value of the latter is likely due to the presence of flow across joint (a) in the system. As expected, the joint reduced the correlation between acceleration measured across it as compared to the data collected from a pair of accelerometers located on a straight section of the pipeline without discontinuities, and consequently resulted in higher LDI value. LDI values of all the selected pairs of accelerometers for various damage severities are plotted in Figure 4-6. As can be observed from Figure 4-6, LDI increases with damage severity for all pairs of accelerometers for the three joint types investigated. Consequently, it can be inferred that the LDI-based approach has the potential to detect leaks through accelerometers located across a joint; however, extensive future studies are required to further validate this claim on larger-scale systems with varying pipe sizes and materials.

Hypothesis-3: In a looped system, accelerometers located on the same pipeline segment as the leak are capable of detecting the leak.

To evaluate the capability of the LDI-based technique in the presence of system complexities and non-uniform boundary conditions upstream and downstream of the leak, it is necessary to investigate the sensitivity of LDI derived from accelerometers placed along the pipeline length.

[1] This notation represents LDI value calculated using the two accelerometers identified as the first two attributes, while the third entry represents the baseline case, and the fourth entry represents the case for which the LDI is being calculated. LDI (1, 4, BS1, BS2) is the LDI value calculated based on acceleration data obtained from 1st and 4th accelerometers for the BS2 case using BS1 as the baseline scenario.

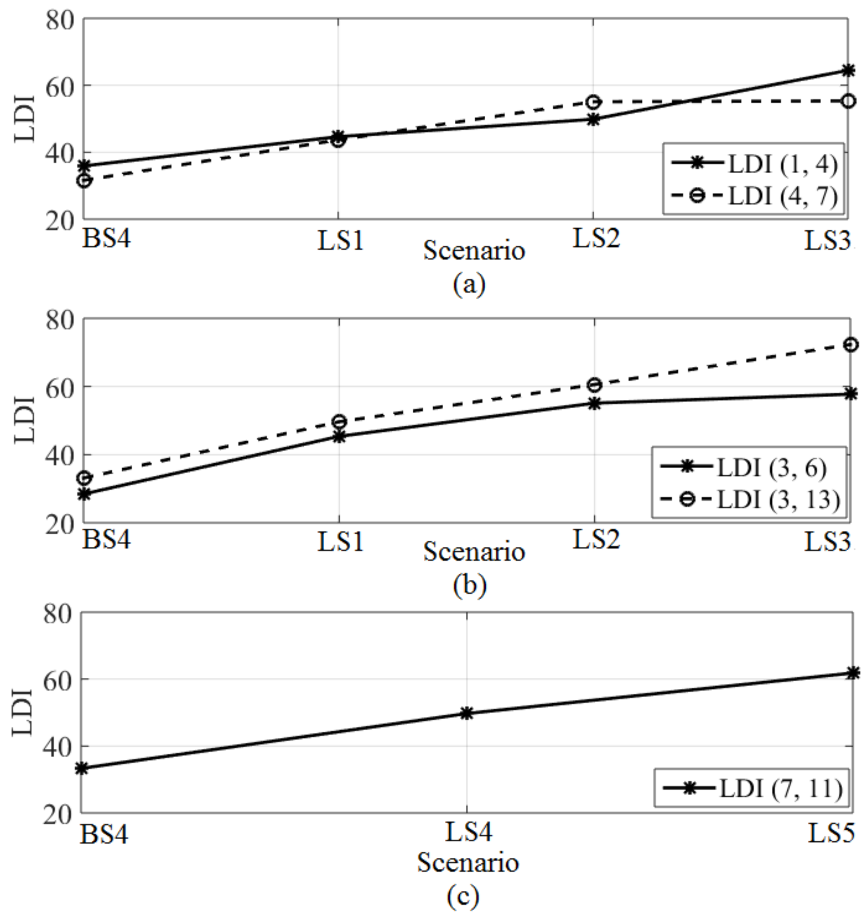

Figure 4-6- LDI values of different pairs of accelerometers which bracket one leak and one joint each with BS3 as the baseline scenario

To test this hypothesis, three pairs of accelerometers located each on 76 mm and 102 mm pipelines are chosen to compare LDI values for various leakage severities. The three pairs on 76 mm pipeline, housing the L1 leak, are (1, 6), (3, 4) and (1, 5), while those on 102 mm pipeline, housing the L2 leak, are (9, 12), (10, 11) and (8, 12). Figure 4-7a illustrates the change in LDI of the three pairs of accelerometers located on 76 mm pipeline, while Figure 4-7b illustrates the change in LDI of accelerometers located on 102 mm pipeline for various leakage severities. In Figure 4-7, LDI increases with leakage severity in all the cases investigated. It can be inferred from this observation that accelerometers located on the same pipe segment (i.e., not separated by any joints) as the leak in a complex pipeline system can be leveraged to detect leakage using the LDI-based technique.

Additionally, it is worth noting that the energy dissipation of leak-induced excitation in a pipeline system is a function of the structural damping of the transient pressure wave resulting from the fluid-structure interaction (Keramat et al., 2012). Such damping, which is characterized by the damping coefficient (C), increases with the diameter of the pipeline as can be observed from the following equation (Budny et al., 1991):

$$C = 2\xi A\sqrt{E\rho_p} \tag{3}$$

where, ξ is damping ratio, A is cross-sectional area of the pipe, E is Young's modulus of elasticity, and ρ_p is mass density of pipeline.

E and ρ_p in Eq. 3 would be the same for a given pipe material, and it is reported that variation in ξ will be negligible for various pipes in terms of sizes and materials (i.e., within 1 to 4 percent variation) (Budny et al., 1991; Lay et al., 1997). Consequently, it can be inferred that larger diameter pipelines (with greater value of A) exhibit greater rates of energy dissipation per unit length. As a result, the leak-induced pressure fluctuation will be attenuated faster in larger pipes compared to the smaller ones. While it can be clearly seen from Figure 4-7b that the LDI-based approach is capable of detecting leakage in the larger diameter pipeline of the experimental set-up, the damping analysis suggests that the accelerometers may need to be placed closer to each other compared to a smaller diameter pipeline to detect a comparable leak with similar LDI values. This assessment is supported by the fact that LDI (10, 11, BS3, LS4) is less than LDI (3, 4, BS3, LS1), as can be seen in Figure 4-7, despite the leakage severity in LS4 being twice that of LS1 and the distance between accelerometers 10 and 11 being the same as that between 3 and 4. The lower value of LDI derived from accelerometers placed on the larger diameter pipeline is due to rapid damping of leak-induced effects despite higher leakage severity. While it will need further research to quantitatively evaluate the variation in LDI values with pipe size, the LDI-based approach will be suitable for leakage assessment in pipelines of various sizes.

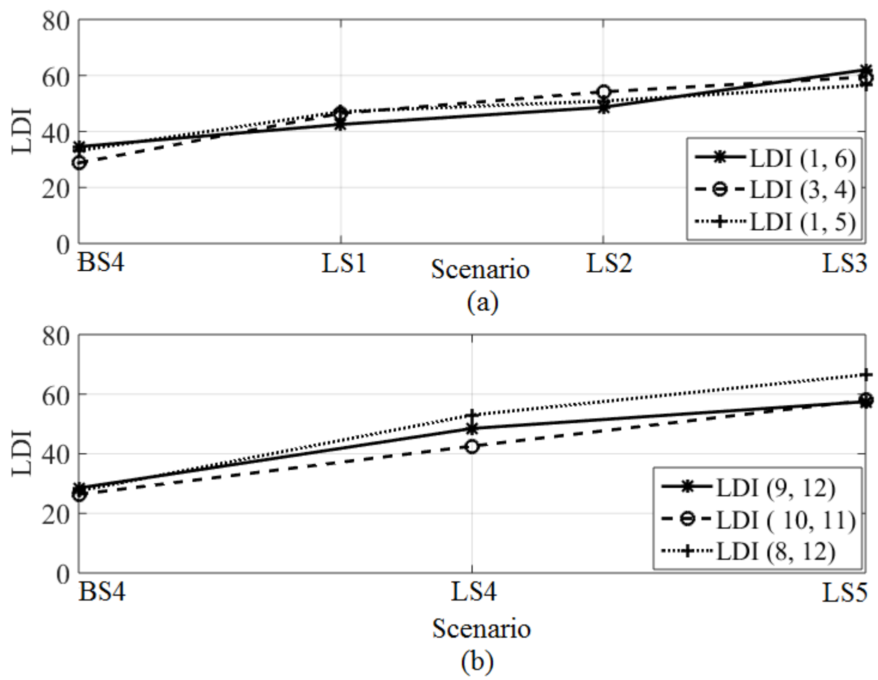

Figure 4-7- Comparative LDI plots for accelerometers located on the same pipeline as the leak with BS3 as the baseline scenario

<u>Hypothesis-4: In a looped pipeline system, accelerometers located on a different pipeline as the leak have the potential to assess the leak.</u>

Detecting leaks on a pipeline that does not house any accelerometer is a valuable capability for monitoring large-scale water supply systems, especially since it is economically unfeasible to embed sensors on each pipeline segment (Movva, 2014). Consequently, the sensitivity of the LDI-based technique to detect leaks in one pipeline using accelerometers placed on a different pipeline in the system is evaluated.

To test this hypothesis, three pairs of accelerometers located each on 76 mm pipeline and 102 mm pipeline are chosen to compare LDI values for leaks not located on the same pipelines. The three pairs on 102 mm pipeline are (9, 12), (10, 11) and (8, 12), while those on 76 mm pipeline are (1, 6), (3, 4) and (1, 5). LDI values of the three pairs of accelerometers on 102 mm pipeline are calculated with respect to L1, located on the 76 mm pipeline, and similarly LDI values of the accelerometer pairs on 76 mm pipeline are calculated with respect to L2, located on 102 mm pipeline. As can be observed from the selection of accelerometer pairs, those that are at varying distances from each other are paired to nullify the effect of distance between the accelerometers on LDI values. Figure 4-8a depicts the change in LDI of accelerometer pairs located on the 102 mm pipeline for BS4, LS1, LS2, and LS3 scenarios, while Figure 4-8b depicts the change in LDI of accelerometers located on the 76 mm pipeline for BS4, LS4 and LS5 scenarios. In Figure 4-8, LDI values are significantly higher for leaky scenarios compared to the baseline scenario in all cases. Based on the resulting observations from the conducted experiments, it seems possible to detect a leak through LDI based technique, without needing to directly monitor the pipeline with the leak; other near-by pipelines may be monitored. Additionally, it can also be observed from Figure 4-8 that LDI increases with damage severity in all the cases, thereby showing promise in the technique for assessing the relative damage severity. It will however require extensive testing with larger scale distribution systems to further validate this claim.

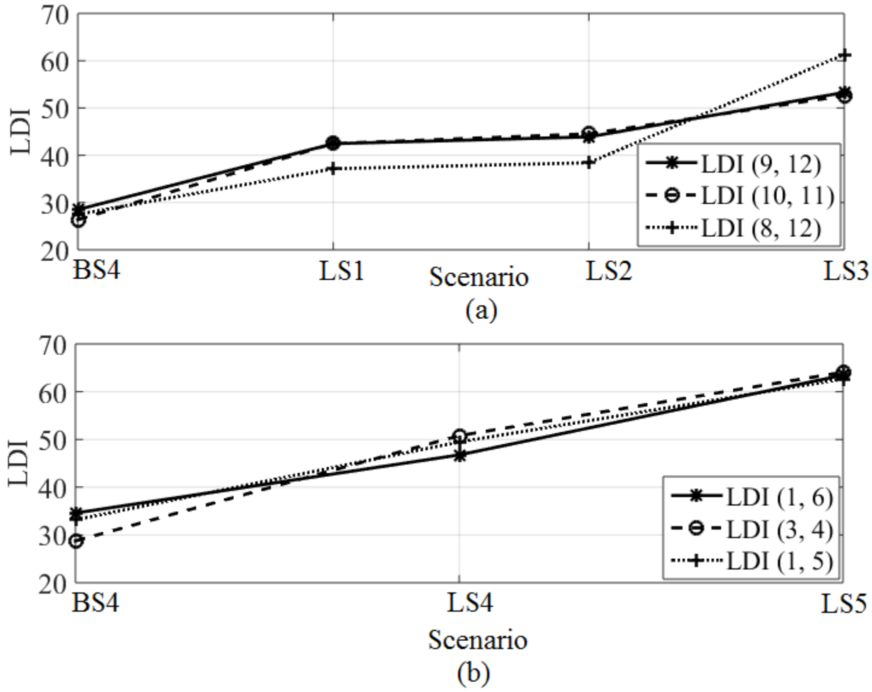

Figure 4-8- Comparative LDI plots for accelerometers located on different pipeline as the leak with BS3 as the baseline scenario

Hypothesis-5: LDI-based technique has the potential to work amid several system complexities.

Various sources of transient disturbances that are common in pipeline systems make it difficult for some previous leak detection techniques to distinctly identify the onset of a leak (Covas et al., 2005). To evaluate the capability of the LDI-based technique in presence of several system complexities put together, (1, 6) pair of accelerometers, located on the 76 mm pipeline before and after the 102 mm loop, are chosen to compare LDI values for various leakage scenarios.

LDI (1, 6, BS1, BS2) = 23.80 is lower than LDI (1, 6, BS3, BS4) = 34.58, which is due to the imposed disturbances that arise in the looped system. The variation in LDI for (1, 6), with BS3 as the base case, across different damage severities is presented in Figure 4-9. As can be observed from Figure 4-9, LDI increases consistently with damage severity from BS4 to LS3 scenarios (representing various severities of L1 leak alone). It can also be observed from Figure

4-9 that LDI continues to increase for LS6 and LS7 scenarios that represent multiple leakages (i.e. through L1 and L2 simultaneously). It is hypothesized that onset of multiple leaks with a similar combined leakage flow rate as a single leak, will result in greater noise and subsequently a higher LDI value. Consistent with such expectation, LDI (1, 6, BS3, LS8) (multiple leaks with total leakage flowrate of 10.6 lit/min as can be observed from Table 4-1) is higher than LDI (1, 6, BS3, LS2) (single leak with leakage flowrate of 12 lit/min). Despite the reduction in the total leakage flow in LS8 when compared to LS2, the LDI value increases, which can be attributed to additional disturbances in the system that arise due to the onset of multiple leaks. Similarly, LDI (1, 6, BS3, LS6) (multiple leaks with total leakage flowrate of 16.8 lit/min) is higher than LDI (1, 6, BS3, LS3) (single leak with leakage flowrate of 22.1 lit/min). While it is promising to observe that LDI values corresponding to multiple leaks are greater than that to single leaks with similar leakage flows, it needs further investigation to conclude the merits of the LDI-based technique in differentiating multiple leaks.

Overall, it can be inferred that the presence of a complex loop between two accelerometers does not prevent the LDI-based technique in assessing leakages. It is also observed from the limited testing carried out in this study that LDI values for multiple leaks with similar combined leakage flow as a single leak are greater than that of the single leak. The importance of such capability becomes more significant when implementation of typical leak detection strategies such as district metered area (DMA) has been reported to be less suitable for old districts area with parallel pipelines or several loop lines (Li et al., 2011). It will however require extensive testing to optimize the sensor spacing distance and deal with several interesting practical pipe layout patterns. Furthermore, although the trade-off between LDI accuracy and sensor-to-sensor spacing is not known as of yet, previous studies suggest that leak-induced vibrational characteristics can be sensed at distances of over 100m (Pal et al., 2010; Nestleroth et al., 2012 and 2014; Martini et al., 2014 and 2015).

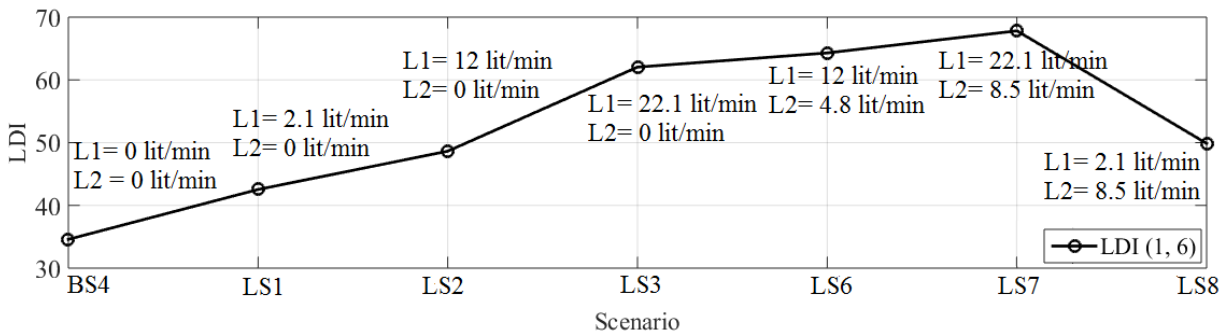

Figure 4-9- LDI values for several single and multiple leak scenarios with BS3 as the baseline scenario

4.5 Conclusions and Recommendations

In an attempt to address the leakage problem of water distribution systems which is becoming a prevalent concern, the evaluation of a vibration-based leak detection technique for water pipelines is presented in this paper. The technique assesses leakage through monitoring of cross-correlation of surface acceleration along the pipe length, which is quantified by the proposed leak detection index (LDI). This technique is evaluated using a two-looped complex pipeline system that comprises pipes of two different sizes, several valves, bends, T-joints, and elevation differences. The performance of the technique in a complex pipeline environment revealed its merits and highlighted the limitations that should be addressed in the future.

The results from various experiments reported in this paper revealed that the LDI-based technique is generally capable of assessing leakages, i.e. detecting the onset and relative severity of leakage, in complex pipeline environments. Specific findings of this study include:

1) Larger diameter pipelines exhibit greater attenuation of leak-induced pressure fluctuations along the length, from which it can be inferred that LDI values will be lower in these pipelines than in smaller diameter pipelines for comparable leaks.
2) LDI-based technique is capable of leakage assessment through accelerometers placed across a pipeline bend; and LDI values derived from accelerometers placed across a bend are usually higher than those derived from a straight section of a pipeline.
3) LDI-based technique is capable of leakage assessment through accelerometers placed across a T-joint.
4) LDI-based technique is capable of assessing the leakage through accelerometers located on the same pipe segment as the leak, as well as through accelerometers that are located on a different (yet near-by) pipe segment in a looped system.
5) LDI values for multiple leaks with a similar combined leakage flow as a single leak are higher than that for the single leak.

Some directions for future research to address the shortcomings of this study include: (a) the effect of surrounding soil backfill on the vibrational characteristics of the buried pipeline should be investigated to ensure practical feasibility of the LDI-based approach; (b) the sensitivity of the LDI-based approach to sudden, significant and legitimate system demands should be explored; (c) while the use of ball valves for leak simulators conveniently served the purpose of controlled leakages in this study, more realistic leakage flows through orifices made in pipelines may further validate the practical use of the LDI-based technique; (d) the ability of the LDI-based technique to accurately locate leaks should also be investigated in the future using an appropriately scaled experimental set-up where system complexities (e.g. bends, T-joints) are sufficiently spaced out such that LDI values are not greatly influenced by them; (e) the ability of the LDI-based technique to distinctly identify multiple leaks; (f) the LDI-based approach should be more extensively validated on real-world pipeline systems; and (h) the sustainability of network-wide LDI-based leakage monitoring system needs to be evaluated by estimating its life cycle cost and energy consumption, which depend on characteristics of physical pipeline infrastructure, monitoring hardware, and data communication schemes.

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CHAPTER FIVE

SUSTAINABILITY ANALYSIS OF A LEAKAGE MONITORING TECHNIQUE FOR WATER PIPELINE NETWORKS[1]

Water infrastructure plays a crucial role in delivering freshwater for survival and economic prosperity of communities. Regrettably, drinking water pipeline infrastructure in the U.S. and many other developed and developing nations is in a deteriorated state becoming increasingly prone to leakages, which are estimated to be 20% and above. Although several sensor-based leakage-monitoring systems have been previously developed to address this pressing challenge, the sustainability of such monitoring systems was never investigated, especially in the context of monitoring large-scale water distribution systems. This paper investigates the life cycle aspects of a vibration-based leak detection technique accounting for its cost and energy consumption. Numerous sensing and communication hardware options are reviewed to develop suitable conceptual prototypes for the proposed leakage monitoring system. Batteries and solar panels are considered as options for power supply. The water distribution network in the Charleston peninsula region in South Carolina is used for estimating the life cycle cost and energy consumption of leakage monitoring using the proposed prototypes. The sensitivity of cost and energy consumption to data sampling rate, data transmission rate and sensor spacing are also evaluated in this study. The results presented in this paper will be of interest to researchers working on sensor-based monitoring systems for water infrastructures and to water utility managers.

5.1 Introduction

Water distribution networks (WDNs) across the U.S. have deteriorated and become increasingly prone to leaks and other failures that often go undetected until a

[1] Yazdekhasti, S., Piratla, K. R., Sorber, J., Atamturktur, S. and Khan, A. (2017, ready for submission). Sustainability Analysis of a Leakage Monitoring Technique for Water Pipeline Networks, Journal of Resources, Conservation and Recycling.

WDN component fails. Unaccounted water losses in the U.S. are reported to be in the range 15-25%, of which about 60-75% is recoverable leakage squandering an estimated 3.85 GW-h of energy spent on collecting, treating and distributing the lost water [1]. Given that many regions across the nation are expected to face water shortages in the next few years [2] and with the tight greenhouse gas emission-reduction targets, it is vital to take measures to minimize water distribution leakage. It is our belief that sustainable monitoring systems leveraging embedded sensing networks can enable the continuous monitoring of WDNs for leakage detection and prevention. Embedded wireless sensor networks (WSNs) have been recently studied as a feasible alternative to address the limitations of traditional leak detection surveys using labor-intensive, acoustics-based techniques. Smart WSNs offer the distinct advantage of providing real-time monitoring of water distribution pipelines, which can consequently prompt immediate interventions [3, 4]. Specifically, three previous models highlighted the utility of WSNs in WDN leakage detection: (a) PipeNet [4], (b) PipeTect [3], and (c) WaterWise@SG [5]. These previous WSNs not only had difficulties in differentiating actual defects from stochastic ambient noises, but their sustainability merits remain largely unknown. It is desirable that pipeline-monitoring systems that are put in place, especially in the constrained environments of underground, will continue to work for a long period with minimal maintenance and operational hassles. It is also important that these monitoring systems are affordable, energy efficient and worth investing in. In such regards, this paper evaluates the sustainability of a network-wide pipeline leakage monitoring system by estimating the life cycle cost (LCC) and life cycle energy (LCE) consumption. A previously demonstrated leak detection index (LDI) technique is employed for monitoring needs [6]. Water distribution infrastructure data for the Charleston peninsula region of South Carolina is used to demonstrate the life cycle analysis presented in this paper.

5.2 Leak Detection Index (LDI) Technique: a Brief Overview

The authors recently presented and validated the leak detection index (LDI) algorithm for leakage detection through monitoring of the vibration profile of a pipeline under ambient flow conditions. The LDI technique works through tracking the variation in the Cross Spectral Density (CSD) function of acceleration measured at multiple locations along the pipe length under ambient excitation of the enclosed flow. The leak detection index (LDI) quantifies the change in the CSD of acceleration due to a leakage outbreak, as follows [6]:

$$LDI(x, y, SC_b, SC_d) = \frac{\int \left| f_{x-y}{}^{d}(t) - f_{x-y}{}^{b}(t) \right|}{\int \left| f_{x-y}{}^{b}(t) \right|} \tag{1}$$

where, x and y are two locations along the pipeline length where the acceleration data is collected, SC_b is the baseline scenario, SC_d is the damaged scenario, $f_{x-y}{}^{b}(t)$ is the CSD of data from x-y locations in the baseline system state, and $f_{x-y}{}^{d}(t)$ is the CSD of data from x-y locations in the damaged system.

The LDI metric characterizes the difference between the CSD of acceleration at any two locations in a leaky state (i.e., after leakage outbreak) and the baseline system state (i.e., before leakage outbreak) [6]. The LDI technique was validated in a two-step experimental campaign carried out on a complex pipeline test-bed made of polyvinyl chloride (PVC) pipes [6, 7]. Bruel and Kjaer 4507 B 006 (hereafter called “B&K”) type of accelerometers with nominal sensitivity of 500 mV/g were used in both phases of the experimental campaign. Accelerometers were mounted on the exterior surface of the PVC pipeline along its length to monitor the vibration profile of the pipeline. The vibrational frequency range of interest in the experimental campaign was 0-1000 Hz and this was chosen to cover the frequency span of the flow energy distribution [6, 8]. Other recent studies focusing on smaller diameter (i.e., ≤200 mm) plastic pipelines corroborated this frequency range of interest for leakage monitoring [9, 10]. The results from the two-phase experimental campaign established the merits of the LDI technique in not only detecting the onset of a leak, but also distinguishing leaks of various severities [6, 7].

5.3 Sensing Hardware and Communication Schemes

As illustrated in Figure 5-1, critical factors that influence the cost and energy consumption of a network-wide leakage monitoring scheme using LDI technique include but not limited to choice of monitoring sensors, physical and environmental characteristics influencing the propagation dynamics of leak-induced changes across the water supply system, suitable monitoring frequencies, monitoring periods, and data communication schemes. These factors are characterized for the LDI technique in this section.

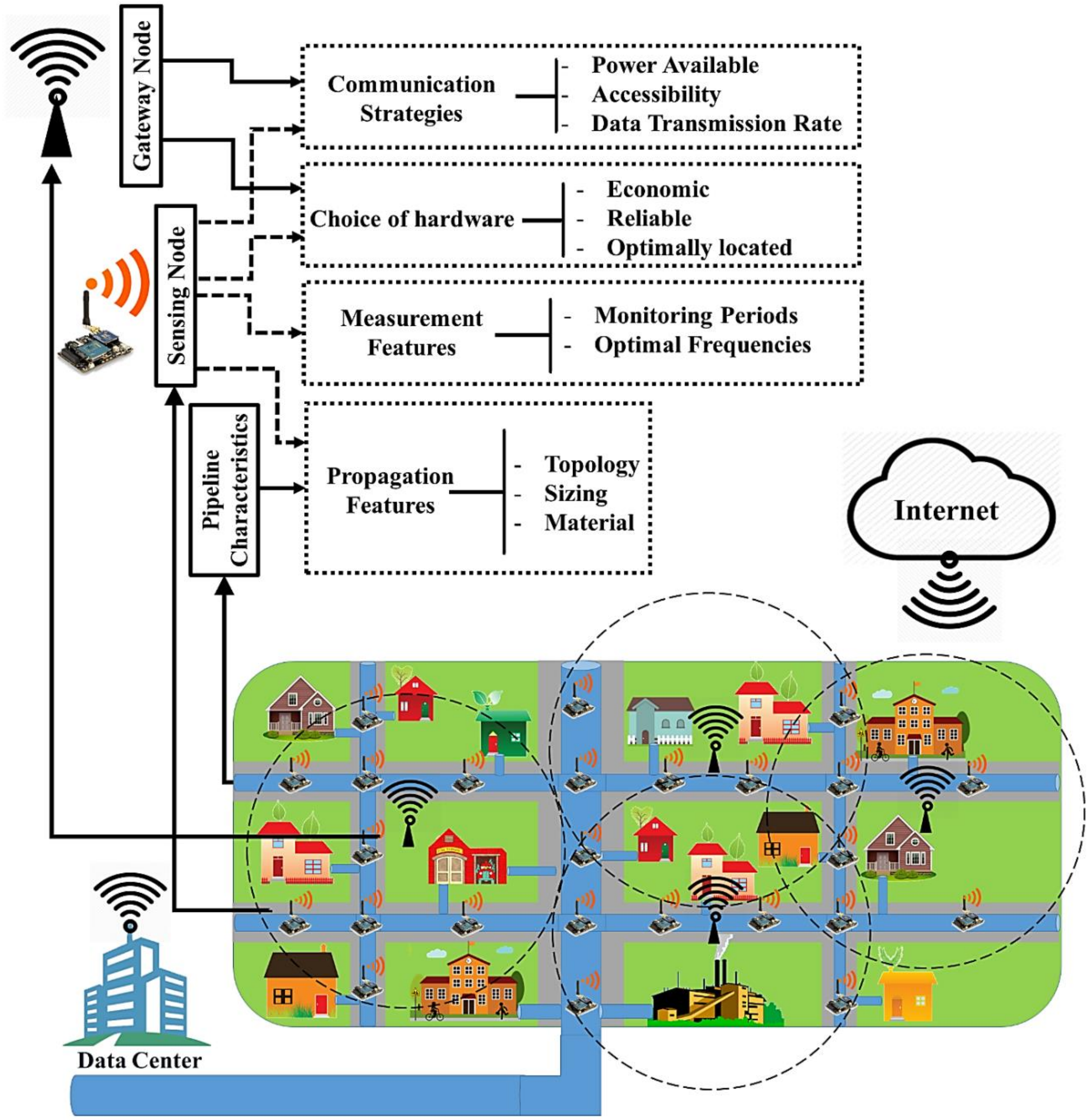

Figure 5-1- Schematic representation of the proposed network-wide monitoring scheme

Monitoring Sensors: Despite the results obtained from prior demonstrations of the LDI technique being promising, the use of expensive B&K accelerometers in real-world applications is not economically viable. Consequently, they need to be substituted with cheaper alternatives that will preserve the monitoring accuracies desired for the LDI technique. A viable alternative should be capable of reliably monitoring the frequency span of interest that will enable the LDI technique to work when employed on a variety of pipe materials, sizes and amidst various system complexities. Additionally, sensitivity and noise floor level of the chosen accelerometer should also suit the LDI technique.

Frequency Response: The frequency range of interest for capturing the leak-induced vibration signals in small diameter plastic pipelines is 0-1000 HZ, as reported by [6, 9, and 10]. A smaller range of 0-200 Hz was reportedly used for detecting leaks in large diameter (i.e., > 200 mm) pipelines [9, 11]. The efficacy of LDI technique while monitoring 0-200 Hz for small diameter pipelines is experimentally evaluated in the preliminary investigations of this study. As can be seen in Figure 5-2b, it is observed that LDI values became smaller but remained distinguishable for various damage severities when compared to those for 0-1000 Hz presented in Figure 5-2a. The reduction in LDI values for small diameter pipelines is understandably due to the exclusion of leak-induced vibro-acoustic response that is exhibited in the frequency range of over 200 Hz [12]. Limiting the monitoring range to 0-200 Hz ignores the contribution of structural modes that emerge in higher range of frequency (>200 Hz) and consequently reduces LDI values and makes them less sensitive to smaller leakages. It can however be seen from Figure 5-2b that LDI is very much capable of detecting the onset of leak as well as its relative severity even while monitoring the 0-200 Hz frequency range. Consequently, 0-200 Hz is considered adequate for detecting the onset of leakage and assessing its relative severity, especially in large diameter pipelines, which tend to be more concerning than smaller diameter pipelines for leakage issues. Therefore, the frequency response of the selected accelerometer should be at least 200 Hz.

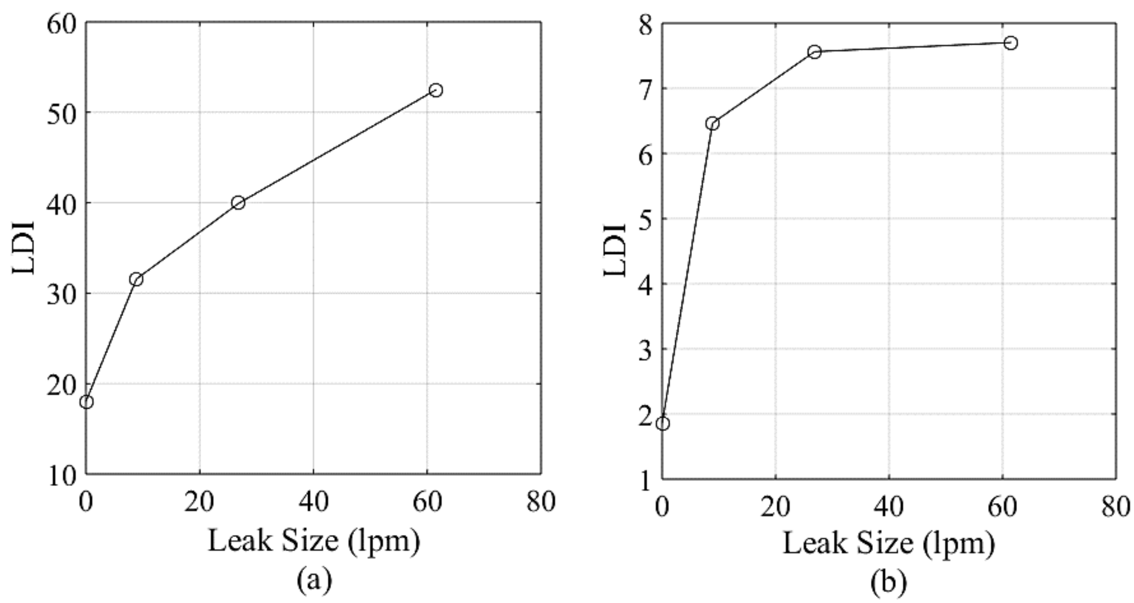

Figure 5-2- Variation of LDI over various damage severities when monitoring: (a) 0-1000 Hz; and (b) 0-200 Hz

Sensitivity and Noise Floor: Accelerometers convert mechanical energy into an electrical signal that is recorded as the output. The sensitivity of the output electrical signal to variation in the input mechanical energy is crucial, and transducers with higher sensitivities are preferred [13]. On the other hand, noise floor level is another important parameter, as high noise floor level of an accelerometer would mask the low amplitude vibrational signals thereby preventing their detection.

Table 5-1 presents various suitable alternatives to B&K accelerometers with their frequency response ranges, sensitivities and noise floor levels specified. The unit costs and reported power requirements of the sensor alternatives are also identified in

Table 5-1. The goal is to choose an alternative that is similar to B&K accelerometer in terms of technical capabilities while being cheaper.

Among the various alternatives in Table 5-1, SD1521 (manufactured by Silicon Design, Inc.) is one suitable option with relatively low noise floor, high sensitivity, and lower price compared to the B&K accelerometer. It is also comforting to note that a previous version of SD1521, named SD1221, reportedly performed well in low amplitude excitation (≈ 2.6 mg rms) and remarkably better than ADXL202 in reliably measuring vibration profiles [14].

Furthermore, the ADXL362 is an ultra-low power sensor with relatively low noise floor compared to other sensors whose costs are similar to ADXL362 (such as ADXL202). Unlike analog accelerometers, the ADXL362 produces 12-bit digital readings, eliminating the need for an ADC (Analogue-Digital Convertor) [15], and consequently saves initial cost and operational energy consumption. It should be noted that the sensitivity of ADXL362, unlike other sensors listed in Table 5-1, is measured in mg/LSB, which is the typical unit of sensitivity for transducers that produce digital output. For comparison purposes, the sensitivity of B&K accelerometer, which is an analogue-output transducer, is estimated to be 1.6 mg/LSB when working in the voltage range of 0-3.3 V (operation voltage of typical micro-processor) which is a value that is comparable to that of ADXL362 (1 mg/LSB). It should however be noted that the sensitivity of B&K can be increased to 6 mg/LSB, by raising the operational voltage range of transducers to its maximum capacity of 0-13 V, and this is why B&K accelerometers are much more expensive than other alternatives listed in Table 5-1.

In summary, SD1521 and ADXL362 are two potentially suitable alternatives to B&K for use in the LDI technique. SD1521 offers higher sensitivity, comparable noise floor levels and cheaper cost (about one-fourth) relative to B&K. ADXL362, on the other hand, is shortlisted due to its ultra-low cost. Additionally, the ADXL362 produces digital-output which is highly beneficial, and its sensitivity is comparable to that of B&K. A high-pass filter is to be used on the collected data to compensate for the higher noise floor level of ADXL362 compared to B&K. The ADXL362 sensors may also need to be placed closer to each other compared to SD1521.

Sensor Spacing: Sensor-to-sensor spacing of 100 m is recommended in the literature for plastic pipelines using accelerometers, while this distance could be as much as 200 m in case of metallic pipelines [16]. Specifically, leakage-induced vibrational characteristics have been reported to be detectable on a 600 mm cast iron pipeline using accelerometers of sensitivity 1000 mV/g when spaced 100 m apart [17, 18]. Although the analysis approach of LDI technique is different from that used in [17], it is evident that accelerometers are capable of detecting the leak-induced vibrational changes when placed as far as 100 m apart. The optimal accelerometer spacing would however be dependent on the combination of pipeline material and size characteristics, size and location of the leaks, propagation of leak-induced features, and monitoring schemes. Due to the resulting uncertainty associated with the optimal spacing of sensors, this study considered various distances for sensor spacing to evaluate its effect on the LCC and energy consumption of the network monitoring system. Specifically, distances ranging from 30m to 100m with 10m increments are considered in various scenarios for analysis.

Table 5-1- The unit cost and specifications of various sensor options

Type	B&K 4507B006	PCB 393A03	PCB 352B	SD1521	SD 1510	Kistler 8784A5	ADXL202	ADXL206	ADXL362
Sensitivity (mV/g)	500	1000	1000	800	800	1000	312	312	1 (mg/LSB)[1]
Frequency response (nominal, 3db) (Hz)	6000	6000	10000	300	600	6000	5000	400	200
Noise floor (µg/(√Hz)	2	0.2	2	7	32	100	500	100	175
Unit Price	$600	$570	$520	$200 (for one) $ 140 (for over hundred)	$120 (for one) $100 (for over hundred)	$430 (for one) $390 (for over fifty)	$5	$569	$3.97
Input range	±14 g	±5 g	±5 g	±2 g	±5 g	±5 g	±2 g	±5 g	±2, 4, 8 g
Operating Voltage (Volts)	13	18-30	20-30	5	5	18-30	3-5.25	4.75-5.25	3.5
Operating current (mA)	2-20	2-20	2-20	5	6	2-20	0.6	0.7	0.013
Specific Characteristics	Hermetic case[2]	Hermetic case	Hermetic case	Hermetic case	Hermetic case	-	-	-	-
Reference	[86]	[87]	[88]	[89]	[89]	[90]	[91]	[92]	[93]

[1] The output of this accelerometer is digital with the resolution of 12-bit.
[2] Accelerometer equipped with hermetic case are more suitable for humid environment.

Communication Schemes: Three possible communication pathways can be envisioned for the proposed network-wide leakage-monitoring scheme, as shown in Figure 5-3, depending on the locations of the transmitters and receivers. They are *aboveground*, *underground-to-underground* and *underground-to-aboveground*. Communication networks that connect sensor nodes to a data center can either be wired or wireless. The deployment of wired networks in the underground environment is not feasible both economically and practically [19]. Accordingly, wireless sensor networks (WSNs) have become an attractive alternative, especially if they are cheaper compared to wired networks [20]. It should be noted that WSNs were already tested for underground pipeline monitoring purposes in the past [21] and several vital design considerations, such as power efficiency, energy harvesting, and network reliability, have been pointed out accordingly. Current wireless communication technologies for underground applications can be broadly grouped into two categories namely, Electromagnetic-based (EM) and Magnetic Induction-based (MI) [22, 23].

Electromagnetic-based (EM) Communication: Most WSNs leverage current wireless network standards such as LAN (IEEE 802.11), Bluetooth, or Zigbee (based on IEEE 802.15.04), all of which use Electromagnetic (EM) waves for communication. Among these techniques, LAN and Bluetooth suffer from high power consumption [24, 25]. Additionally, Bluetooth is limited in terms of transmission range (i.e., about 10 m) [26], which makes it inadequate for pipeline monitoring purposes due to the resulting low coverage density.

Zigbee, on the other hand, is a simple, low cost and low-power communication standard that is suitable for supporting long battery lifetimes [27]. Although the maximum rate of data transmission supported by Zigbee is low (about 250 kbps), compared to IEEE 802.11, making it less useful for image, voice, or video transmission, it is sufficiently capable of data transmission [28] of the kind required in network-wide infrastructure monitoring. Zigbee will however have the following challenges in cases of *underground-to-underground* and *underground-to-aboveground* communications: (a) significant path loss due to high level of absorption in underground environment; and (b) high dependence on properties of the soil and its environment (e.g., water content) which could vary both spatially and temporally [29]. A previous study reported that a communication hardware platform (i.e., MICAz) comprising the same data communication standard as Zigbee (i.e., IEEE 802.15.04) mandates that the transmitter-receiver distance for *underground-to-underground* communications, as illustrated in Figure 5-3b, cannot be more than 0.1 m at a burial depth of 0.4 m when the mote is operating at 2.4 GHz [29]. It has been reported in a different study that the maximum transmitter-receiver distance for *underground-to-underground* and *underground-to-aboveground* (as illustrated in Figure 5-3) communications cannot be more than 0.95 m and 3 m, respectively, at a burial depth of 0.4 m and transmission power of +10 dBm, when a mote similar to Mica2, which utilizes Zigbee standard, is operating at 433 MHz [22] – an acceptable frequency band for pipeline monitoring purposes [30]. Although the transmission range is expected to improve when the frequency band is reduced from 2.4 GHz to 433 MHz, it would still be insufficient for sensor-to-sensor communications in buried environments as envisioned in the proposed leakage monitoring system (i.e., at a minimum of 30 m to a maximum of 100 m spacing). Zigbee can however support aboveground data transmission (illustrated in Figure 5-3a) within a range of up to 300 m [31- 34], making it suitable for the proposed LDI-based network-wide leakage monitoring. Consequently, it is proposed that Zigbee technology be utilized for network-wide communications aboveground (Figure 5-3a), while the data from the sensor node located on the surface of the pipeline be transmitted through a wired connection to the ground surface. The radio transmitter prototype suggested for use in Zigbee comprises a CC1150 radio chip [35], which is known to be an ultra-low-power transmitter capable of operating at the frequency of 433 MHz, as well as a Pulse Helical Wired Antenna [36], whose unit costs and power consumption characteristics are presented in Table 5-2.

Magnetic Induction-based (MI) Communication: MI-based communication is reportedly another promising technique for underground communication applications, as the attenuation of magnetic fields in the soil is not significantly more than that in the air [37]. Furthermore, the MI pathways do not change drastically due to variation in soil properties [19], unlike EM waves. In an attempt to take advantage of MI fields for *underground-to-underground* communication, a simple 3D MI coil, as depicted in Figure 5-4, was proposed as a transmitter and receiver [38]. Furthermore, to extend the transmission range while reducing the path loss, relay points, which are intermediate MI coils with insignificant energy needs, were proposed to be installed [39]. Metallic pipelines will not require relay points as the pipe itself can act as the magnetic core [19]. Relay coils are required for non-metallic pipelines with a suggested relay coil spacing of 5 m and maximum transmitter-receiver spacing of 100 m [19]. A transmitter circuit prototype for MI-based communication, presented in Table 5-2, has been adapted from [40] to make it more energy efficient.

While the MI-based communication principles in underground environments are promising, the technology is yet to evolve to an extent where it is technically feasible to employ. Key challenges that need to be resolved include: (a) the lack of a commercialized prototype transmitter units that are suitable, and (b) higher cost and power requirements of the transmitter circuit presented in Table 5-2 compared to the prototype of the EM-based counterpart. Due to these limitations and the added inconvenience of burying intermediate relay coils, the MI-based underground communication alternative is excluded from further analysis presented in this paper.

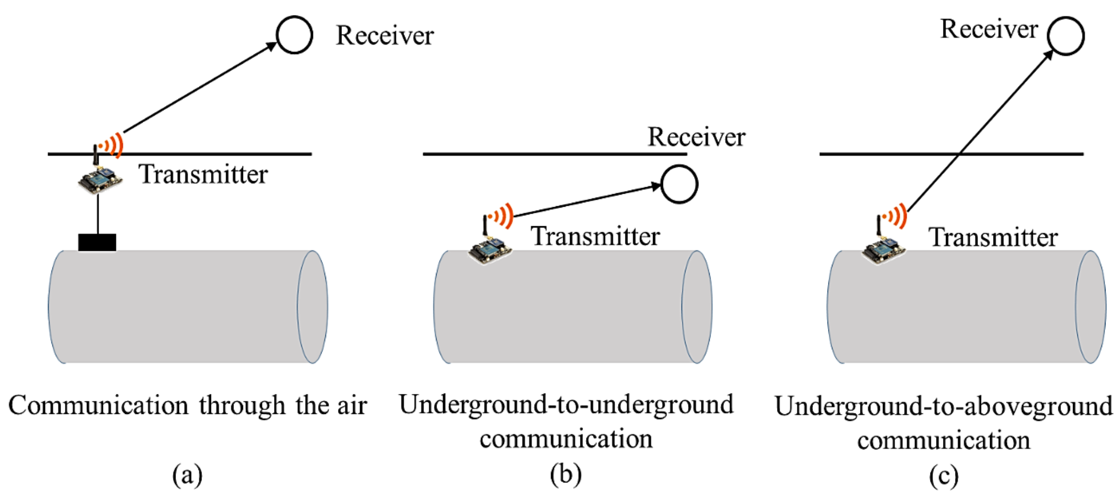

Figure 5-3- Schematics of possible communication pathways for LDI technique

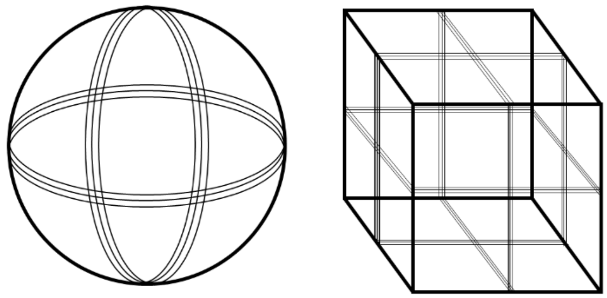

Figure 5-4- 3D Magnetic Induction coil

5.4 Sensing and Communication Schemes: Model Architecture

Two types of nodes, namely *sensor node* and *gateway node,* are characterized in the proposed network-wide monitoring scheme. Sensor nodes, which are attached to the surface of the pipeline, acquire acceleration data from the pipeline environment and transmit to a closely located gateway node. Gateway nodes, on the other hand, acquire data from a cluster of closely located sensor nodes for local processing and subsequent transmission (i.e., through Zigbee-GPRS gateway module or satellite communication) to a centralized data center that supports eventual leakage intervention-related decision making.

Sensor Node: The sensor node comprises an accelerometer (i.e., SD1521 or ADXL362 type) that is attached to the pipeline surface and a transceiver located on or closer to the ground surface. The accelerometer is connected to the transceiver using a cable that may induce undesirable noises and aggravate attenuation of analogue data that is being transmitted, especially over longer distances in the case of SD1521 [41]. The use of a micro-controller chip equipped with an analogue-digital-converter (ADC) will enable digitizing data for hassle-free communication through a wire. The proposed sensor node set-up is depicted in Figure 5-5. Table 5-3 presents the unit costs and specifications of all the hardware required for such a sensor node. It should be noted that the voltage requirement of SD1521, which is 5V, is beyond the operating voltage of a typical microprocessor (i.e., 3V) and therefore, an electronic circuit equipped with a voltage doubler is proposed to be placed in series with a linear regulator, as represented in Table 5-3, to modulate the voltage [14] between the microprocessor and SD1521 accelerometer.

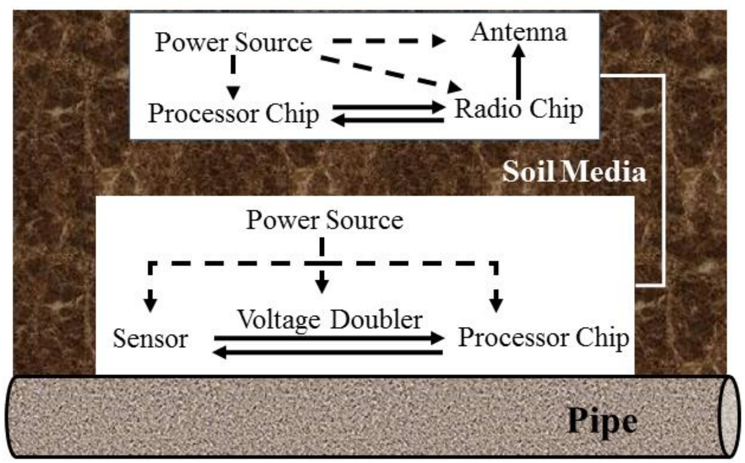

Figure 5-5- Schematic of the conceptual sensor node prototype

Similarly, Table 5-4 presents the required hardware of a prototype sensor node if ADXL362 is employed as the accelerometer. The use of an ADC will not be necessary because ADXL362 directly produces digitized output.

The micro-controller/radio-chip proposed in Table 5-3 and Table 5-4 operates in IEEE 802.15.4 WSN protocol similar to the one used with Mica2 mote [42]. Mica2 is a popular "smart" sensor node used in various monitoring applications that include but not limited to damage detection in bridges using vibrational characteristics [43, 44], seismic structural health monitoring, indoor/outdoor environmental monitoring [27], and moisture content measurement in soil [22]. Mica2 motes are however expensive for continuous monitoring applications due to their high power consumption [45]. The energy consumption (i.e., 100 μA in active mode) of the micro-controller chip (i.e. MSP430FR6989) suggested to be used in the proposed sensor node, as shown in Table 5-3 and Table 5-4, is significantly less than that of the processor unit of Mica2 (Amtel with 8 mA in the active mode) [46]. It is comforting to note that successful performance of MSP430 microprocessor chips have been reported in various wireless sensor network applications [47].

Gateway Node: The gateway node has similar architecture as the sensor node except that it needs a more powerful micro-controller for local data processing. Consequently, the energy consumption of a gateway node will be greater than that of a sensor node, especially when dealing with large data sets. The energy consumption of a gateway node will however be less than what it would be when all the sensor data is transmitted to a centralized data center for analysis [43, 48]. Among various high performance processing platforms available (e.g. Arduino Uno, Raspberry Pi and BeagleBone Black), BeagleBone with a unit cost of $55 and an estimated power consumption of 210-400 mA@5V (depending on the load and processor speed) offers a promising combination of interfacing flexibility and rapid processing [49- 51]. Such a processor will ideally suit the requirements of locally calculating the Cross Spectral Density (CSD) functions of acceleration data collected from various pairs of accelerometers [52]. BeagleBone is equipped with an Ethernet socket that can be easily plugged in for data transmission, should an internet source become available [51]. Otherwise, a cellular modem would suffice for the transmission needs. SparkFun Cellular Shield - MG2639 with a unit cost of $59 and energy consumption of 80 mA [53], along with a Quad-band Cellular Duck antenna SMA (unit cost of $7) will appropriately serve as a cellular modem [54].

Node Deployment Algorithm: Sensor nodes are grouped into clusters that transmit data to gateway nodes and the locations of the gateway nodes are optimized in this study to ensure maximum network-wide communication at minimum cost. Sensor node clusters are determined by using the K-means algorithm [55- 58] which comprises the steps shown in Figure 5-6.

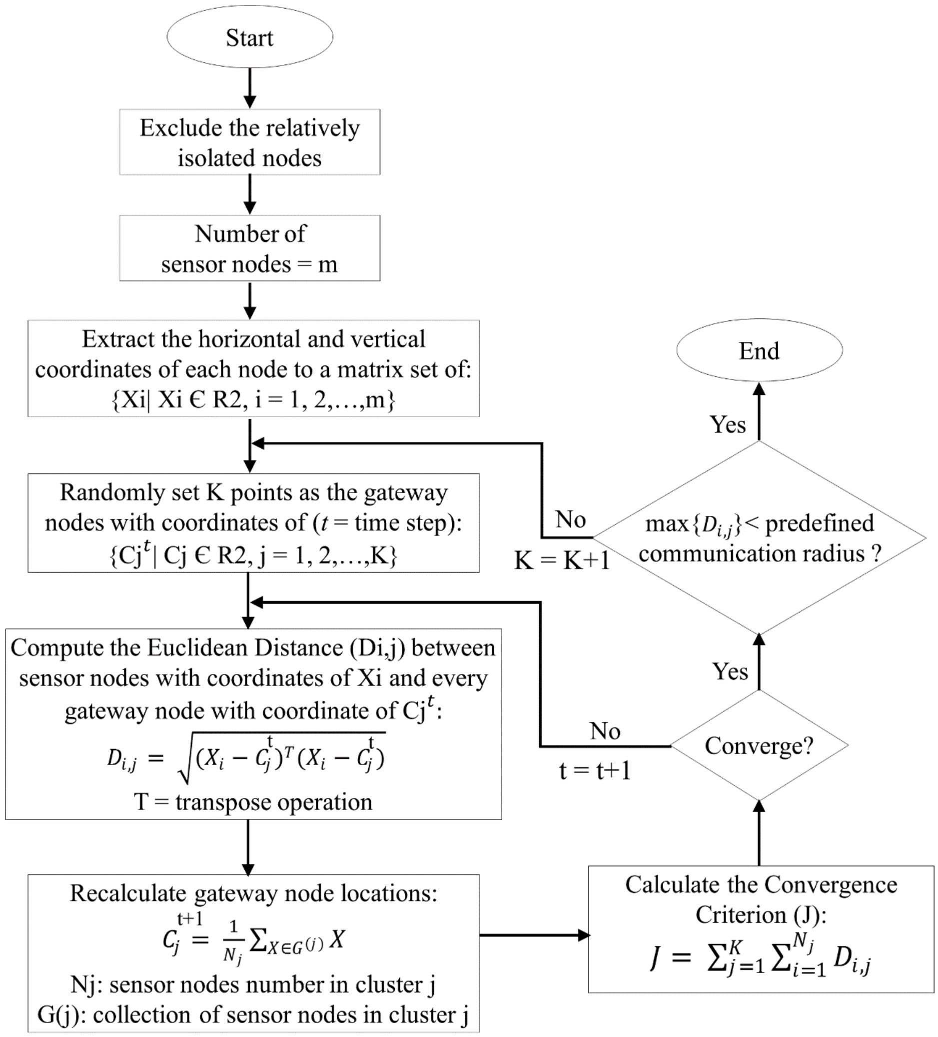

Figure 5-6- K-means algorithm for clustering of sensor nodes

<u>Communication Schemes</u>: The communication channel in the proposed network-wide monitoring system is a shared medium where multiple sensor nodes simultaneously transmit data to a gateway node. Numerous protocols exist to support effective communication in shared medium networks. Two such protocols that were successfully employed in numerous WSN applications are proposed in the LDI-based monitoring scheme. In order to facilitate the transmission of signals from multiple sensors to the gateway node over a common frequency channel without interference, the Time Division

Multiple Access (TDMA) protocol is proposed. TDMA enables sharing of the same frequency channel by multiple users through dividing their respective signals into different time slots and offering a frame-based scheduling (Figure 5-7) [59]. Each sensor node uses its own time slot while using only a portion of the frequency channel capacity. The communication efficiency can be further improved by avoiding potential collision of signals that are sharing a busy frequency channel, and this can be achieved by using the Carrier Sense Multiple Access (CSMA) protocol, which can be integrated with the TDMA scheme. As illustrated in Figure 5-7, the CSMA protocol enables the sensor node to look out for channel traffic before transmitting a signal [60]. Both TDMA and CSMA were successfully employed for shared channel access and control in numerous previous WSN applications [61, 62].

Conceptual Prototypes: Proposed conceptual prototypes of sensing and gateway nodes along with their cost estimates are presented in this section. The hardware is selected based on cost and efficiency goals upon reviewing their past successful applications [63]. Limited LCC analysis of the proposed prototype on a small benchmark water network using only one accelerometer as an option is presented in [63]. This study presents not only an extended LCC analysis but also a LCE analysis of the proposed leakage monitoring scheme accounting for a wider range of potential influential variables including: (a) the type of accelerometer to be used (i.e., SD1521 or ADXL362), (b) sensor-to-sensor spacing, (c) data sampling rate at the sensor nodes, (d) monitoring frequency at the sensor nodes, (e) data transmission rate from sensor to gateway nodes, and (f) power source for sensor nodes.

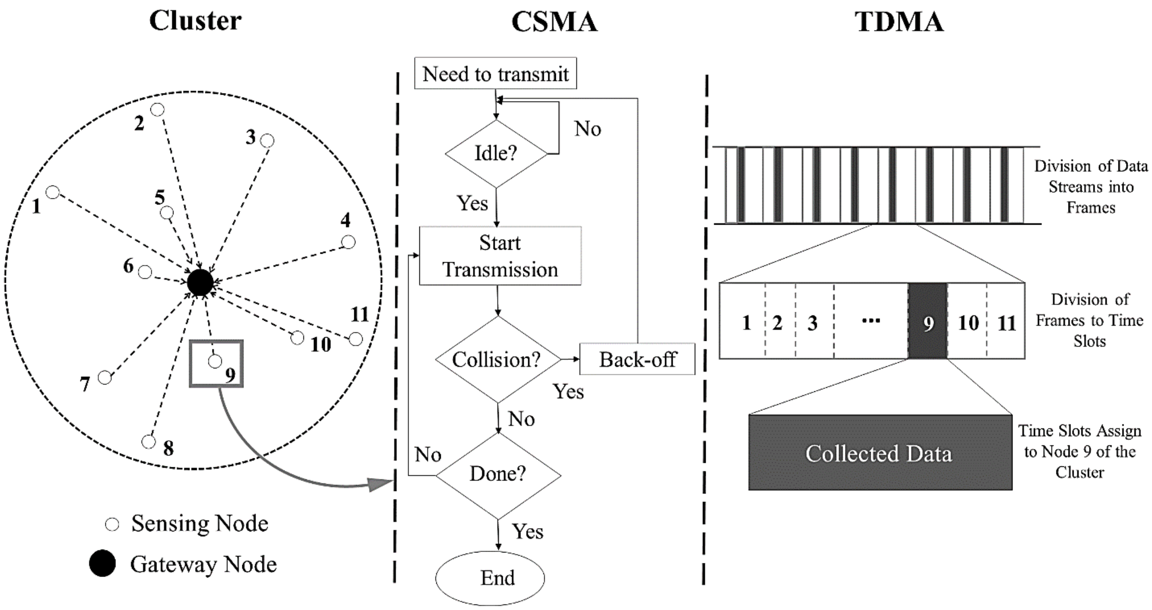

Figure 5-7- Illustration of TDMA algorithm and CSMA procedure for a typical cluster (Adapted from [85])

5.5 Proposed Data Sampling Scheme

Operational cost of the proposed network-wide monitoring system is strongly coupled with the amount of energy consumed for sensing and data transmission. Improving energy efficiency requires that only required data be collected and transmitted, and that too only when required. It is therefore proposed that the sensor nodes monitor the pipeline vibrational characteristics during midnight when the background noise levels are expected to be the least, a strategy consistent with previous leak assessment approaches [10]. Ten-second samples of vibrational data from each sensor node is proposed to be collected at five minute intervals over a period of five hours starting from 00:30AM, which would result in sixty data sets per night. Since the leak-induced vibrational phenomena exhibit stationary signals, relatively short time histories (i.e., 10 secs) of data have been reported to be adequate for monitoring purposes [9]. The data collected in one night will produce 60 LDI values for each pair of sensor nodes that will together characterize the vibrational characteristics of the network and its variation over the five-hour monitoring period. In order to eliminate the non-leakage related noises, such as those induced by traffic or legitimate consumption, only 10 least LDI values out of the total of 60 are considered for the comparative analysis that will inform the presence of leakage. Similar monitoring frequencies, cycle times and data shortlisting procedures were used in previous leakage assessment studies [9, 10]. A leakage-monitoring index (*LMI*) is calculated to summarize the data analysis from each night. *LMI* is calculated for each pair of sensor nodes as the mean value of 10 least LDI values derived from one night:

$$LMI_{i,a,b} = mean\ (LDI_{i,a,b,l10}) \tag{4}$$

where, $LDI_{i,a,b,l10}$ is the vector of 10 least LDI values for the accelerometer pair (a, b) collected from i^{th} night; and $LMI_{i,a,b}$ is the leakage monitoring index for the accelerometer pair (a, b) collected from i^{th} night.

5.6 Demonstration

The water distribution system in the peninsula area of Charleston, SC is used as a case study to estimate the LCC and energy consumption of the proposed network-wide leakage monitoring scheme and to subsequently evaluate their sensitivity to possible variations in the monitoring scheme. Monitoring large diameter (≥ 300 mm or 12 inches) distribution pipelines in the study area is considered as a specific application scenario in this study. Leakages in large diameter pipelines are highly consequential as they result in loss of large volumes of water and may eventually lead to the failure of the pipeline that can be devastating [64]. Figure 5-8a depicts the water distribution network in the Charleston peninsula region with all the large diameter pipelines highlighted. As depicted in Figure 5-8b, sensor nodes would be deployed at all the pipeline intersections (dark dots) and along the pipelines (white dots) if their length is more than the minimum specified sensor spacing in a given scenario. The K-means algorithm is used to cluster the sensor nodes, as depicted in Figure 5-8c, and to determine the location of a gateway node for each cluster.

The sensitivity of the network-wide energy consumption and LCC to variation in sensor spacing, type of sensor, and data sampling rate is investigated for the study area. A sensor spacing range of 30m-100m at 10m increments is considered in different scenarios for analysis. Figure 5-9 depicts the sensor nodes and their clustering required for monitoring large diameter pipelines in the Charleston study area as determined by the K-means algorithm, which was written and executed in the MATLAB programming interface [63]. Specifically, Figure 5-9 a, b , c, and d present the results of the sensor node clusters obtained for sensor spacing of 30m, 50m, 70m, and 100m, respectively. Similarly, sensor clusters are determined for 40m, 60m, 80m sensor spacing as well. Thirty-eight clusters of sensor nodes were determined to be required for the study area. Figure 5-9 also depicts the number of sensor nodes in each cluster. As the sensor spacing decreased, the number of sensor nodes in each cluster increased. The amount of data collected, transmitted and analyzed will get larger with increasing number of sensor nodes in a given cluster. The amount of data collected at each sensor node depends on the data collection cycle time (i.e., 10 secs) and data sampling frequency. The data sampling frequency should be reportedly at least 2.56 times greater than the highest frequency that is monitored (i.e., 200 Hz in the current study) [65]. Consequently, data sampling frequencies starting from 500 Hz are used for evaluating the sensitivity of network-wide energy consumption and LCC. Specifically, data sampling frequencies 500, 600, 700, 800, 900, 1000, and 2000 Hz (or samples/sec) are used in different scenarios of analysis.

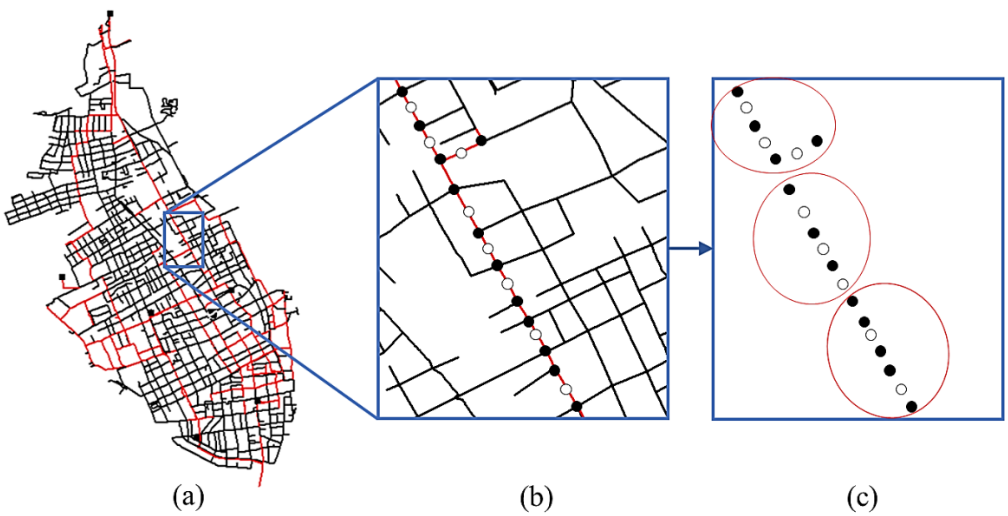

Figure 5-8- (a) Water distribution network in the Charleston peninsula area, (b) proposed sensor deployment scheme, and (c) sample clustering of sensor nodes

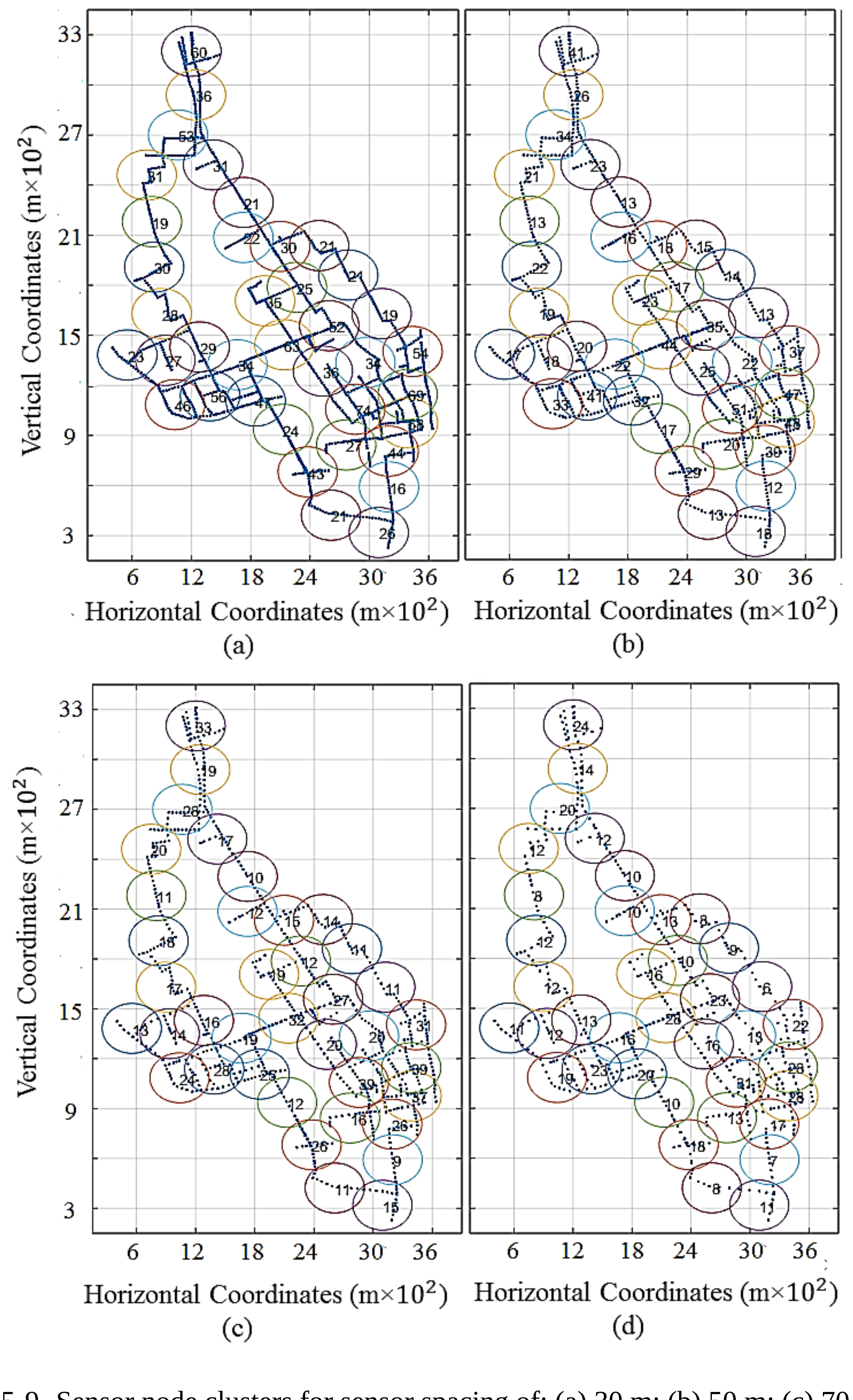

Figure 5-9- Sensor node clusters for sensor spacing of: (a) 30 m; (b) 50 m; (c) 70 m; and (d) 100

Table 5-2- Specifications and unit cost of communication hardware using EM-based and MI-based techniques

Transmission Technique	Component	Suggested hardware for a prototype design	characteristics	Power consumption	Price (for 100 units)	Reference
EM-based	Radio Chip	CC1150	Ultra-low-power operating in the 315/433/868/915 MHz bands	23.9 mA for output power of 8.1 dBm	$1.6	[35]
	Antenna	Pulse Helical Wire Antenna		-	$1.2	[36]
MI-based	Transmitter Circuit	Oscillator AEL1211CSN		40 mA	$2.0	[94]
		AD8056 Amplifier	Dual easy-to-use voltage feedback amplifier	12 mA	$2.5	[95]
		OPA3695 Amplifier	a triple, very high bandwidth, current-feedback operational amplifier	12 mA	$4	[96]
		Coil	8 turn coils winded (e.g. on square frames) with an edge length of 10 cm. The used wire is 26 AWG wire with unit length resistance of 0.1 ohm/m.	Max: 120 mA Typically: less than 60 mA	$1.36 ($22 /30 m of wire)	[97]

Table 5-3- Specifications and unit cost of communication hardware using EM-based technique (with SD1521 as accelerometer)

Component	Suggested hardware	characteristics	Power consumption	Price (for 100 units)	Reference
Accelerometer	SD1521	Refer to Table 2	5 mA	\$140	[89]
Micro-controller Chip	MSP430FR6989	Supply voltage range: 1.8-3.6 V, 12-Bit ADC	Active mode: 100 µA/MHz Standby mode: 0.4 µA Shutdown mode: 0.35 µA	\$4.5 (×2)	[46]
Voltage Doubler	TPS560200QDGKRQ1	Output Voltage Range: 0.8 V to 6.5 V	100 µA	\$1.0	[98]
Radio Chip	CC1150	Ultra-low-power operating in the 315/433/868/915 MHz bands	23.9 mA for output power of 8.1 dBm	\$1.6	[35]
Antenna	Pulse Helical Wire Antenna		-	\$1.2	[36]
Cable			-	\$1	[99]
			Total	~\$150	

Table 5-4- Specifications and unit cost of communication hardware using EM-based technique (with ADXL362 as accelerometer)

Component	Suggested hardware	characteristics	Power consumption	Price (for 100 units)	Reference
Accelerometer	ADXL362	Refer to Table 2	0.013 mA	\$3.97	[93]
Micro-controller Chip	MSP430FR6989	Supply voltage range: 1.8- 3.6 V 12-Bit ADC	Active mode: 100 µA/MHz Standby mode: 0.4 µA Shutdown mode: 0.35 µA	\$4.5	[46]
Radio Chip	CC1150	Ultra-low-power operating in the 315/433/868/915 MHz bands	23.9 mA for output power of 8.1 dBm	\$1.6	[35]
Antenna	Pulse Helical Wire Antenna		-	\$1.2	[36]
Cable			-	\$1.0	[99]
			Total	~\$12	

Energy Consumption: Detailed power consumption profiles of all the hardware used in sensor nodes, gateway nodes and the communication network in various modes (i.e., active and dormant[1]) are developed. Table 5-5 and Table 5-6 present the power requirements of the hardware used in sensor and gateway nodes, respectively, for both active and dormant modes[2].

The daily energy consumption for monitoring the large diameter pipelines of Charleston study area using the LDI technique is estimated to be 0.024 kWh and 0.022 kWh using SD1521 and ADXL362, respectively, for the baseline scenario with data sampling frequency of 500 Hz, sensor-gateway data transmission rate of 250 kbps (a typical value for Zigbee) [67], and sensor spacing of 100m.

Sensitivity Analysis: The sensitivity of daily energy consumption to type of accelerometer, sensor spacing, data-sampling rate, data transmission rate, and measurement frequency is evaluated. Figure 5-10 illustrates the variation in daily energy consumption with sensor spacing and sampling frequency when SD1521 accelerometer is used in all the sensor nodes and data transmission rate from sensor to gateway node is assumed to be 250 kbps, which is the maximum possible value for the used radio chip (CC1150) and typical to Zigbee applications [67]. As can be observed from Figure 5-10, the daily energy consumption has increased with higher sampling rates and decreased with longer sensor spacing distances. Data transmission rates of 10 kbps and 130 kbps are also tested and it was found that the daily energy consumption is not considerably

[1] The low power state of micro-controller Chip MSP430FR6989 is LPM3 mode with the ultra-low operating current of 0.4 μA.

[2] The current consumption of CC1150 radio chip is estimated by "power dissipation model" [66]

sensitive to variation in data transmission rate. Specifically, increasing the data transmission rate from 10 kbps to 250 kbps resulted in an increase in the current of every radio chip by a negligible amount of 24e-6 A. The trends in the variation of daily energy consumption for ADXL362 are found to be similar to that of SD1521; although, the absolute values are smaller.

Furthermore, Figure 5-11a presents the variation of daily energy consumption over various sensor-spacing distances at 700 Hz data sampling frequency, while Figure 5-11b presents the variation of energy consumption over various data sampling frequencies for a sensor spacing of 70 m. It can be observed from Figure 5-11 that the estimated daily energy consumption using SD1521 is only marginally greater than that of ADXL362. Despite the higher (about 400 times) power requirements of SD1521 compared to ADXL362, the daily energy consumption of the network-wide monitoring system using these accelerometers is not considerably different because majority of the energy consumed is for data transmission which is independent of the accelerometer type. This observation is consistent with relevant literature [68].

To further investigate the sensitivities, the percentage increase in daily energy consumption, compared to the scenario with a sampling rate of 500 Hz and sensor spacing of 100m, for the following scenarios is studied: (a) reducing sensor spacing to 80m at a sampling rate of 500 Hz; and (b) increasing the sampling rate to 600 Hz at the same sensor spacing of 100m. The total number of sensors needed has increased from 583 to 685 when the sensor spacing reduced from 100m to 80m in scenario (a). The additional 102 sensors would result in the collection, transmission and analysis of an additional 510,000 (i.e., 500 samples/sec * 10 secs * 102 sensors) data samples per one collection cycle of 10 secs. Similarly, increasing the data sampling frequency from 500 Hz to 600 Hz in scenario (b) results in the collection, transmission and analysis of an additional 583,000 (100 samples/sec * 10 secs * 583 sensors) data samples per each 10 sec monitoring cycle. The percentage increase in daily energy consumption using SD1521 accelerometer for scenarios (a) and (b) are 17.15% and 17.57%, respectively, and it is 17.11% and 19.53% with ADXL362. The increase in the daily energy consumption is expectedly proportional to the number of additional data samples that need to be collected, transmitted and analyzed.

Finally, the low noise floor level of ADXL362 compared to SD1521 may need to be compensated through the combination of: (a) using of high pass filter on the collected data which would not result in additional cost or energy consumption due to the processing capability of the BeagleBone micro-controller; and (b) reduction in the sensor spacing. Table 5-7 presents the ratio of daily energy consumption using ADXL362 for various sensor spacing distances to that of SD1521 at a fixed sensor spacing of 100m. For example, it can be seen from Table 5-7 that the daily energy consumption using ADXL362 for a sensor spacing of 30m is 2.13 times of that using SD1521 at a sensor spacing of 100m and data sampling rate of 500 Hz. It can be further observed from Table 5-7 that while the ratio of daily energy consumption using ADXL362 to that of SD1521 (ADXL362/SD1521) increased with sampling rate for any sensor spacing distance, the rate of increase (per Hz) diminished at higher sampling rates. This is due to the dominant contribution (increased with sampling rate) of data transmission phase in the estimated total daily energy consumption which neutralizes the variation in energy consumption associated with measurement between ADXL362 and SD1521.

The daily energy consumption for continuous real-time monitoring, as opposed to only five hours of monitoring during nighttime, will be proportionately greater depending on the number of data points collected, transmitted and analyzed. For the case of collecting 10 sec samples at 5 minute intervals over a 24-hr period, the total number of samples will be 288 (i.e., 2,880 secs of monitoring data) and the daily energy consumption is estimated to be 4.8 (i.e., 288/60) times of the estimates presented in Figure 5-10 and Figure 5-11.

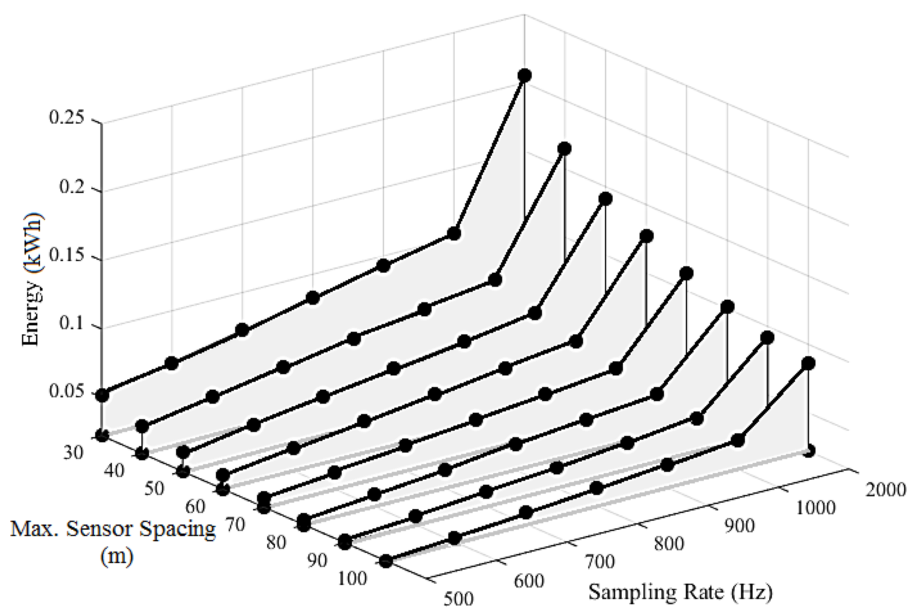

Figure 5-10- Daily network-wide energy consumption estimates using SD1521

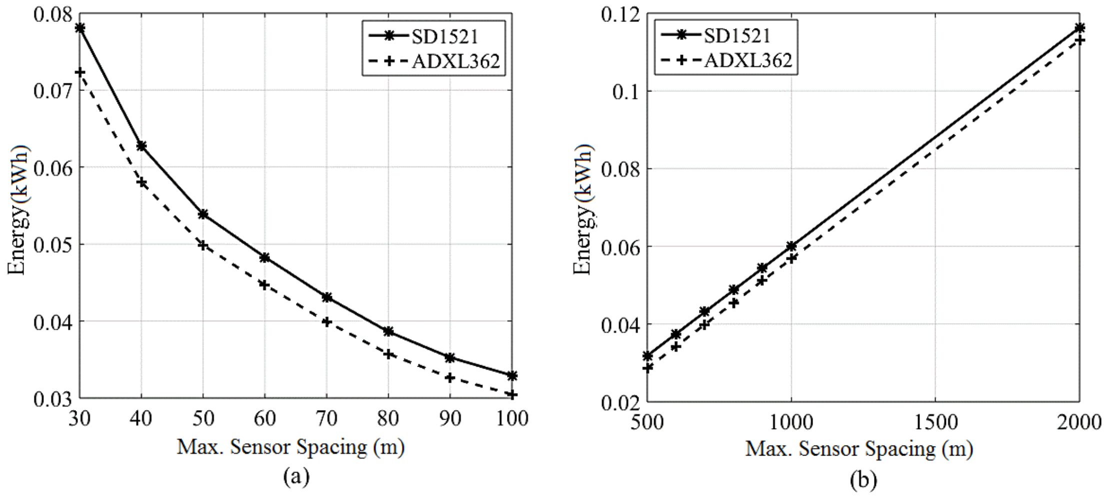

Figure 5-11- Variation in daily network-wide energy consumption with: (a) sensor spacing distance (at a data sampling frequency of 700 Hz); and (b) data sampling frequency (at a sensor spacing distance of 70 m)

Life Cycle Cost (LCC): Life cycle cost of the proposed network-wide leakage-monitoring set-up mainly comprises: (a) initial cost, and (b) operation and maintenance cost.

Initial cost or capital cost entails *equipment* and the *installation* expenses of the monitoring set-up. *Equipment* cost is be estimated by multiplying the unit cost of required hardware per each sensor or gateway node with the number of such nodes. The unit costs of the two types of sensor nodes (i.e., SD1521 and ADXL362) and a conceptual prototype of gateway node were presented in the preceding section. It should be noted that these unit costs are independent of the pipeline characteristics. The number of sensor nodes is however derived based on the pipeline layout and the specified minimum sensor spacing. On the other hand, the number of gateway nodes varies with the transmission range and the amount of data that needs to be transmitted and processed in a cluster of sensor nodes. The K-means algorithm is employed to determine optimal number and locations of gateway nodes based on the transmission range, which is considered as the only key characteristic of gateway nodes in this study. The BeagleBone processor platform, which has a SDRAM memory of 512 MB [51], is used in the gateway node for local data processing. It is determined to be capable of processing data and calculating LDI values even in the congested parts of the study area with least sensor spacing (i.e., 30 m) and highest data sampling frequency (i.e., 2000 Hz). Therefore, gateway nodes are not constrained by their processing abilities and consequently same number of gateway nodes (i.e., 38) with similar initial costs will be required for monitoring the case study area irrespective of the sensor spacing.

Installation of sensor nodes that need to be attached to the surface of the buried pipeline poses several construction-related challenges. The sensor node must be accessible for the purpose of maintenance over its life cycle and to accommodate accessibility, it is proposed that a small diameter plastic pipeline be used, as shown in Figure 5-12. Specifically, a 1.5m long, 25.4mm PVC pipe is proposed to be installed vertically from the ground surface to the top of the buried pipeline to facilitate access to the sensor node as well as to run a wired connection to the transceiver, which will be hooked to the PVC pipe closer to the ground surface. A unit cost of $1.16/m for PVC pipeline is used for estimating purposes [69]. The installation cost includes cost of labor and equipment used in excavation and placement of the sensor node. A state-of-the-art potholing technology, namely air-vacuum excavation, is proposed to be used for safely [70] excavating the soil for installing the 25.4mm PVC pipeline. The excavation cost is estimated to be \$4.7/node based on the project location and unit cost data [71]. The installation cost of wireless senor nodes is reported to be insignificant [72, 73], but a nominal cost of \$0.3/node is considered in this study. The installation cost of the gateway nodes, on the other hand, is considered about 50% of their hardware cost.

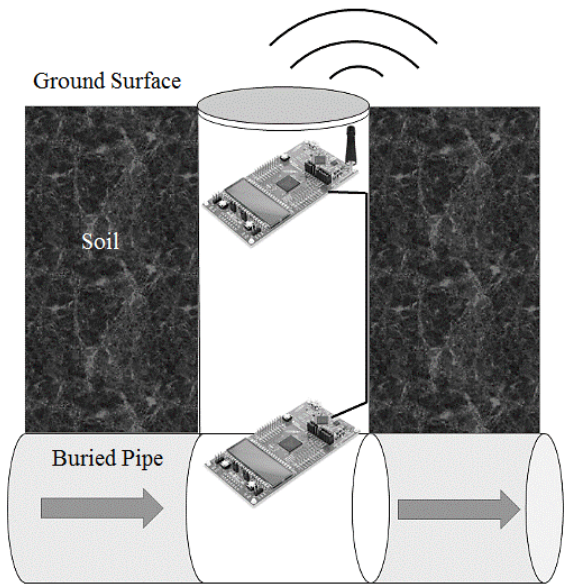

Figure 5-12- Schematic arrangement of a sensing node

The operational expenses are mainly related to the power consumption of the monitoring system. Two power supply options for sensor nodes are considered in this study namely, batteries and solar panels. AA batteries have been reported to be successful with MSP430 microprocessor chips (Milenkovic et al., 2005) and therefore two AA batteries at a unit cost of \$0.4/each [74] are considered for power supply cost estimating using the battery option. As per the energy specification of typical AA batteries, they will need to be replaced every 2 years when used with SD1521 accelerometer and every 10 years with ADXL362 accelerometer [63] when used at a sampling rate of 500 Hz. A conservative battery replacement frequency of 5 years [75] is considered in this study for the ADXL362 accelerometer. On the other hand, for the solar panel option, a low cost circuit prototype for transferring the energy generated by the solar cell into a storage unit, such as a rechargeable battery, has been presented and evaluated by [76] for typical WSN applications. The estimated total cost of such energy harvester unit is reported be \$14/node, when employing Lithium Ion 300 mAh type of battery [77] and amorphous silicon thin film as the solar panel [78]. Installation costs of solar panel are considered 25% of the equipment cost [79, 80]. On the other hand, gateway nodes with superior processing capabilities would need more power and it would be more appropriate to supply aboveground AC power to such nodes. The cost of their operations is therefore estimated using the power requirements listed in Table 5-6 along with active operational time and unit power cost in the Charleston study area.

Maintenance work mainly entails replacing batteries. The estimated maintenance cost is the product of unit cost of battery and the total number of batteries that need to be replaced over a 20-year life cycle period. The labor expenses associated with the replacement of each battery is estimated to be \$2.67/node assuming unit labor cost of \$16 per hour [81] and considering a 10 min set-up time for each node. For estimating the maintenance costs, a 5-year replacement cycle is considered for the rechargeable battery [75] and a 1% of the initial cost is considered the annual maintenance cost for the remaining components of the harvester unit [82]. A contingency of 15% is included in the life cycle costs of the proposed monitoring system along with the equipment cost, installation cost, operational and maintenance costs.

A 20-year life cycle period is used for estimating the LCC of the LDI-based leakage monitoring system for the Charleston study area. The LCC for the baseline scenario with a data sampling frequency of 500 Hz, sensor spacing of 100m, and using battery as the power source is estimated to be $152,000 and $37,000 when using SD1521 and ADXL362, respectively. Subsequently, under that specific condition, it can be concluded that the LCC of monitoring system with SD1521 is about four times more than that with ADXL362, while the unit cost of a single sensor node with SD1521 is more than ten times that of ADXL362. The sensitivity of LCC is estimated for variation in the type of accelerometer (i.e., SD1521 and ADXL362), the type of power supply (i.e., battery and solar panel), the data sampling frequencies (i.e., 500, 600, 700, 800, 900, 1000 and 2000 Hz), and the sensor spacing distance (i.e., 30, 40, 50, 60, 70, 80, 90, and 100 m).

Sensitivity Analysis: Figure 5-13 illustrates the variation of LCC with sensor spacing and sampling rates for sensor nodes that are powered with solar energy. As per Figure 5-13, LCC is found to be highly sensitive to sensor spacing with it diminishing by almost half when sensor spacing is increased from 30m to 100m. On the other hand, while LCC increased with higher sampling frequency, the increments are only marginal and insignificant. Similar inferences can be drawn from Figure 5-14a and Figure 5-14b. Larger data sets are produced and analyzed with higher data sampling frequencies. The initial cost of the system would not vary with data sampling frequencies mainly because of the capabilities of the microprocessor proposed to be used in the gateway nodes. It may however take longer and consume more energy for data transmission with higher data sampling frequencies and therefore higher frequencies would increase the operational costs, but not significantly. The sensitivity of LCC to data sampling rate is in contrast with that of the energy consumption, which is presented in Figure 5-10. On the other hand, reducing the sensor spacing distance will require more sensing nodes, which results in higher initial cost, as well as operation and maintenance costs. As can be observed from Figure 5-14a, the reduction in sensor spacing has considerable effect on LCC and it is found that the *SD1521 and solar power* combination resulted in highest LCC, as can be observed from Figure 5-14a, irrespective of the sensor spacing distance.

Furthermore, the LCC of SD1521 with battery power option for a sensor spacing of 100m is about twice of that of ADXL362 with battery power option for a sensor spacing of 30m. Consequently, even if the sensor spacing with ADXL362 needs to be smaller than that with SD1521 because of its lower noise floor level, the LCC with ADXL362 will definitely be lower. Similarly, the LCC of ADXL362 with solar power for a smaller sensor spacing is also less than that of SD1521 with solar power option.

The sensitivity of energy consumption and LCC of the proposed leakage monitoring system to multiple variables were analyzed in this section. While several pipeline leak detection techniques currently exist, they are often used in an ad-hoc manner and not many support continuous monitoring. The monitoring of large diameter pipelines with these ad-hoc techniques will reportedly cost about $15/m and $40/m, respectively, using inline inspection [17] and excavation techniques [83]. Snapshot inspection of large dimeter pipelines in Charleston study area (which has 42 km of pipelines) with such ad-hoc techniques would cost an estimated $630,000 (with inline inspection) and $1,680,000 (via excavation), as compared to the maximum 20-year life cycle cost of continuous monitoring using LDI technique which is estimated in this study to be about $349,000. The total cost of such network-wide monitoring system is highly dependent on the initial cost as shown in Figure 5-15. On the other hand, the total energy consumption of the network monitoring system is highly dependent on the amount and extent of data transmission. Further development of the proposed prototypes and eventual field deployment may involve several challenges, which need to be studied in the future. Resource constraints, dynamic topologies, harsh environmental conditions, and data redundancy [84] are some of the challenges needing future research.

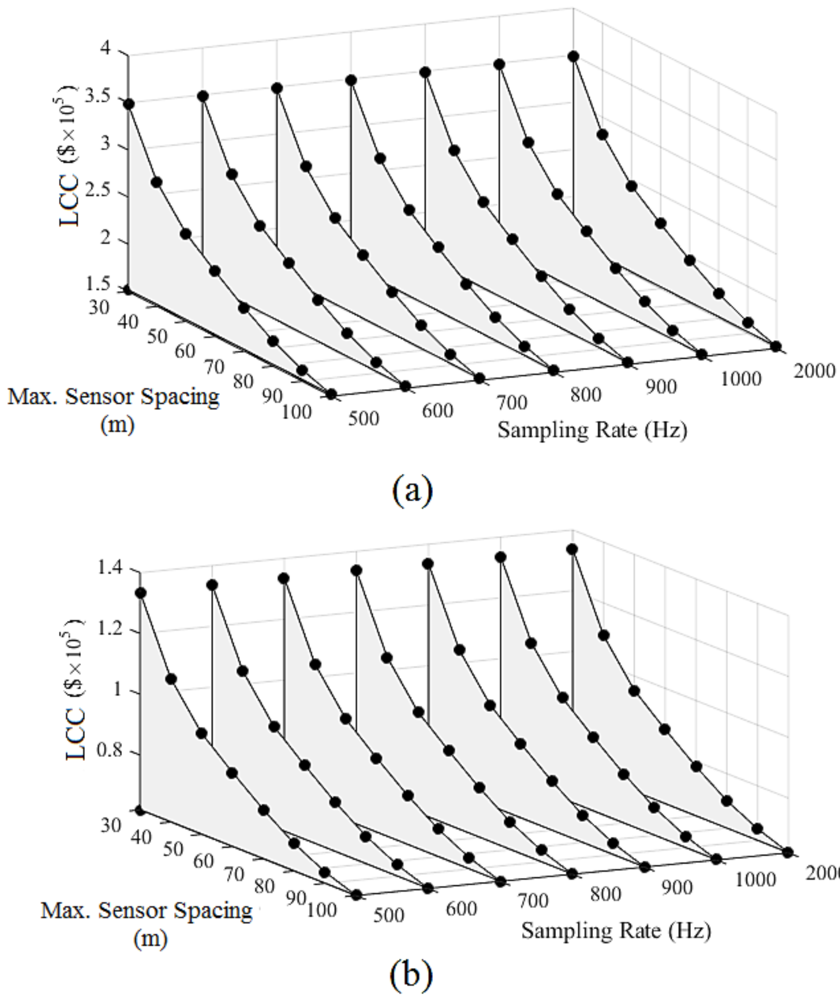

Figure 5-13- Network-wide LCC estimates using: (a) SD1521+solar panel; and (b) ADXL362+solar panel

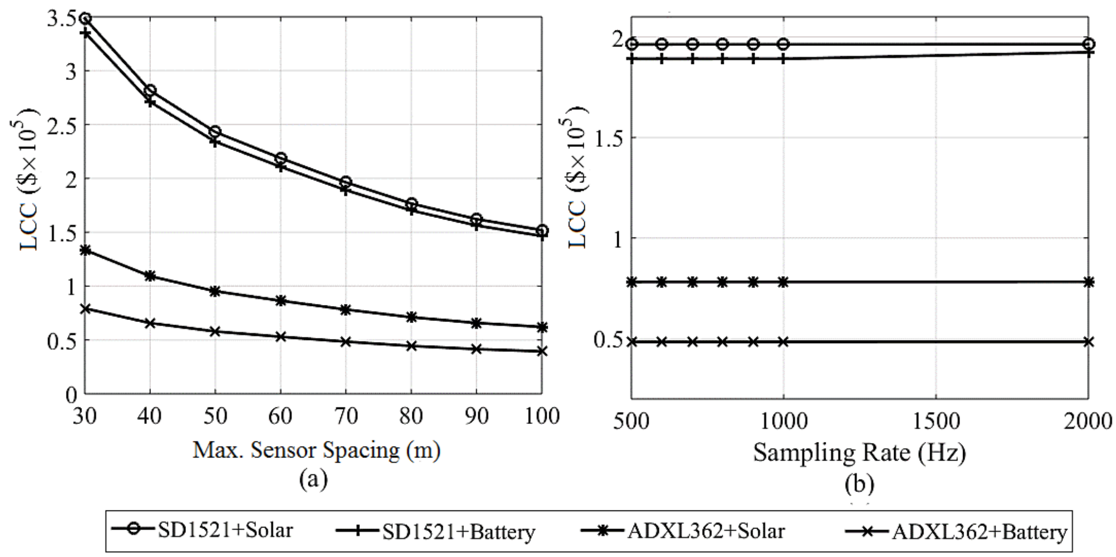

Figure 5-14- Variation in network-wide LCC over 20 years with: (a) sensor spacing distance (at a data sampling frequency of 700 Hz); and (b) data sampling frequency (at a sensor spacing distance of 70 m)

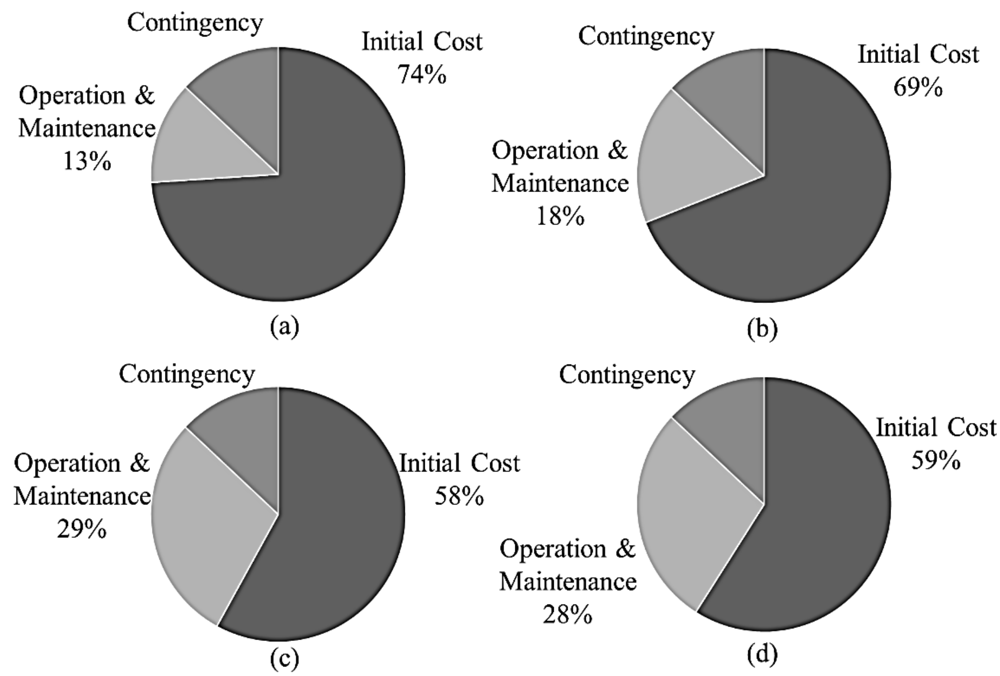

Figure 5-15- The distribution of LCC among various phases with sensor spacing distance of 100m at a data sampling frequency of 500 Hz using: (a) SD1521+solar panel; (b) SD1521+battery; (c) ADXL362+solar panel; and (d) ADXL362+battery

Table 5-5- Power model of sensor node

Application	Component	State	Voltage (V)	Current (µA)	Reference
Measurement (SD 1521)	Accelerometer (SD1521)	Active	5	5000	[89]
	ADC (Micro-controller Chip)	Active	3	0.4	[46]
	Voltage doubler TPS560200QDGKRQ1	Active	3	100	[98]
	Micro-controller Chip MSP430FR6989 (1)	LPM3	3	0.4	[46]
	Micro-controller Chip MSP430FR6989	Active	3	103	[46]
Measurement (ADXL)	Accelerometer (ADXL 362)	Active	3.5	13	[93]
	Micro-controller Chip MSP430FR6989 (1)	LPM3	3	0.4	[46]
	Micro-controller Chip MSP430FR6989	Active	3	103	[46]
Data Transmission	Radio chip CC1150 (2)	Active	3	14600	[35],[66]
	Micro-controller Chip MSP430FR6989	Active	3	103	[46]
	Pulse Helical Wire Antenna	Active	0	0	[36]

(1) LPM3 is the low power mode of the processor
(2) The current is estimated by power dissipation model

Table 5-6- Power model of gateway node

Application	Component	State	Voltage (V)	Current (µA)	Reference
Data Transmission	Radio chip CC1150 (1)	Active	3	14600	[35],[66]
	BeagleBone platform	Active	5	460000	[51]
	Pulse Helical Wire Antenna	Active	0	0	[36]
Calculation	BeagleBone platform	Active	5	460000	[51]

(1) The current is estimated by power dissipation model

Table 5-7- The ratio of daily energy consumption using ADXL362 for different sensor spacing distances to that using SD1521 at a sensor spacing of 100 m

		Sampling Rate (Hz)						
		500	600	700	800	900	1000	2000
Sensing Distance (m)	100	0.90	0.91	0.93	0.94	0.94	0.95	0.97
	90	0.96	0.98	0.99	1.00	1.01	1.01	1.04
	80	1.05	1.07	1.09	1.10	1.10	1.11	1.14
	70	1.18	1.20	1.21	1.22	1.23	1.24	1.28
	60	1.32	1.34	1.36	1.37	1.38	1.39	1.43
	50	1.47	1.49	1.51	1.53	1.54	1.55	1.60
	40	1.71	1.74	1.76	1.78	1.79	1.81	1.86
	30	2.13	2.17	2.20	2.22	2.24	2.25	2.32

5.7 Conclusions and Recommendations

This study estimated the life cycle cost and energy consumption of sensor-based, network-wide leakage monitoring of water distribution systems. It also evaluated the sensitivity of these parameters to various uncertainties. Major takeaways from this study include:

- Based on the proposed conceptual prototype designs and available performance data for EM-based and MI-based communication schemes, the energy consumption of EM-based communication modules is found to be less than that of MI-based; on the cost front too, EM-based modules were estimated to be cheaper than MI-based ones.
- Power consumption by the sensor node is not sensitive to the rate of data transmission to the gateway node; the increase in transmission rate from 10 kbps to 250 kbps resulted in an increase in the current of every radio chip by a negligible amount of 24e-6 A.
- The estimated power consumption of the proposed LDI-based monitoring system for inspecting large diameter pipelines in the Charleston peninsula area is in the wide range of 0.02 kWh (i.e., in the case of using ADXL362 with a sensing spacing of 100

m and sampling rate of 500 Hz) to 0.2 KWh (i.e., in the case of using SD1521 with a sensing spacing of 30 m and sampling rate of 2000 Hz) per day. Although the power consumption of SD1521 sensor was found to be about 400 times greater than that of ADXL362, the daily power consumption of the network-wide monitoring system using SD1521 is found to be in the range of 3% to 11% of that using ADXL362. It is clear from this analysis that majority of the energy needs arise from the transmission phase of the monitoring system. Furthermore, it has been found that the relative benefit of using ADXL362 diminishes with increasing sampling rate, for the power consumption in transmission phase increases with the sampling rate.

- The LCC of the network-wide LDI-based leakage monitoring of large diameter pipelines in the Charleston peninsula area is estimated to be in the range of $37,000 (i.e., in the case of ADXL with battery power, sensor spacing of 100 m and over different sampling rates) to $349,000 (i.e., in the case of SD1521 with solar power, sensing spacing of 30 m and over different sampling rates). While the estimated LCC is found to be highly sensitive to sensor spacing, it is observed that the capital expenditure contributes significantly to the LCC than the operational and maintenance phase. Furthermore, the rate of increase in LCC with decreasing sensor spacing is maximum for a sensor node specification with higher initial cost (i.e., in the case of SD1521 with solar power) and least for a sensor node specification with least initial cost (i.e., in the case of ADXL362 with a battery).
- The estimated LCC of the LDI-based monitoring system for the Charleston peninsula region is found to be less sensitive to the variation in sampling rate. The percentage

growth in LCC when the sampling rate is changed from 500 Hz to 2000 Hz for various sensor node and power supply combinations is found to be negligible and ranging between 0.02% - 0.4%.

The proposed life cycle analysis is based on a conceptual prototype designed to aid leakage detection using a previously demonstrated algorithm. Although the proposed monitoring set-up can accommodate the requirements of water networks with different configurations, the hardware and communication schemes need to be thoroughly evaluated and validated in the future to establish their merit for monitoring real world WDNs. Furthermore, the uncertainties associated with network connectivity of WSNs in real world applications arising from the dynamic topologies and environmental hassles were not adequately incorporated into the life cycle analysis presented in this study. For example, accumulation of dust or high humidity levels may lead to data transmission interference and result in malfunctioning of the monitoring system, which needs to be evaluated in the future.

Future research should also focus on: (a) investigating physical (e.g., flooding or deliberate attacks) and cyber security (e.g., denial-of-service attacks) issues associated the proposed infrastructure monitoring system; (b) investigating improvements to the LDI damage detection algorithm to minimize long-range data transmission and maximize local data processing for optimal energy usage; and (c) investigating options to build redundancy into the proposed monitoring system to overcome sensing and communication failures.

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CHAPTER SIX

CONCLUSIONS

6.1 Summary of Research

In the United States, more than 20% of all treated water is estimated to be lost every day through distribution pipeline leakages, and such losses exceed even 50% in some developing and underdeveloped countries (Mutikanga et al., 2012). Given the increasing deterioration of pipeline infrastructure resulting from the lack of adequate capital improvement investment, pipeline leakage is expected to only increase in the coming years. While the suitability of conventional water pipeline leak-detection techniques is limited to snap-shot monitoring of distribution systems, some of them are also intrusive in nature and offer limited compatibility with some of the most commonly pipe materials such as plastic. Therefore, an affordable, automated and non-intrusive leak detection mechanism that is suitable to a wide range of pipeline materials is desirable. In an attempt to address this need, in this study, a novel leak-detection technique (LDT) has been developed, and the practical applicability of the technique has been evaluated using a two-loop experimental set-up made of Polyvinyl Chloride (PVC) pipe that is representative of a real-world pipeline system. The proposed LDT relies on the variation in the Cross Spectral Density of pipeline surface vibration data, collected continuously along the length of pipe. Preliminary findings based on a two-phase experimental campaign revealed the capabilities of the proposed leak detection index (LDI) technique to detect leakages in a real-size, multi-looped pipeline system made of PVC that is comprised of various complexities such as joints, bends and pipes of multiple sizes.

Furthermore, the sustainability merits of the LDI scheme are estimated through conceptual development of the sensing, communication and computational schemes for monitoring the large diameter pipelines in the distribution network of the Charleston peninsula region in South Carolina. Specifically, life cycle cost and life cycle energy consumption needs along with their sensitivities to various uncertainties are estimated.

6.2 Major Findings of this Dissertation Study

This dissertation study has made the following contributions to the body of knowledge:

Findings from the review of literature on leak detection practices for water pipelines (Chapter 2):

- There are outstanding research needs and technology gaps in development of a suite of leak detection techniques that are suitable for a wide range of pipe materials and sizes.
- Monitoring large diameter metallic and small diameter plastic pipelines is reported to be a challenge with conventional external techniques such as listening devices and leak noise correlators due to the greater attenuation of acoustic noises compared to other pipe materials and sizes.
- Internal techniques, such as free-swimming acoustic and tethered acoustic techniques, are found to be suitable for highly attenuating pipelines, such as non-metallic pipes, as they directly pass adjacent to the source of noise (i.e., a leak). It may however not always be convenient to employ these internal

techniques because of their access needs, especially in case of small diameter pipelines.

Findings from the development and experimental evaluation of a vibration-based technique for detecting water pipeline leakages (Chapters 3 and 4):

- The onset of a leak causes expulsion of water, which results in a change in the pressure fluctuation and subsequent vibration fluctuation of the pipeline. Therefore, monitoring the vibration profile of a pipeline using accelerometers under ambient flow conditions can enable the detection of a leakage presence.
- The results from phase-I experimental testing demonstrated the capabilities of LDI technique. It was revealed that LDI is likely able to detect leaks as small as 3/8th inches (or 9.525 mm) in diameter. Furthermore with LDI, it is possible to detect leakages located between two monitored locations as well as leakages located outside the sensing boundaries. It is also revealed that LDI and leakage severity have good correlation and the R-squared values for all pairs of samples for different scenarios is more than 0.90. LDI is found to be able to detect leakages in noisy environments, but it is less sensitive to damage severity at high noise levels.
- Due to the difficulties faced by many previous leak detection approaches in distinguishing leaks from pipeline system complexities, the phase-II of the experimental testing entailed evaluating the merits of LDI approach on an extended experimental set-up which comprised of two-loops of PVC pipeline with multiple pipe sizes, valves, bends, T-joints, and multiple leaks. The

results from this phase revealed that larger diameter pipelines exhibit greater attenuation of leak-induced pressure fluctuations along the length, from which it can be inferred that LDI values will be lower in these pipelines than in smaller diameter pipelines for comparable leaks. It was also revealed that LDI is capable of detecting leakages through accelerometers placed across a bend, T-joints or across a loop. Furthermore, it seemed plausible to distinguish between multiple leakages in the system.

- While the results of this study are limited to the obtained data from the experimental campaign on PVC pipelines, it is expected that the LDI approach will also work on metal pipes based on the comparable damping coefficients of small diameter PVC pipelines with small or even larger diameter metal pipelines. Although, further validation is required to determine the true extent of the merits and limitations of LDI technique on metal pipelines.

Findings from the sustainability analysis of the leakage monitoring system for water supply networks (Chapter 5):

- Based on the specifications of various accelerometers (e.g. frequency response range, sensitivity, noise floor level, and cost), SD1521 and ADXL362 seemed feasible for the LDI technique in lieu of the expensive B&K accelerometers that were used in the experimental campaign of this study.
- Based on the proposed conceptual prototype designs and available performance data for Electromagnetic-based (EM-based) and Magnetic Induction-based (MI-based) communication schemes, the energy consumption

of EM-based communication modules is found to be less than that of MI-based; on the cost front too, EM-based modules were estimated to be cheaper than MI-based ones.

- The LCC of the network-wide LDI-based leakage monitoring of 42 km of large diameter pipelines (≥ 300 mm or 12 inches) in the Charleston peninsula area for a life cycle period of 20 years is estimated to be in the range of \$37,000 (i.e., for the case of ADXL with battery power, sensor spacing of 100 m) to \$349,000 (i.e., for the case of SD1521 with solar power, sensing spacing of 30 m), which translates to about \$950/km to \$8,300/km. However, the snapshot inspection of pipeline using ad-hoc techniques, such as inline inspection and excavation, will reportedly cost about \$15,000/km and \$40,000/km, respectively (Nestleroth et al., 2017).
- While the estimated LCC is found to be highly dependent on the sensor spacing, it is observed that the initial cost contributes significantly to the LCC than the operational and maintenance phases.
- Power consumption by the sensor node is not sensitive to the rate of data transmission to the gateway node; the increase in transmission rate from 10 kbps to 250 kbps resulted in an increase in the current of radio chip by a negligible amount of 24e-6 A.
- The life cycle energy consumption rate of the proposed monitoring system for inspecting the large diameter pipelines in the Charleston peninsula area for a life cycle period of 20 years is estimated to be in the wide range of 0.02

kWh/day (i.e., for the case of using ADXL362 with a sensing spacing of 100 m and sampling rate of 500 Hz) to 0.2 KWh/day (i.e., for the case of using SD1521 with a sensing spacing of 30 m and sampling rate of 2000 Hz). It is observed from the life cycle energy analysis that majority of the energy needs arise from the transmission phase of the monitoring system. Therefore, the relative benefit of using lower-power accelerometers, such as ADXL362, diminishes with increasing sampling rate, as the power consumption in transmission phase increases with the sampling rate.

6.3 Limitations and Recommendations for Future Work

This dissertation provides insights into the capabilities of a vibration-based leak detection technique for water pipelines. Such inspection seeks to quantitatively identify changes in the system condition to inform leakage presence for eventual pipeline condition rating and essential repairs. Future studies can build upon the work presented in this dissertation to further evaluate the LDI technique and other similar non-intrusive techniques with the goal of developing them into more practical approaches. The technique proposed herein is designed to be generally applicable for any water pipeline system; however, there are certain limitations and assumptions that must be recognized. First and foremost, the LDI-based technique is only useful for detecting the onset of new leaks, and not the pre-existing leaks. The effects of pre-existing leaks would be inherent to the baseline states of the system and will therefore not be recognized. Secondly, the leak-induced effects on the system’s vibrational features vary with the leak type, size, location (joint vs. pipe wall) and also whether or not there are any splits and corrosion pits in the pipe wall (Hunaidi et al., 2004). Therefore, simulating real leakage through pipeline walls as well as joints may further reveal the practical feasibility of LDI approach. Furthermore, a slow joint leak may not affect the internal pressure changes and the surface vibration, but it can potentially change the surrounding temperature profile (Sadeghioon et al., 2014). Therefore, monitoring temperature of the pipeline and the surrounding soil near the joints, in conjunction with the monitoring of the vibration profile of the system, may be more effective; this hybrid monitoring system needs to be further developed and evaluated. . Thirdly, the estimated life cycle cost and energy consumption of network-wide leakage monitoring system are based on analysis conducted on a specific water distribution system; and consequently the conclusions need to be further validated using additional case studies. Finally, the sensor research and development is a fast-growing area. Accordingly the alternatives for B&K accelerometer evaluated in this study are expected to be improved through the on-going R&D and consequently, the suitability and performance of them, or even other potential alternatives, need to be periodically evaluated.

While the results from the preliminary experimental campaigns are promising, further validation is required to gain confidence in the LDI technique for practical applications. Few suggestions for follow-up studies include: (a) the influence of backfill soil on the vibrational characteristics of the pipeline and subsequent influence on LDI should be evaluated; (b) the data collection, communication and processing should be practical tested and optimized to enable sustainable design of the LDI technique; and (c) the use of locally harvested energy must be explored to power the sensors for monitoring and transmitting data for real-time leakage detection. In closing, the methods and prototypes presented herein provide a step forward for our capabilities to continuously monitor water pipelines of various materials and sizes for leakage. The smart water distribution networks offer the distinct advantage of providing real-time monitoring intelligence, which can consequently prompt immediate interventions.

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