Vibration Interpretation Technique for Water Leak Detection in Small Diameter Pipelines

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Declaration of Authorship

I, Nayna Ann Moni, declare that this thesis titled, "Vibration Interpretation Technique for Water Leak Detection in Small Diameter Pipelines" and the work presented in it are my own. It has not been presented and will not be presented to any other university for a similar or any other degree award.

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CERTIFICATION

The undersigned certifies that they have read and hereby recommend for acceptance by the Faculty of Engineering a thesis titled: **Vibration Interpretation Technique for Water Leak Detection in Small Diameter Pipelines,** in fulfilment of the requirements for the degree of Master of Engineering in (*Computer and Telecommunications*) of the BIUST.

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Abstract

Context: Clean drinking water is a very scarce and precious resource, a basic need for life, and requires proper management. Inconspicuous water leaks over a long period of time contribute to the loss of potable water. It also results in inexplicably high water bills, low pressure and damage to property. Therefore, leak detection is a conservation technique that has highly peaked research interest in the recent years. There are quite a number of approaches to leak detection in existence but most are inaccurate or expensive to implement.
Objectives: In order to address unnecessary water losses, the main objective of this work is to implement an efficient method of water leak detection in real-time. As an abundant library of research work on leak detection exits, there are plenty of methods with their own strengths and limitations. Therefore the second objective of this thesis is to review existing literature to better understand their advantages.
Methods:To achieve the objectives stated, a research on the various methods used for water leak detection is conducted, and having considered vibration interpretation as an effective tool, a systematic literature review on the several analysis techniques is done. From which a solution to implement on pipelines is tested and discussed.
Results: It was discovered from the literature review that although much effort has been made towards leak detection in distribution systems, there is a limited number of studies on detection in small-diameter pipelines and end-user premises. To address this, an experimental data set is analysed to detect leaks effectively using vibration interpretation. An application of the detection system using a LoRaWAN architecture is discussed.
Conclusion: In Conclusion, from the meta-analysis it was evident that a leak analysis system using vibration interpretation is feasible and that the study of leakage detection in consumer networks is still in its infancy. Therefore, une-leak algorithm that detects leaks by analysing vibration signals was developed and tested. However, the results were not tested in real time.

Acknowledgements

First and above all, I thank my Lord and savior Jesus Christ for giving me the strength and capability to complete this work.

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I would also like to appreciate my family, my friends, and colleagues for the emotional support throughout the period of my studies.

I thank you all for everything and may God bless you all.

Now he who supplies seed to the sower and bread for food will also supply and increase your store of seed and will enlarge the harvest of your righteousness. You will be enriched in every way so that you can be generous on every occasion, and through us your generosity will result in thanksgiving to God.- 2 Corinthians 9:10-11

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Dedicated to my dearest Appa and Amma
for always believing in me.

Chapter 1

Introduction

1.1 Importance of Leak Detection

Fresh-water is a necessity for life and the loss of this resource is becoming more apparent in recent years due to population growth and climate change. The Cape Town water crisis in 2018 [1] is an example of the consequences of the growing water shortage worldwide. In Botswana, water resources are limited and most of her surface water is from rainfall. As there has been a decline in rainfall due to climate changes the security of water access is at risk [2]. According to an article by Central Statistics Office, about 90% of the residents of Botswana have access to tap water [3]. Pipelines have been used over the years to transport water. These pipelines cross populated areas and cover a vast area of land. Damage to pipelines may be caused by corrosion, excessive stress due to pressure or land movements. A study [4] carried out in Ramotswa, Botswana found that most of the water infrastructure in the Gaborone-Ramotswa area are more than 25 years old. Although a leak may be small, they are not insignificant as they grow larger with time and lead to clean water wastage, economic loss and environmental damage [5]. A leak detection system does not prevent leaks but will largely reduce the time needed to detect and locate a leak and therefore reduce its consequences. Leak detection in water distribution systems is a major research field and many solutions have been proposed to try to rectify this problem.

Many households pay high water bills even when there are no obvious signs of leakage and are not using a lot of water [6]. Water Utilities Corporation (WUC) will not assist in finding or fixing any leaks in households [7]. As shown in Figure 1.1, once the water has passed the water meter, any water loss is the customer's responsibility to discover and resolve. A study on residential end uses of water found that leaks accounted for 24.5 percent of the average daily use in the top 100 homes with the highest average of daily indoor water use [6]. Leaks can be very costly and therefore it is important to find the fault as soon as they occur. A common method of checking for leaks in a household is shutting all the taps and checking if the scale on the water meter still moves, in which case, it indicates the presence of a leak.



FIGURE 1.1: Separation of water meter between distributer and end-user [8]

1.1.1 What is a Water Leak?

A water leak in this context can be described as a crack, hole, or other gaps in a water-carrying pipeline, through which water is lost. Water leaks can be classified as apparent leaks and real leaks. Apparent leaks are leaks that cannot be found using acoustic methods and they always exist in pipelines, these are losses due to billing errors, theft, etc. Real leaks are those leaks whereby water is lost from a pipeline at joints, through orifices or bursts. Real leaks can be further divided into reported and unreported leaks[5]. Unreported leaks are leaks which are usually not noticeable because they're hidden below ground whereas reported leaks eventually appear above ground as shown in Figure 1.2 [9]. Table 1.1 shows the highest percentage of water losses recorded between 2000 and 2009 in some towns in Botswana. These were non-revenue leaks, water that was not billed as it was lost during transportation, outside billing areas [4].

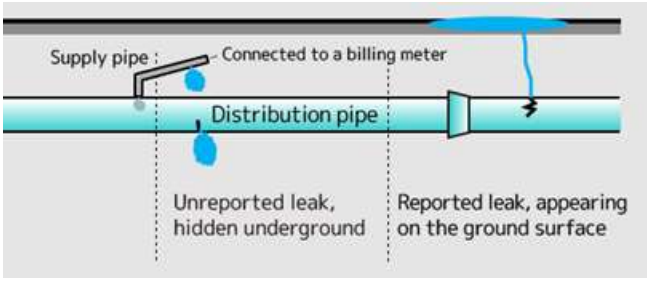


FIGURE 1.2: Types of real leaks [10]

TABLE 1.1: Water losses (%) recorded in major towns in Botswana [4]

Year	Town	Loss
2002	Molepolole	45%
2004	Ramotswa	57%
2005	Serowe	62%
2007	Kanye	43%

1.2 Motivation for Thesis

A significant amount of water is lost during water transmission due to undetected leaks in the piping system. According to the Botswana Water Accounting Report 2014-15 [11], about 25 percent of the distributed water is lost before reaching the consumers every year. The small amount of water lost at the domestic level may seem insignificant but can lead to large loss of water and capital if lost over a long period of time. It causes damage to property and individuals end up having to pay for wasted water. It also poses as a health risk especially to children as leaks lead to dampness in the house and drinking water may get contaminated through the orifices [12]. Therefore, quick and reliable leak detection is very important. If leaks can be found and fixed within a short period of time then it will bring about many economic and health benefits.

Many methods have been proposed to detect leaks in pipelines in general but few have focused on detecting leaks at a smaller scale such as in households [13]. The methods may either be uneconomic for most households to employ or too slow to detect leaks and have complex procedures [14]. This shows that there is need for an affordable method that can be implemented on a smaller scale.

1.3 Research Objectives

Water leaks can be very costly. Proper water management requires constant monitoring of the water pipe network and fast detection of leaks. Sometimes water leakage may go undetected for a long time, especially if it is below ground, concrete, lawns or inside walls. Water leaks can be very costly if undetected for a long time as it may lead to environmental damage, economical loss and clean water wastage [15].

In order to reduce water loss, the objectives of this research work are as follows:

1. To systematically evaluate leak detection methods in existence.
2. To propose and develop an algorithm for leak detection in small-diameter pipelines.
3. To validate the proposed leak detection algorithm for accuracy and efficiency.

1.4 Scope of Work

Due to climatic changes and human activity leading to water pollution over the years, conservation of clean water demands immediate attention in modern society. Leak detection in water distribution pipelines is one of the water conservation strategies implemented. Therefore, vast research has been done on leak detection and many methods exist. This thesis focuses on leak detection in small-diameter pipelines using vibration analysis. The data used for analysis is obtained from an experimental setup by Ismail *et al.*[16], on small-diameter pipelines.

1.5 Contribution to the Knowledge Base

The following publication is a result of the work done for this thesis.

Moni, N.A., Sigweni, B., Mangwala, M. and Kolobe, L., 2019, September. Water Leak Detection from Irrigation Pipelines in Botswana using Vibration Interpretation Technique. In 2019 IEEE AFRICON (pp. 1-6). IEEE.

1.6 Thesis structure

The introductory chapter outlines the issue of water loss and the need for research on leak detection. The following chapter briefly explains the background and other work pertaining to leak detection. Several methods used for leak detection are highlighted in this chapter. Chapter 3 discusses the process used to review different vibration interpretation techniques used for leak detection by researchers. Theses methods are compared and the trend over the years is determined. The different pipeline materials used and the effectiveness of the leak detection methods on the

material are also studied. Furthermore, research that focuses on the detection capability of the systems as the leak size changes is studied. Chapter 4 presents an algorithm, describes its usability and discusses the results. Finally, chapter 5 concludes the thesis by giving a summary of the work done, highlighting the drawbacks and contributions of the study, and discusses future works to be done.

Chapter 2

Background and Related Work

2.1 Water Leak Detection Methods

Potable water is a scarce resource and its conservation has become more important with an increase in population and water demand. Therefore, discussions regarding leak detection have dominated research in recent years and a large body of work exists since a water leak is the most common and hardest to determine component of overall water loss [9]. Most techniques used in leak detection work well in metal pipes, hence more researchers have focused on improving these techniques for plastic pipelines. According to a study by Dighade *et al.* [5], about 30-50% of freshwater in developing countries is lost through leaks in water distribution networks.

The existence of a leak in pipelines can be detected by several techniques. In an overview by Adedeji *et al.* [9], these are separated into two categories: internally-based methods and externally-based methods. Internal methods discussed are mainly software analysis techniques like signal processing, data analysis and model-based methods, whereas external methods are hardware-based such as acoustic emission, fiber optics and magnetic induction methods. Combining these methods to create hybrid methods often gives improved results [9].

In a household, people take different measures to deal with leaks. Below are some intervention methods practiced by homeowners.

1. Searching along the pipeline for any noticeable leaks and quickly mending the leak.

2. When the owners are aware of an existing leak, but cannot locate it, they may close the main stop tap before the water meter when the users are not at home.

Since these methods are neither very effective in reducing water loss nor economical, algorithmic systems have been developed to help in detecting and locating leaks. Some of the many algorithms proposed by researchers do not focus on households but on a larger distribution network.

2.1.1 Hardware-based leak detection

Hardware-based leak detection is the use of hardware devices to find leaks. These include the use of acoustic equipment, Leakage area sampling, gas tracing, and visual equipment [10]. Some examples of these methods are as follows:

Acoustic Equipment

1. Listening rods

A Listening rod is a device that amplifies the vibrations along a pipeline. A user wearing a headphone connected to the rod has to walk along a pipeline listening for leak noises. A usual method of detecting leaks involve dividing the distribution network into areas called District Metered Areas (DMA) and then using listening rods to search for leaks in the DMA. These areas are too large to manually scan and the method is very time consuming [17].

2. Leak Correlators

Leak correlators use acoustic sensors placed at either ends of a leak to estimate the leak location, see Figure 2.1. Leak Correlators are widely used to estimate a leak position with good precision [18]. The leak sound, which is a broadband noise with a

lower Signal to Noise Ratio (SNR) than normal flow, is received by the sensors. The time delay estimate (T_0) is evaluated by the peak in the cross correlation function $(R_{x_1x_2}(\tau))$ of signal $x_1(t)$ and $x_2(t)$ from sensor 1 and sensor 2 respectively. T_0 is used to calculate the distance of the leak from the sensors. The distance d_1 to the leak from sensor 1 in Figure 2.1 is given by Equation 2.1 taking into account propagation speed c of the leak noise and the distance d between the two sensors [19].

$$d_1 = \frac{d - cT_0}{2} \tag{2.1}$$

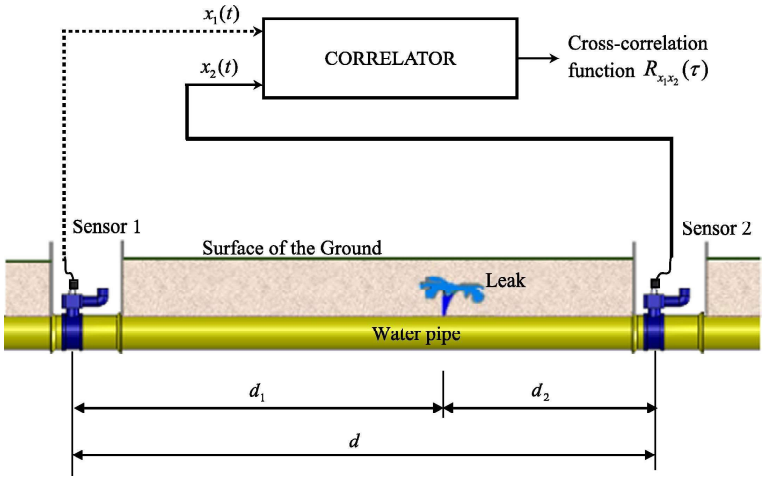


FIGURE 2.1: Using a leak correlator for leak detection [19]

Leakage Area Sampling

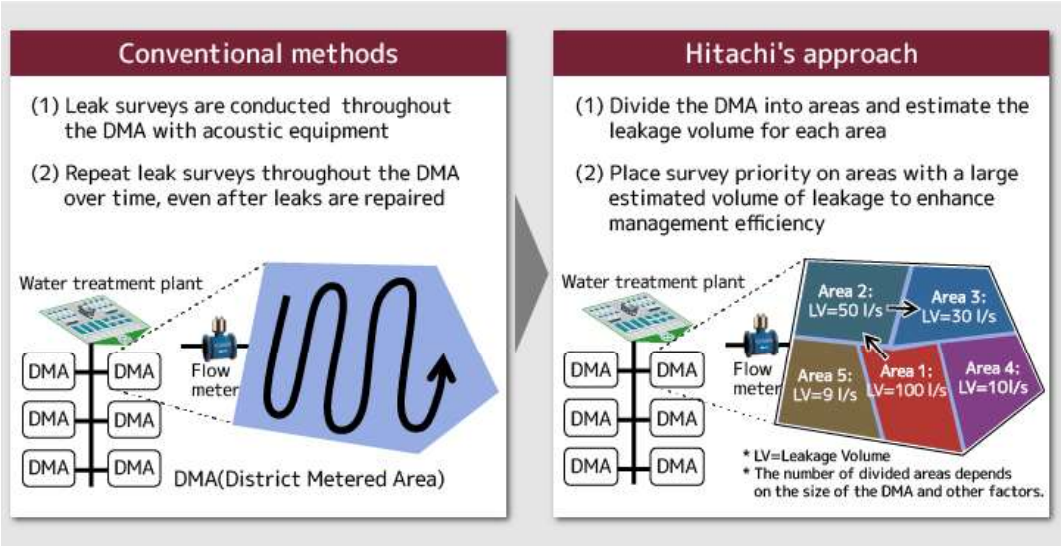


FIGURE 2.2: Hitachi's approach [10]

A company called Hitachi proposed an approach (Figure 2.2) whereby the DMA are divided into smaller areas and the leakage volume of each area is computed [10]. The areas with a higher amount of leakage (leakage hotspots) are surveyed more often than others. The aim of this method is to find the spots with a higher

risk of leakage. This priority first model detects leaks in areas with leakage hotspots quickly, hence reducing the water loss.

Visual Device

1.Thermal Infrared Imaging
This is the use of a thermal camera to scan along the pipelines for signs of leakage. The thermal camera uses infrared radiation to create images indicating temperature [20]. Figure 2.3 shows an image obtained from a thermal camera of a leakage from hot water pipes. The difference between temperature caused by leakages can be used to estimate the position of the leak in the pipeline. Thermal Infrared Imaging is advantageous in terms of precision, performance and real-time leak detection. However, it is easily affected by soil type and weather conditions [21].

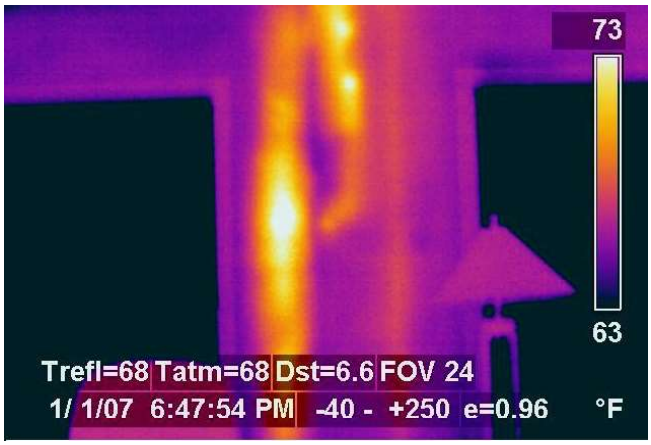


FIGURE 2.3: Thermal Infrared camera output [22]

2.Ground Penetrating Radar (GPR)

A GPR uses a radar transmitter and receiver to search for leaks on the ground. A pulse is sent into the ground and the echo is analysed for amplitude and strength difference to determine the presence of water in the ground. This is easier to use in drier areas where there is a high contrast between wet and dry soil.

2.1.2 Software-base leak detection

Audio fingerprinting method

Solomon et al. [15] used this method for household water leakage detection. An audio fingerprint is a digital summary of an audio signal which can be used to identify an audio sample or to find similar signals in a database. For leak detection, this method is used to profile water-use patterns referred to as fingerprints, which are stored in a database. Any new fingerprint with a high variance from the ones that are produced by normal household activity is identified as a possible leak and the user is alerted. This method has high accuracy in detecting leaks, however, the database needs to be trained every time it is installed into a new house to learn the pattern of the water-use in the house. It will only detect the leaks which occur after the installation of the system in a household. Which means it will not detect the

leaks that are already existing at the time of installation. The steps of the audio fingerprinting method are shown in Figure 2.4. Complexity and memory requirements deem this method unsuitable.

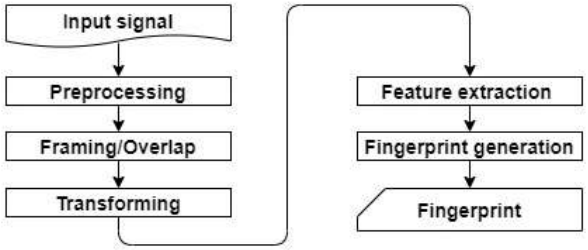


FIGURE 2.4: Audio fingerprinting method as described by [15]

Dictionary Learning

This is a model in the context of unsupervised learning using sparse coding. In leak detection, the following steps are taken to identify and localize leaks [23].

- The set of nodes where the sensors will be mounted is obtained.
- The training data is constructed from the sensors.
- The dictionary is trained.
- Any unusual data is recognised as a leak.
- The position of its largest entry is identified as the area/node with the fault.

This method is used in the detection of leaks in large distribution systems and has shown high efficiency. It has not yet been tested on a smaller scale, therefore it may be unsuitable for small-scale farmers.

Fault Model Approach

This algorithm assumes the presence of virtual leaks in the distribution system. An extended Kalman filtering procedure is applied to the signal. The leak size and location are estimated using an adaptive state estimator which is derived from a finite difference method and discretized partial differential equations [24]. Complexity and memory requirements deem this method unsuitable.

Another common technique that is used by researchers in other parts of the world for leak interpretation is Basic Cross-Correlation(BCC). Sensors are placed at two distinct points on a pipeline to obtain vibration/acoustic signals and BCC is applied, a sharp peak can be seen in the cross-correlation of the two signals [25]. Time Delay Estimation is also a common technique which focuses on measuring the time taken between the transmission of a pulse signal and the reception of its echo to estimate a leak [26].

2.2 Water Flow Characteristics

The microscopic view of the water flow in a pipeline is seen in Figure 2.5, though the average water flow is in the x direction, the drag and turbulence causes molecules to be pulled in different directions. This causes vibrations along the pipeline.

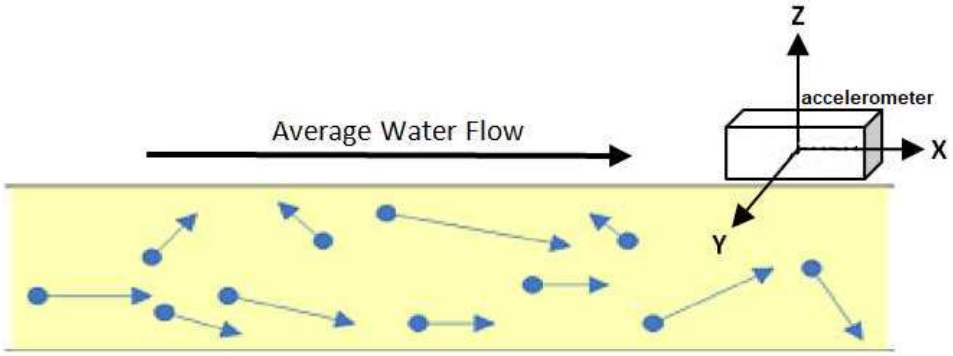


FIGURE 2.5: The microscopic view of water flow in a pipeline [16]

Water flow can either be laminar,transient or turbulent. Laminar flow is whereby water layers slide over each other smoothly, giving a constant flow. Turbulent flow is whereby the fluid flow fluctuates randomly and the layers mix vigorously. Transient flow is both laminar and turbulent. Figure 2.6 shows the flow of water in these states using a dye, known as the Reynold's experiment [27], [28]. The Reynold's number Re (Equation 2.2) of a liquid with viscousity μ can be used to determine the flow of the fluid, where ρ is the density of the liquid, u is the velocity of the flow and L is the lentgth of the pipeline. If Re is less than 2000, a laminar flow is expected and a transient flow if Re is between 2000 and 3000. Turbulent flow is when the Re is greater than 3000.

$$Re = \frac{\rho u L}{\mu} \tag{2.2}$$

In the pipelines, a turbulent flow is expected due to the low viscosity and the high velocity of the input water [29]. Figure 2.7 shows a segment of a pipeline. Assuming that the water in pipelines is an incompressible liquid, the principle of continuity of fluids states that the mass entering a system is equal to the mass leaving the system as mass can neither be created nor destroyed [27]. Therefore, the volume (V_i) of water input into the pipeline with velocity (u_i) is expected to be the same volume of water that is output on the other side (V_o) at a velocity (u_o) and this can be calculated by multiplying the Area (A_i) of the cross-section of the pipeline by the velocity of the water flow [27]. This is summarized by Equation (2.3) and it can be used to monitor the amount of water used.

$$V_o = A_o u_o = V_i = A_i u_i \tag{2.3}$$

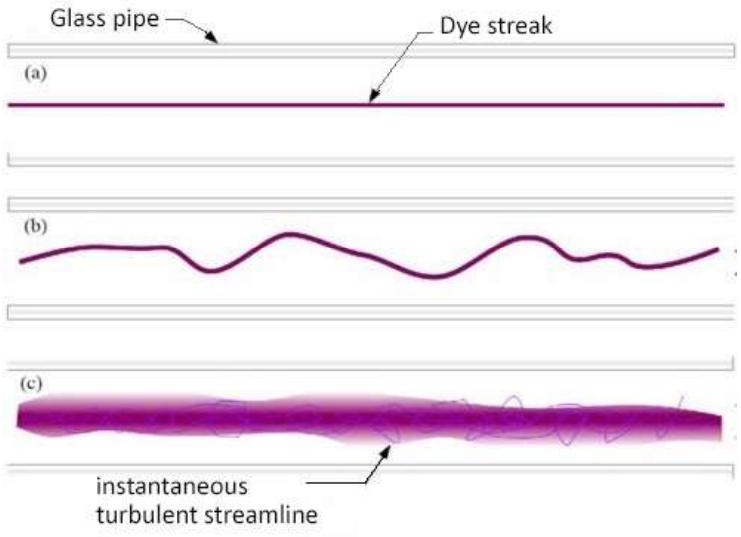


FIGURE 2.6: Reynolds experiment. (a) Laminar Flow, (b) Transient flow, (c) Turbulent flow [28]

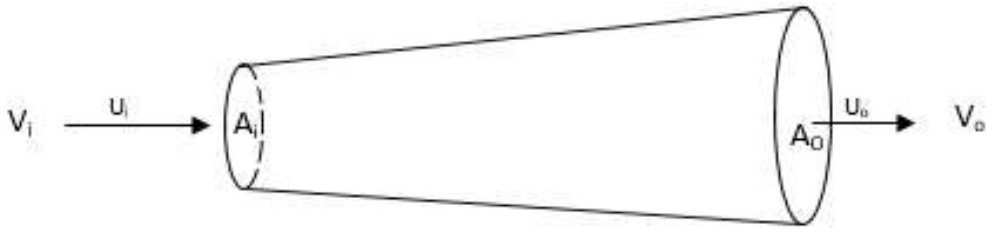


FIGURE 2.7: water flow in a pipeline: principle of continuity

Chapter 3

A Review of Vibration Interpretation Techniques for Leak Detection in Buried Pipes of Water Supply Networks

Leak detection plays a vital role in the conservation of potable water. Unfortunately, leak detection methods, used along pipelines, are often inaccurate. Many water leak detection methods have been proposed including Vibration Interpretation Techniques (VIT) [14], [30]. In order to improve VIT detection accuracy, various modification and implementations have been proposed by many researchers [14], [18], [19], [31], [32]. This chapter is a systematic assessment of empirical evidence in order to determine whether these vibration interpretation techniques lead to improved leak detection. These techniques are analysed by looking at the approach, strengths and weaknesses, leak evolution inclusion and performance with different materials. A systematic literature review was conducted of published and refereed primary studies on VIT, publicly available. 23 relevant primary studies and 2 secondary studies were identified. A range of different techniques were found from these. Benchmark comparisons with standard VIT were made by only 4 out of 23 studies and 3 out of these 4 reports improved accuracy. The actionable conclusion from the analysis of all appropriate empirical evidence in the study is that they support the use of VIT. Therefore, it is recommended that researchers should seriously consider their adoption. However, studies on copper pipelines have been neglected, only 1 study out of the 25 studies investigated copper pipes even though copper is widely used as last mile pipeline.

VIT are methods used to analyse vibration/acoustic signals, are commonly used to detect and estimate the leak positions. This systematic literature review (SLR) identifies and evaluates existing VIT used in water leak detection, examining studies published between 1999 and 2020, these are listed in Table 3.2. The adopted characteristics for the SLR are summarised in Table 3.1 and elaborated in the following subsections and sections. The results of the study show that most researchers focused on the detection of water leaks in buried plastic pipelines as the propagation of vibration signals in plastic is slower than in corresponding metal pipes. They also concentrate on using basic cross correlation (BCC) or TDE to detect and estimate the existence and position of a leak.

The rest of the chapter is arranged as follows. The subsequent section summarises the different VIT leak detection and estimation methods. Six research questions are then set out that we intend to address with the SLR. In section IV the results are presented, arranged by research question. Finally, the paper discusses the implications of this meta-analysis for researchers and practitioners in conclusion.

3.1 Vibration Analysis

Acoustic emission/ vibration signal analysis often generate quite accurate results and combining this method with software-based leak interpretation techniques can give improved results. Vibration signals are measured over a period of time, compared with the new measurements and analysed using a signal processing technique such as Fourier transform and wavelet transform. Vibration can be defined in this context as a periodic movement of particles of a body in alternately opposite directions, from a position of equilibrium when the equilibrium has been disturbed [33]. Water in transmission makes constant contact with the pipe walls causing vibration due to drag and turbulence. The vibration signals can be detected and measured using different sensors like accelerometers, geophones and hydrophones. The pipe material may have an effect on the result obtained and several materials are used for water transporting pipes including PVC,copper and concrete. Leak detection seems to be more difficult in plastic pipes than metal pipes as vibration signals in plastic

pipes are narrow-band and have a low frequency. Therefore, most users are sceptical about the accuracy of detection in plastic pipes and a lot of research focuses on increasing the detection accuracy in plastic pipes [34].

Leak detection using vibration analysis can be summarised by the following steps:

1. Vibration detection
2. Vibration interpretation
3. Leak localization

Vibration Interpretation involves signal analysis and noise filtering [31]. VITs are software based methods used for analysing vibration signals obtained from sensors. It is important to be able to determine whether a VIT is effective or not. Water pipelines are mostly found underground, in different types of soil, temperatures, dimensions and materials, and level of external activities like vehicle movement. These factors affect the readings from the sensors [19], [35]. Several standards for determining the quality of leak detection has been introduced by societies like The American Petroleum Institute(API) and Technische Regeln für Fernleitungen(TRFL). They have documented standard parameters that can be used for evaluating leak detection software[36][37][38]. The parameters set by API are sensitivity, reliability, accuracy and robustness. Figure 3.1 gives a general overview of the requirements by TRFL, an effective Leak Detection System (LDS) should be able to monitor a pipeline

TABLE 3.1: Systematic Literature Review Summary

Characteristic	**Value**
Review type	Systematic literature review
Research question(s)	What are the validation methods or techniques used in the studies (RQ1)? The range and diversity of VITs in leak detection (RQ2), Has the method been used in households (RQ3)? Their strengths and weaknesses (RQ4), does the study include leak evolution (RQ5) and what is the trend of study over the years (RQ6)?
Purpose	Guide researchers and practitioners using estimation by analogy techniques.
Audience	Researchers
Search method	Automated and hand search, citation analysis, previously known articles plus approached authors.
Databases used	Hindawi, EBSCOHost, IEEE Xplore, ScienceDirect, Google scholar,MDPI , Springer Link and Scopus
Population	Empirical studies relating to VITs in water leak detection
Study types	Experiments, case studies, observational studies, simulation.
Inclusion criteria	(i) Refereed paper (journal or conference) (ii) Empirical study (iii) Copy of the article available
Language	English language only
Search date	February 2020
Article dates	2000-2019

for leaks continuously during both turbulent and transient operation. It should also be able to detect leaks when the water is not moving along the pipeline and gradually growing leaks. An effective LDS should also be able to localize leaks quickly. Machine learning techniques like artificial neural networks, deep learning and genetic algorithms are applied by several researchers in leak detection[15][39] [40]. Internet of things can be used in implementation of VITs as described by Ng et al. in their design of an automatic leak detection system[41].

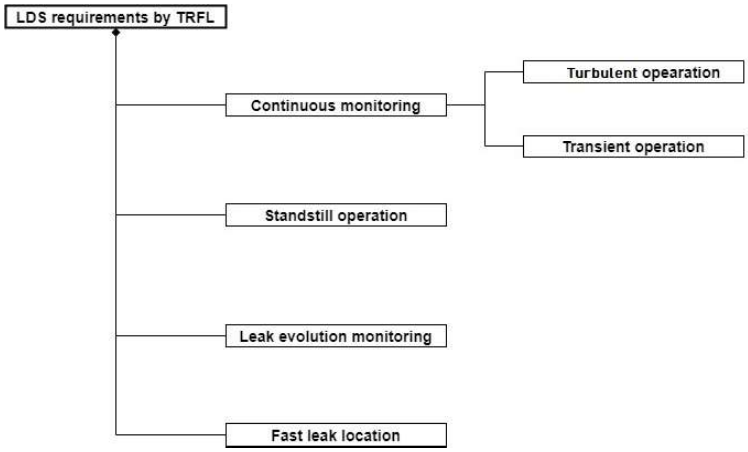


FIGURE 3.1: TRFL requirements for a leak detection system [38]

3.2 Methodology

This systematic literature review follows the steps used by Sigweni et al [42] in a previous review. Therefore, our approach is also strongly influenced by the methodological work of Kitchenham and Charters [43]. However, we deviate from their methodology in the following aspects, mainly because of the limited number of papers involved as our review was focusing on VITs for leak detection in buried water pipelines only.

1. We did not seek an external review of our systematic review protocol.
2. No formal quality instrument was used for our studies. Hence, the quality of the study was assessed in terms of peer review of the candidate studies only.
3. The authors of the papers used in this review were not contacted due to limited number of papers located.

3.2.1 Research questions

This systematic literature review mainly answers whether vibration interpretation techniques improve leak detection in water pipes. A range of proposed VITs need to be reviewed and how they have been empirically evaluated has to be considered. This will act as a guidance that can be used by researchers and practitioners to discover further research areas to enhance the capability of current leak detection methods. In order to achieve this objective, six research questions were conceived and are stated below.

RQ1: What are the validation methods or techniques used in the study?
Rationale: To allow comparison between VITs to determine the best leak detection method as various factors affect their accuracy and some VITs may prove to perform better under certain conditions. This enables one to determine the effectiveness and accuracy of VITs in the detection of leakage in water supply networks.

RQ2: What is the range and diversity of VITs in leak detection?
Rationale: Practitioners may use the identified VITs as candidate solutions in their work.

RQ3: Has the method been used on small-diameter pipelines in the last mile?
Rationale: Research suggests that there is sparse literature on leak detection methods in small-diameter pipelines. Therefore, this will help determine the frequency of the application of the studied VITs in households.

RQ4: : What are the strengths and limitations of VITs?
Rationale: This may help practitioners to understand the capabilities of existing VITs and to determine what improvements need to be made in future works.

RQ5: : Does the technique include leak evolution?
Rationale: This will aid in determining the severity of the leaks or early detection of leaks as most methods may only be good for detecting certain sizes of leaks.

RQ6: : What is the trend of study carried out on VITs over the years?
Rationale: This may assist researchers to perceive which methods are most focused on and the ones which are least studied.

3.2.2 Search Strategy

Search terms

The following criteria was used to create a search string to identify the documents.

1. Attain major terms from the research questions.
2. Determine alternative spellings and synonyms for major terms.
3. Using the Boolean logic AND and/or OR to incorporate and link alternative spellings and synonyms.

The resulting search strings from the above criteria is described as follows: (Vibration /OR Acoustic) AND water AND (leak /OR loss) AND (detection /OR identification /OR diagnosis) AND (methods /OR techniques) AND (Households /OR "last mile" /OR "small diameter")

Literature sources

Several databases were used to obtain the literature used. The concepts of backward and forward snowballing as described in [42] were applied to find papers that did not appear in the search results. Other works by the authors of the selected papers were also checked for useful content. To have a wider coverage, any paper that met the inclusion criteria was selected.

Eight electronic databases were searched using the search terms. The databases are: EBSCOHost, IEEE Xplore, Google Scholar, Springer link, Science Direct, Hindawi, MDPI and Scopus. The selected papers were compared and duplicates were removed.

Search process

The search process used for this review can be broken down into two steps:

Step 1: Each database was individually scanned for papers that met the inclusion criteria.

Step 2: The references of the selected literature and the papers that cited them were searched for relevant work.

The references were stored and managed using database software. Figure 3.2 illustrates the search and selection process and the number of papers identified at each phase.

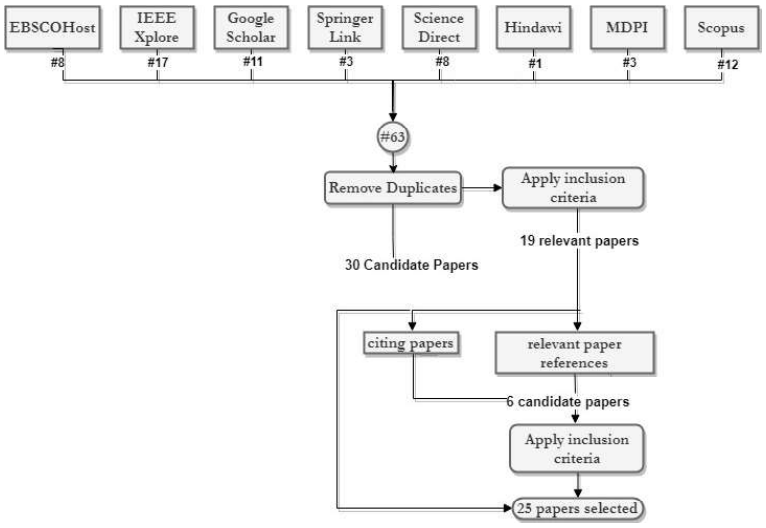


FIGURE 3.2: Search and selection process

3.2.3 Study selection and data extraction

A total of 63 related papers were found. Since they were from independent sources, duplicates were checked and removed, of which 30 papers remained. These papers were rechecked to ensure they fall under the inclusion criteria. A total of 19 papers were chosen, the references for these papers were searched for useful papers and the papers that cited the work were also checked. 25 relevant papers were finally selected for the review purpose.

3.2.4 Data Synthesis

Data were extracted from the selected papers to answer the review questions about VITs. Different techniques were used to answer the review questions. The papers were read, and the questions were answered in a table format on a spreadsheet. The collected data was then visualised using graphs.

TABLE 3.2: Selected studies

ID	Year	Source	Pipe diameter	Detection	Localisation	Cite
[S01]	2000	Journal	Large	No	No	[44]
[S02]	2004	Conference	Large	Yes	No	[45]
[S03]	2005	Journal	Large	Yes	No	[30]
[S04]	2006	Journal	Large	Yes	No	[25]
[S05]	2008	Journal	170mm	Yes	No	[32]
[S06]	2009	Conference	Various	Yes	No	[46]
[S07]	2014	Journal	Large	Yes	Yes	[47]
[S08]	2014	Conference	Various	Yes	No	[48]
[S09]	2015	Journal	Small	Yes	No	[49]
[S10]	2015	Conference	Small	Yes	No	[16]
[S11]	2016	Journal	Not reported	No	No	[14]
[S12]	2016	Journal	54mm-60mm	Yes	No	[39]
[S13]	2016	Journal	Not reported	Yes	No	[50]
[S14]	2016	Journal	90mm	Yes	No	[51]
[S15]	2017	Journal	Various	Yes	Yes	[52]
[S16]	2017	Conference	170mm	Yes	Yes	[53]
[S17]	2017	Conference	10mm-22mm	Yes	No	[15]
[S18]	2017	Journal	32mm	Yes	No	[54]
[S19]	2017	Conference	10mm-28mm	Yes	Yes	[55]
[S20]	2017	Journal	Large	Yes	No	[19]
[S21]	2018	Journal	76mm-102mm	Yes	No	[56]
[S22]	2018	Journal	150mm-160mm	Yes	Yes	[57]
[S23]	2018	Journal	25mm	Yes	No	[58]
[S24]	2018	Conference	Small	Yes	Yes	[59]
[S25]	2019	Conference	Not reported	Yes	No	[60]

The goal of data synthesis is to find different VITs from the selected papers so as to answer the research questions. The obtained data from the studies had both quantitative data (e.g., Pipe diameter) and qualitative data (e.g., strengths and weaknesses of VITs). Different strategies were used to analyse the extracted data relating the research questions and they are explained in detail below:

To answer RQ1, RQ2 and RQ6, The VITs were identified and tabulated. 10 different VITs were identified and the exploitation of each VIT across the studied literature was recorded. The results were then quantified and visualised.

For RQ3 to RQ5, the selected papers were studied to check if they have addressed the matter in each question. The results from each paper recorded in table format for easy analysis.

3.3 Results

This section discusses the results from our SLR. An overview of the selected studies is followed by the findings of this SLR for each research question.

TABLE 3.3: Vibration Interpretation Techniques

Technique	**Studies**	**Total**
Basic Cross Correlation (BCC)	[S01],[S02],[S03],[S04],[S05],[S06], [S07],[S10],[S15],[S16],[S20],[S22],[S25]	13
Fast Fourier Transform (FFT)	[S03],[S10],[S11],[S13],[S14],[S19], [S20],[S21],[S22], [S23],[S24],[S25]	12
Phase Transform (PHAT)	[S04], [S15], [S22]	3
Time Delay Estimation (TDE)	[S02],[S03],[S04],[S05],[S06],[S07], [S11],[S12],[S13],[S14],[S15],[S16], [S20],[S21],[S22],[S25]	16
Wavelet Transform (WT)	[S06], [S11], [S12], [S15], [S17]	5
Standard Deviation (SD)	[S08], [S09], [S18], [S25]	4
Support Vector Machines (SVM)	[S11]	1
Maximum Likelihood Estimators (MLE)	[S04], [S06], [S15], [S23]	4
Monitoring Index Efficiency (MIE)	[S08], [S09], [S18]	3
Finite Element Method (FEM)	[S16]	1

A total of 24 original primary studies and 1 secondary study were identified to be included in this SLR which were published between 2000 and 2019. Of the 25 selected studies, 16 (64%) were published in journals and 9 (36%) of the studies appeared in conference proceedings and no papers from book chapters were located. Table 3.2 shows the corresponding numbers, year of publication and the respective sources of the selected studies. Only six papers were published in the first half of this time period (2000-9) and a further 15 were published in the second half (2010-19), which is more than twice the rate of output, this is a clear indication of the topic gaining momentum over the years. Figure 3.3 shows the number of papers that studied each method by year. Some researchers have mentioned more than one method in some papers.

Of the 25 located papers, 24 were experimental and one was a review of different pipeline fault detection methods. Lastly, it should be noted that the quality of studies selected were linked to our inclusion criteria, which ensures that only papers from refereed sources that represent good experimental and research practice are included.

The different leak estimation methods are highlighted in Table 3.3. The table shows the selected papers that studied the VITs and they are further elaborated in the section below.

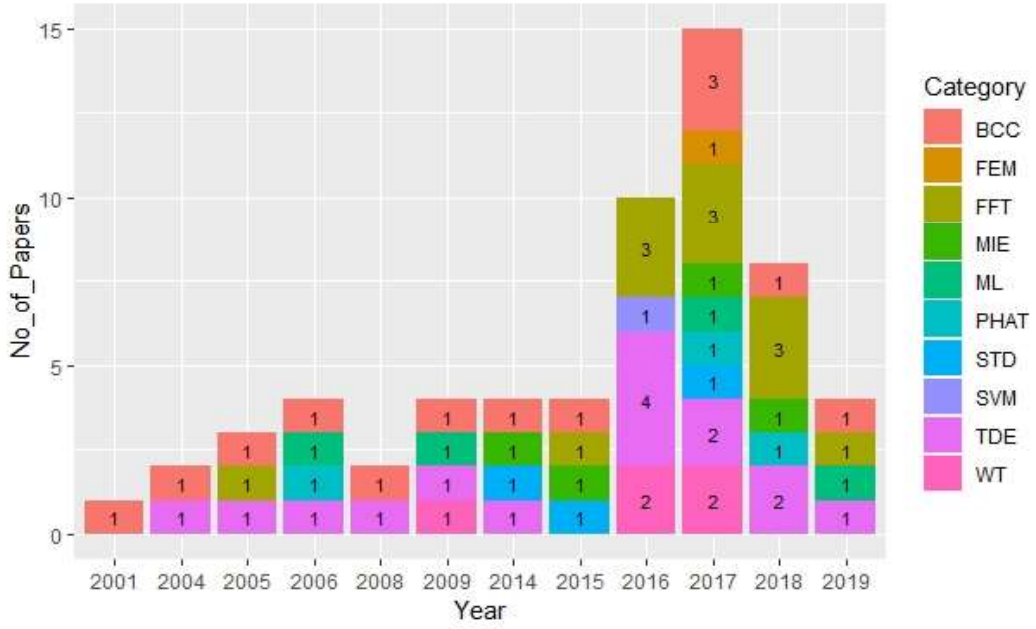


FIGURE 3.3: Vibration Interpretation Methods used throughout the papers

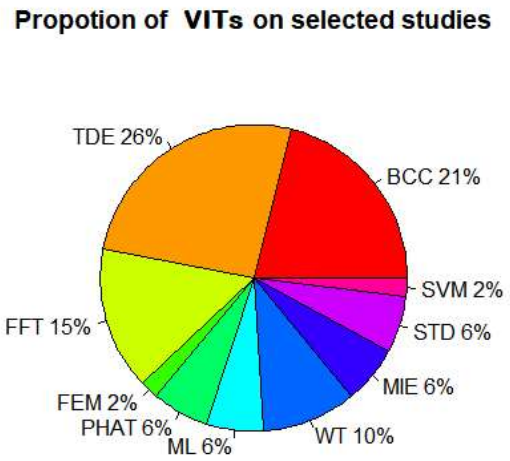


FIGURE 3.4: Vibration Interpretation Methods used throughout the papers

Cross-Correlation

There are two types of cross-correlation that can be seen across the documents reviewed, BCC and GCC. In BCC the signals are Fourier transformed, convolved and the inverse Fourier transform of the signal is then obtained. Figure 3.5 shows the process of BCC, two input signals $x_1(t)$ and $x_2(t)$ are transformed to the frequency domain by Fourier transform to get the functions $X_1(\omega)$ and $X_2(\omega)$ respectively. $*$ represents conjugation and the inverse Fourier transform of $X_1(\omega)X_2(\omega)$ is found

to get the cross-correlation function $R_{x_1x_2}(\tau)$.The difference between the two cross-correlation techniques is that, for GCC, the signals are passed through filters before performing the cross-correlation [25]. In leak detection, sensors are placed at two distinct points on a pipeline to obtain acoustic signals and a sharp peak in the cross-correlation function of the two signals indicates the presence of a leak [25].
Strengths: This is a common method used for leak detection throughout the papers as it is easy to compute, insensitive to system resonances and efficient for use in noisy areas.[39].
Limitations: Cross correlation can often give misleading results when analysing non-stationary signals.

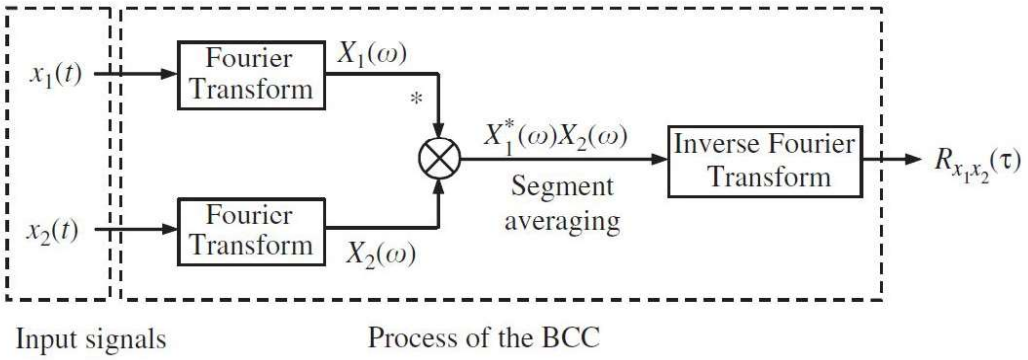


FIGURE 3.5: Process of basic cross correlation [25]

Time Delay Estimation

The travel time of an acoustic or electromagnetic wave between sensors can be estimated using TDE methods. TDE can be classified as either Time of Arrival (TOA) estimation or the Time Difference of Arrival (TDOA) estimation [26]. In leak detection, TOA focuses on measuring the time taken between the transmission of a pulse signal and the reception of its echo whereas TDOA focuses on finding the time difference between two spatially spaced sensors.
Strengths: It is a commonly used method throughout the texts. Time difference is an easy to analyse characteristic of acoustic signals.
Limitations: TDE of acoustic signals can be greatly affected by high external noise, the signal should be filtered to get a plausible signal to noise ratio [19].

Fast Fourier Transform

Fourier transform is an operation that converts data from the time domain to the frequency domain [61].

Continuous Fourier Transform (CFT): This refers to fourier transform in continuous time.

Discrete Fourier Transform (DFT): This refers to the discrete version (sampled real-time signals) of the transform using a discrete time and frequency scale.

Fast Fourier Transform (FFT): This is a computational tool for efficiently computing the discrete Fourier Transform of a series of data samples using a digital computer [62].

FFT can be used to analyse vibration data from the frequencies produced by normal and abnormal conditions of the water pipe [16].
Strengths: FFT algorithm is efficient as it is a time optimal method in comparison to DFT. This is because to obtain DFT the same calculation is repeated several times. FFT makes use of algebraic properties to reduce the amount of calculation required to obtain the Fourier transform [63].
Limitations: The method is not very reliable as it is sensitive to factors such as background noise and geometry of the leak in the pipeline [39].

Phase Transform

Conventional BCC is used with FFT in most commercial leak noise correlators for TDE. For plastic pipes that act as low pass filters because of their material properties, the TDE method is not very effective. Therefore, pre-whitening, a process that makes the received signal behave like white noise, is applied to improve the resolution of the cross correlation. This is known as the Phase Transform (PHAT) [53]. The PHAT correlator sharpens the peak in the cross-correlation function and suppresses other additional peaks unrelated to the time delay information [25].
Strengths: It sharpens peaks to improve BCC and suppresses the undesired noise.
Limitations: It is sensitive to additional phase shifts caused by the dynamic characteristics of the water flow [19].

Maximum Likelihood Estimators

The Maximum Likelihood Estimator (MLE) maximises the probability of sampling a given parameter. Given a sample x_i from a probability density function $f(x_i, \theta)$, where θ is the parameter of interest, the MLE $L(\theta)$ is the product of the individual independent probabilities as shown in the equation below[64].

$$L(\theta) = f(x_1, \theta) f(x_2, \theta) ... f(x_N, \theta)$$

Strengths: It can be used for sharpening peaks to improve BCC.
Limitations: May give unreliable results in some situations as it can overestimate or underestimate signals at certain frequencies[25].

Wavelet Transform

This is a time-frequency analysis method. A wavelet is a waveform of limited duration with an average value of zero [39]. Wavelet analysis is whereby a signal is divided into shifted and scaled versions of the original wavelet. It is used to accurately analyse abrupt changes, and this method is very useful for analysing time-variant acoustic signals produced by water in pipelines [46]. There are two types of wavelet transforms, namely Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). They differ based on how they discretise the scale and translation parameters. CWT is used to obtain a simultaneous time-frequency [39] [65].
Strengths: This method filters out excess noise effectively, giving better signal to noise ratios and making the leak attributes more pronounced. It is also effective for fast leak detection. This method is useful where resolution is important[66]. It is also highly effective for analysing non-stationary signals[39].
Limitations: A challenge to using CWT is that the signal representation is redundant and that of DWT is that it can be a challenge to identify the correct position of a leak due to the system noise [67].

Standard Deviation

According to Ye et al. and various researchers [68][25][48][52], the acoustic emission(AE) signal is directly proportional to the standard deviation, i.e. the stronger the AE signals, the greater the standard deviation. It is further established in [68] that there is a linear relationship between the leakage rate and standard deviation(STD). The standard deviation of the leakage signal increases linearly as the leakage rate increases [68].
Strengths: STD is simple to compute and can be used on raw data without extra processing [48]. It is also directly proportional to leakage rate, therefore it can be used to measure the increment rate of leaks.
Limitations: The method may not be appropriate for analysing non-stationary signals.

Monitoring Index efficiency(MIE)

The Monitoring Index (MI) is the average of the 10 lowest STD values over a period of time. The MIE is the ratio between the maximum value of the MI and the averaged MIs over a period in non-leaking state, assuming that the maximum occurs for measurements in a leaking condition. It is used to evaluate the efficiency of the algorithm in terms of sensitivity to leaks. [48]
Strengths: This value can be used as a metric for leak detection as Martine et al.[48] suggests because it is directly proportional to the leak, that is it increases in the presence of a leak.
Limitations: MIE has a poor prediction rate, and improvement in the algorithm is needed for better outcomes.

Support Vector Machine

Given a set of training observations, two categories and a set of indicators attaching a category to each observation, the Support Vector Machines (SVM) algorithm assigns new observations to a category, therefore, acting as a non-probabilistic classifier. The SVM based method discussed by [69] uses optical cables to sense vibration signals in a pipeline. The signals are amplified and filtered for analysis.
Strengths: This method has proven to have high accuracy in leak detection and suitable for real time leak detection[70].
Limitations: The system has to be trained before SVM can correctly classify leaks[71].

Finite Element Method (FEM)

This method is used to solve problems with many unknowns. The domain of the signal which is being analysed, the water pressure acoustic signal, can be divided into numerous small sub-domains (finite elements) [53]. Polynomials are used to estimate the displacement field of each element which are interpolated with respect to prescribed points located on the boundary of the element[72].
Strengths: This numerical model can be used to easily compute acoustic wave speed and attenuation.
Limitations: The results can be affected by background noise.

Figure 3.4 shows a graphical representation of how commonly VITs are used across the studies. It is evident that there is a wide variety of methods but most

researchers have adapted TDE and BCC, most often combining the two methods or alongside other methods.

RQ3: The use of leak detection techniques in the last mile

TABLE 3.4: Pipe materials used in Santiago homes [73]

Material	**Pipe material between meter and home**		**Pipe material between home and tap**	
	Frequency	%	Frequency	%
Copper	952	77.9	860	70.4
PVC	207	16.9	305	25.0
Galvanised steel	33	2.7	32	2.6
Lead	10	0.8	9	0.7
Wrought iron	7	0.6	7	0.6
Don't know	13	1.1	9	0.7
Total	1222	100.0	1222	100.0

TABLE 3.5: Pipe materials used in Botswana homes [73]

Material	**Material between meter and ground**		**Material underground**		**Material in the house**	
	Frequency	%	Frequency	%	Frequency	%
PVC	212	21.2	940	94.0	0	0
Galv. steel	788	78.8	60	6.0	370	37.0
Copper	0	0	0	0	759	75.9
Total	1000	100.0	1000	100.0	1129	112.9

Researchers have proposed solutions to leak detection in the last mile using techniques such as Flow monitoring and pressure analysis [74][75][76][77]. These were not using VITs and therefore was not selected for the review. From the selected studies, only one paper focused on leak detection in households and 4 papers(20%) on small-diameter(10mm-30mm) pipelines. Most researchers (80% of the selected studies) targeted large diameter pipes in the distribution networks.

According to researchers [48] [16], the pipe materials and its surrounding soil affect the accuracy of leak estimation. Plastic pipes give a higher error than metal pipes and therefore most researchers in the selected papers, 16 out of 21, experiment/research on plastic pipes. Plastic pipes have high elasticity as compared to metallic pipes and external factors such as temperature affect the measurements. Only 1 paper out of 21 investigated leak detection in households using copper pipes although, Table 3.4, from a study conducted by Lagos et al. [73] in Santiago, shows

that copper is the most commonly used material with more than 70% in the last mile between the meter and taps.

A survey of 1000 households in Palapye, Botswana was done to determine the most commonly used pipe material locally, Table 3.5 shows the statistics. The pipes were divided into three sections as shown in Figure 3.6 because the materials differ in the three sections. According to the data collected, 75.9% of the households use copper within the house, between the ground and the tap, some households use only galvanised steel while others use a combination of both copper and galvanised steel.

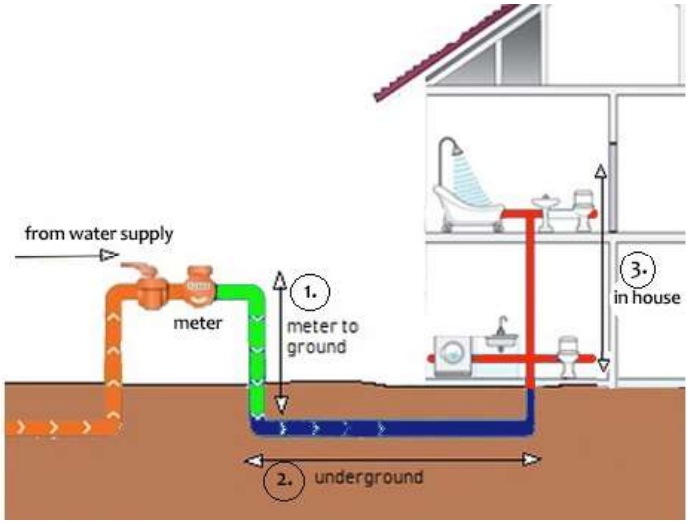


FIGURE 3.6: Materials in the three sections surveyed. 1. meter to ground, 2. underground and 3. within the house

RQ4: Strengths and Limitations of the VITs

In order to leverage or identify gaps, selected studies' strengths and limitations as identified by their authors are presented in Table 3.6. It is evident that while researchers look for ways to improve accuracy, these methods are mostly affected by the distance between the leak and the sensors. Hence finding it a challenge to locate leaks. Only 6 of the selected studies detected and localised leaks as indicated in Table 3.2. The common methods used in these studies are BCC and TDE which are used to estimate the distance of the leaks from the sensor. Ferino et al [59] used FFT for vibration analysis and discusses a Graphical User Interface(GUI) that pinpoints the leak. This shows that although much effort has been put into detecting leaks, pinpointing of leaks has not been well investigated.

RQ5: Leak Evolution Inclusion

In spite of the fact that studies [16] show that frequency and amplitude differences could be used to monitor leak size as a leak grows, only 3 out of 25 investigated on leak evolution. The 12% represents a very low return on an issue we consider being quite significant as leak sizes are not static, that is, as time passes the leak sizes grow. Therefore, techniques or methods that deal with leak evolution, whereby the algorithm is able to detect leaks as the size changes, are required.

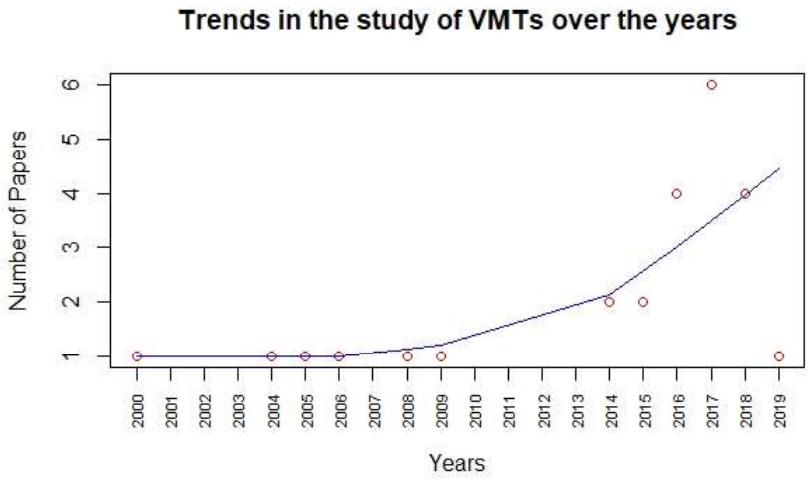


FIGURE 3.7: VITs per year(2000-2018) with a Loess smoother

RQ6: Trends of VIT research over the years

A total of 10 VITs were identified from 25 distinct peer-reviewed papers. The inspection of Figure 3.7 indicates that the publication trend is upwards as illustrated by the smoother. The results clearly show that the number of papers published is growing. However, there is a considerable variation on an annual basis which is hardly surprising given the arbitrary nature of publication bias. Consequently, we apply a Loess smoother which illustrates a strong upward trend.

3.4 Summary

This SLR located a total of 25 primary studies that were published from 2000 up to 2019, these are the studies that explored the application of vibration interpretation techniques in the effort to enhance the water leak detection in last mile pipes. Our main findings are:

1. A plethora of VITs were proposed and with comparatively fewer studies focusing on replications.
2. Case studies are lacking, as well as studies on action research and other detailed studies on household water leak detection. This implies that the application of VITs in the households is still in its infancy.
3. The actionable conclusion from the study is that, with the exception of some methodological reservations concerning our meta-analysis, it is evident that VITs are valuable.
4. Though leak detection is highly studied, there is a need for improvement in localising leaks.
5. The VITs are mostly algorithmic therefore human inspection is not officially studied for leak detection either as an independent technique or to supplement other techniques.

In the same manner as any systematic review there are limitations:

1. All relevant primary studies may not have been located, but it is our belief that the combination of manual search and automation should be sufficiently effective.

2. Due to the limited amount of articles included in the review, our ability to conduct the meta-analysis is also limited, specifically to make comparisons between distinct VITs.

In spite of the latter limitations, the most conspicuous and actionable result of this literature review is that vibration interpretation techniques are invariably beneficial for water leak detection in water pipes. Moreover, we believe researchers will find this information useful.

TABLE 3.6: Evaluation methods used by FWTs

Study	Strengths	Limitations
[S01]	The effectiveness of different methods of acoustic and non-acoustic leak detection in detecting water leaks in plastic pipes are compared.	Modification of automatic mode algorithms and use of more sensitive sensors may improve the effectiveness of leak detection
[S02]	The system can work with different materials. User has to input material and size data before use. It is effective in finding small leaks or in situations with high background noise.	Signal amplitudes become extremely small at higher frequencies and as distance increases.
[S03]	Experiment suggests that accelerometers are most suitable in multi-leak and coherent noise situations.	Peak cross-correlation coefficient of greater than about 0.5 are only possible when the ratio of distances satisfy certain values for pressure, velocity and acceleration responses.
[S04]	In leak detection in plastic pipes, the error that is caused by random noise in time delay estimate is not significant as compared to the resolution of the time delay estimate.	-
[S05]	This paper gives a good understanding on how leak waves propagate in plastic pipes, when different techniques should be used and the development of a signal processing procedure improving BCC.	-
[S06]	MLE has a feature of sharpening the peak in cross-correlation function	"The results in the research needs to be validated by a programme of measurements in a variety of field conditions"
[S07]	All three sensors discussed in the paper can detect strong leaks	Only the hydrophone sensor could not detect the weak leak. Time delay is given by the slope of the gradient which is affected by the type of sensor used.
[S08]	The methods used obtained consistent results	They do not pin point leak location. Poor performance for leaks far from the sensor.

[S09]	the algorithm is capable of dealing with issues affecting measurements such as transient environmental perturbations or saturation effects	Measurements did not follow the natural evolution of leaks over time
[S10]	The sensor can estimate the leak size at pressures between 60 and 100kPa but not for pressures above 120kPa	need to enhance the experimental and the measurement of vibration data with different triple accelerometer sensors
[S11]	The authors discuss several pipeline fault detection methods. It is established that vibration analysis allows easy fault detection.	Cost of the different fault detection techniques were not compared as they could not be found in the studied literature.
[S12]	-	The fixed thresholds are unsuitable due to the presence of non-stationary noise therefore there is a need for adaptive thresholding techniques
[S13]	Desicion tree, Naive-Bayes and Deep Learning techniques have been implemented to distinguish leak from non-leak with high accuracy.	-
[S14]	Acoustic emission technique is used to detect leaks giving satisfactory results	Pipe material and soil presence affected the detection of leaks.
[S15]	The proposed MLE method has higher leak detection than other methods when the distance between sensors are equal.Sensor distance can be higher with the MLE filter.	-
[S16]	-	The shear stiffness of the surrounding soil has an effect on the noise propagation and attenuation of the noise along the pipeline
[S17]	The method is not sensitive to water use by showers/faucets	The fingerprinting database must be built every time the sensor is installed in a new household
[S18]	An algorithm that uses STD was successfully tested on hydrophone signals.	Distant leaks could not be detected using accelerometers.

[S19]	Bending loss of optical fibre induced by acoustic vibration is used as a sensor to detect leaks and the time-domain signal is converted into frequency spectrum using FFT.	Does not focus on the detection of leak location
[S20]	This paper discusses a method that results in an accurate time delay estimation	The procedure discussed in this paper has to be applied manually and therefore is not very practical.
[S21]	The proposed method can assess the severity of leaks and the onset.	Does not address the effect of surrounding soil on vibrational characteristics, the sensitivity of the approach, sudden and legitimate system demands, the ability of the approach to identify multiple leaks,etc.
[S22]	BCC is better for leak detection in plastic pipes as it is insensitive to system resonances	PHAT is sensitive to additional phase shifts due to resonance.
[S23]	This paper shows that the use of multiple axes for leak detection increases accuracy	The system gave accurate results for leaks above 3mm but not for leaks of 1mm diameter.
[S24]	These researchers developed a LDS that meets good API standards of sensitivity, accuracy, reliability and robustness. It is also able to estimate the leak size by vibration analysis.	-
[S25]	This paper proposes a new block average based method for TDE	The method proposed was not tested in real-time on a water pipeline.

Chapter 4

Leak Detection from Irrigation Pipelines in Botswana using Vibration Interpretation Technique

4.1 Leak Detection Approach in Botswana

Botswana is a landlocked country with only a few sources of fresh-water. According to a policy brief on Botswana's Agriculture and water resources, the agriculture sector is the leading water user and the irrigation sector is expected to expand over the years as the country adjusts to climate change [78]. Currently farmers try to detect leaks by observation. Leak detection by observation prove difficult due to the water moving vertically downwards from the leak site instead of spreading in sandy soil [79], Figure 4.1. Additionally, colour of wet sandy soil is not much different from the dry sand and it will take longer to notice a change especially if the leak is underground (water pipes are buried underground to prevent damage due to UV rays and animals(e.g. hyenas) biting into the pipes). However, if a leak water should rise above ground the high temperatures and low humidity result in quick evaporation [80] and it may not be visible until much water has been lost and vegetation starts to grow in the leaking area. Another method is the one used by Water Utilities Cooperation Botswana which employs tracer gas and it is used to find leaks in the distribution network only. When the pressure is constantly low in an area, a leak is suspected and the pipeline network is scanned along its length either using inspection by sight or by using tracer gas. The use of a leak detection system can highly improve water management in the country [81].

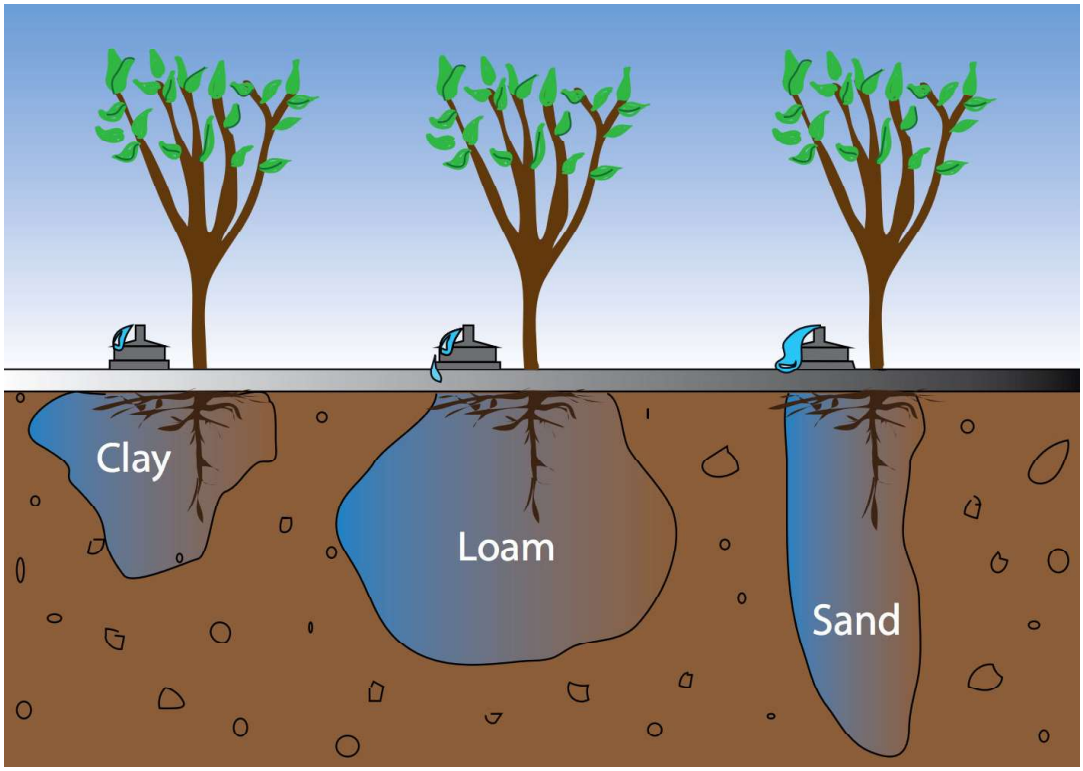


FIGURE 4.1: Shape of water bulb under the dripper in different soil types [82]

4.2 Irrigation Pipelines in Botswana

Arable farms in Botswana have large irrigation systems that are used for horticulture especially in areas with low rainfall [83]. Drip irrigation is a common method

of irrigation. Technology-based Water management in a country with a semi-arid climate is very important in order to save water and thereby water leak detection is necessary. Crop production is mostly rain-fed and horticulture is whereby irrigation is highly used. Water is sourced from nearby water reservoirs, villages, government irrigation schemes, water treatment plants or from boreholes [81]. Irrigation is common in the drier areas of Botswana like the Kgalagadi desert [80]. The soil in this area is sandy and does not hold moisture for long as it is well aerated and has a grain texture. Crop production in sandy soil requires regular addition of nutrients and regular irrigation due to the high seepage rate.

Some water sources may be up to a kilometer away from the farming area and cover a vast area of land. Thus pipelines are used, above or underground, to transport water typically with no means of metering or protection. Damage to pipelines may be caused by corrosion, excessive stress due to pressure or by animals on the farm. A leak detection system can be installed to detect leaks that may occur along these networks and reduce the unwanted wastage of water. The system does not prevent leaks but will largely reduce the time needed to detect and locate a leak and therefore reduce its consequences. About 70-350 Mm^3 of water is consumed by agriculture and irrigation per annum [81].

This chapter discusses an algorithm to monitor water leaks and data analysis techniques that can be used for detecting leaks in crop irrigation systems. Following this section of agriculture and irrigation practices in Botswana, the remainder of this chapter will discuss how accelerometers work, different leak estimation techniques, the proposed method of leak detection, the dataset and the results.

4.3 Vibration Interpretation Technique (VIT) for Leak Detection

The vibrations along a pipeline can be measured using an accelerometer. A triple axis accelerometer is a sensor that measures acceleration in three linear axes x,y and z, therfore improving accuracy. A suitable accelerometer for leak detection would be one with low-power consumption and high sensitivity. Ismail et al. [58] compare three accelerometers and determined ADXL335 to be a suitable accelerometer for leak detection based on its performance. This triple axis accelerometer has four dynamically selectable scales of $\pm$2g, $\pm$4g, $\pm$8g and $\pm$16g [84]. A scale of $\pm$2g can be used to pick up the small vibration caused by flowing water. In order to calculate the volume of water, that is flowing past the accelerometer as in (2.3) following the principle of continuity, the acceleration in each axis can be integrated with respect to time to find the velocity in each direction (4.1), where a and b are consecutive sampling times.

$$\int_a^b f(x, y, z)\, \mathrm{d}t \tag{4.1}$$

Figure 4.2 shows a typical setup for a system using VIT and accelerometers.

The interpreted data would need to be communicated to the farmer to report leak, LoRa is a good candidate as an enabling technology due to its coverage as well as resillience to noise corruption. Hence, the next subsection briefly discusses LoRa.

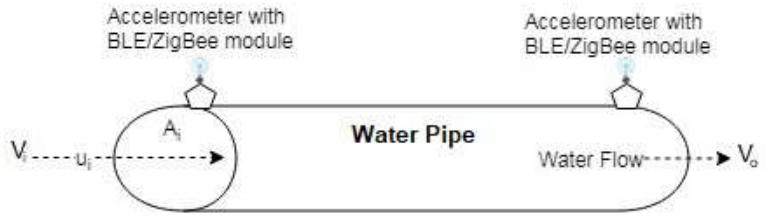


FIGURE 4.2: A layout of the water leak detection system using VIT

4.3.1 LoRa Wireless

LoRa otherwise known as LoRaWAN is a chirp spread spectrum physical layer technology with forward error correction abilities [85]. Ayoub et al. [86] provides an overview of several Low Power Wide Area Networks (LPWAN) including LoRa. DASH7 and NB-IoT are other alternatives to LoRa. However, they do not provide the wide coverage provided by LoRa. DASH7 and NB-IoT have a coverage of up to 1Km only whereas LoRa can ranges between 2-5Km. LoRa uses unlicensed bands and therefore can be easily deployed. LoRa runs the default LoRaWAN protocol but maybe made to run any protocol of choice. The technology operates in the sub 1GHz ISM bands. In addition, LoRa's transmission abilities are of considerable repute, with the technology being able to transmit packets upto 20Km with no packet loss [87]. Moreover, interest in the technology lies in the use of very low transmission powers as well as resilience to noise corruption by utilising six different spreading factors to sacrifice data rates for improved transmission distance [87]. LoRaWAN permits nodes to function in three distinct classes: A, B, and C where class A allows an edge node one uplink followed by two downlink windows from the gateway [88] refer to Figure 4.3. The edge node controls the uplinks and thus this class will often consume the least amount of energy. Class B has scheduled uplinks with the gateway, as well as random/self-determined uplinks similar to class A. Downlink windows are made using time synchronising message from the gateway [88]. Class C has continuous uplink windows that close when there is a downlink in progress from the gateway. LoRaWAN connections are set to star topologies by default. As a result nodes have independent connections to the gateway with packets capable of being 243 bytes in size.

4.4 The pipeline monitoring and leak detection system

Accelerometers can be placed along the water pipes as shown in Figure 4.2 creating a mesh network. The measurements from the sensor can be used to monitor the flow of water. The data will be collected using LoRa wireless modules and sent to a network server. Any abnormality in the flow rate will be reported to the user by SMS, and the user may choose to shut the water flow remotely by SMS using the LoRa module connected to the valve. The possible position of the leak will be estimated by calculating the distance from the accelerometers using the principle of continuity of water between the sensors.

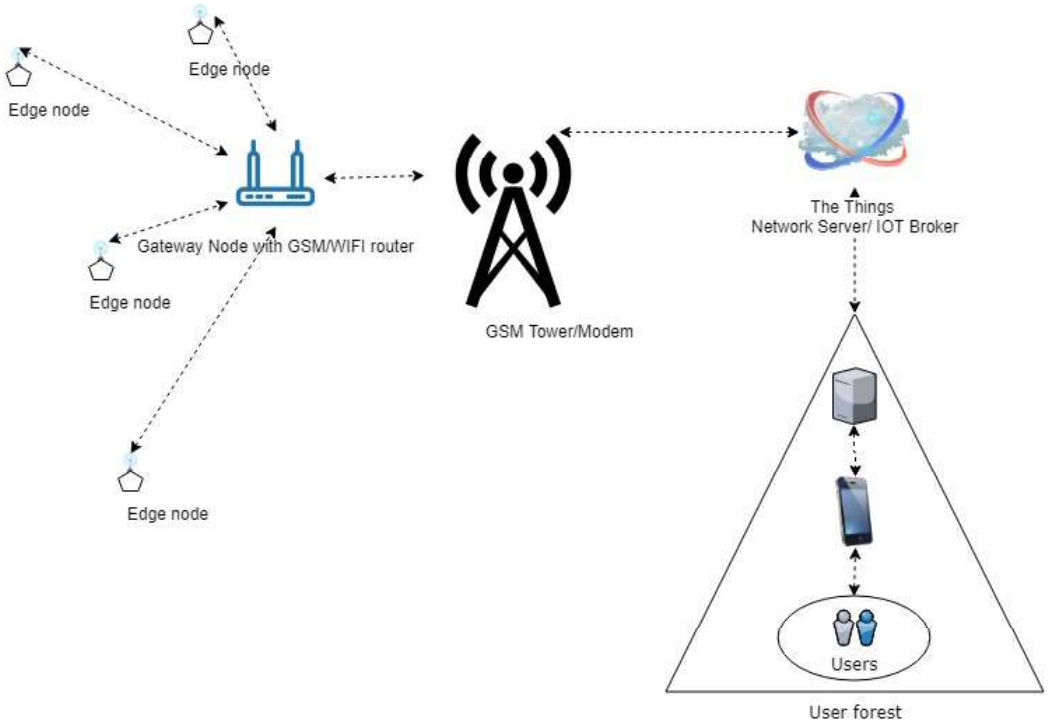


FIGURE 4.3: LoRaWAN architecture

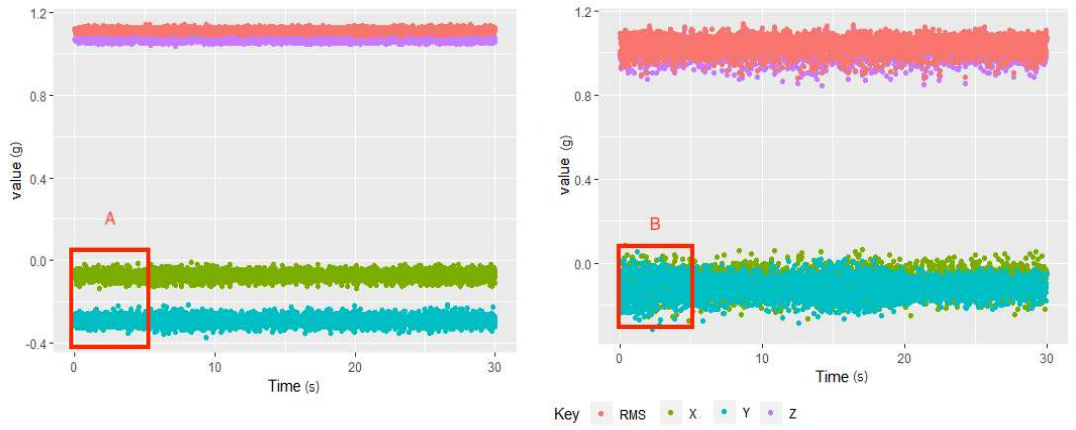
4.5 Data for VIT

TABLE 4.1: A snippet of data used for analysis purpose [16]

Time(s)	**No Leak**				**Leak**			
	X	Y	Z	RMS	X′	Y′	Z′	RMS′
0.01	-0.0500	-0.3133	1.0667	1.1167	-0.0900	-0.1667	1.0700	1.0900
0.02	-0.0733	-0.3133	1.0667	1.1200	-0.0867	-0.0567	0.9933	1.0067
0.03	-0.0500	-0.2800	1.0667	1.1067	-0.0667	-0.0567	0.9767	0.9900
0.04	-0.0800	-0.2900	1.0700	1.1167	-0.0600	-0.267	1.0400	1.0633
0.05	-0.0800	-0.2700	1.0600	1.1000	-0.1400	-0.2267	1.0100	1.0467

A sample data was obtained from [16] who conducted an experiment on leak detection in Universiti Teknologi Malaysia. Data was collected in leak and no-leak conditions from a testbed with an inch of ABS pipe diameter and 10 meters length. An MPU6050 3-axis accelerometer was used to measure the acceleration along the pipeline, with the x-axis of the accelerometer in the direction of the water flow. The measured values are in gravitational acceleration(g) which is approximately $10 m/s^2$ The data was collected at a 10ms interval for 30 seconds and transmitted to a laptop over a Zigbee network. The sample leak and no-leak data were compared against each other, and python scripts were used to identify a distinction between each condition. More details of this experiment can be found on [16]

Table 4.1 shows a snippet of the data obtained from the first five readings of the accelerometer. RMS can be calculated by (4.2). The X′,Y′,Z′ and RMS′ values are the measurements obtained in the Leak condition.



(A) Scatter plot of values with no leak condition (B) Scatter plot of values with leak condition

FIGURE 4.4: Comparing 'No leak' with 'leak' values

$$RMS = \sqrt{X^2 + Y^2 + Z^2} \tag{4.2}$$

The next section discuss the data analysis for designing the algorithm for leak detection.

4.6 Data analysis and Algorithm development

Visual inspection of data in Table 4.1 suggest that RMS' (leak) is *always* smaller than RMS (no leak). The trend can be observed in Figure 4.4a which shows a scatter plot of the values obtained in the first 30 seconds.

$$\begin{aligned} (RMS_{n+1} - RMS_{n+2}) &< (RMS_n - RMS_{n-1}) \\ and (X_{n+1} - X_{n+2}) &> (X_n - X_{n-1}) \\ or (Y_{n+1} - Y_{n+2}) &> (Y_n - Y_{n-1}) \\ and (Z_{n+1} - Z_{n+2}) &> (Z_n - Z_{n-1}) \end{aligned} \tag{4.3}$$

Unfortunately, implementation of this observation/assumption using Equation (4.3) resulted in 99.2% true positives, and 45.8% false positives. See Table 4.2. Meaning that about half of the time the system would indicate that there is a leak when there is no leak. This can be costly and time consuming for the users. Hence, further analysis of the data was required.

TABLE 4.2: Results of comparing only the RMSs

	True Positive	**False Positive**
Leak	99.2%	45.8%
No Leak	54.2%	0.8%

Further analysis of the data suggested overlapping of X and Y values in leak conditions. Fluctuations in the individual axes were considered. Figures 4.4a and 4.4b show how the X,Y,Z and RMS values differ for the leak and no leak conditions respectively. Compare the square labelled A to B. These values were compared in

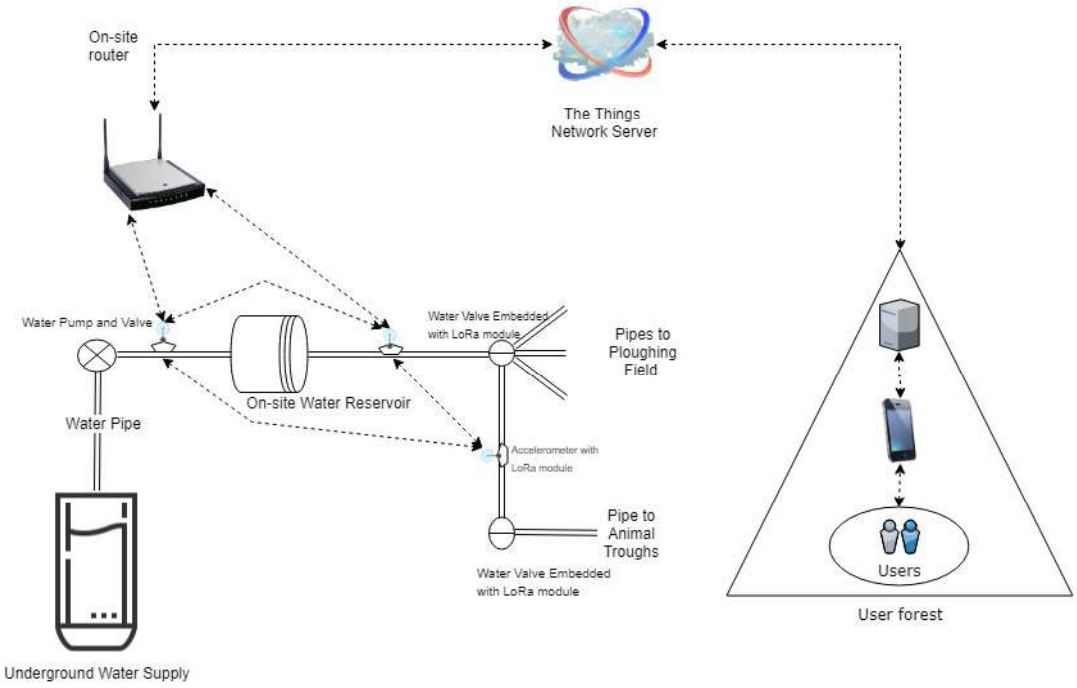


FIGURE 4.5: A layout of the water monitoring and leak detection system

small grouped samples (10 seconds worth of data) to improve accuracy. The mean (μ) of X is clearly different to $\overline{Y}$ for all the data recorded for no leak condition (see Figure 4.4a).
Data from both leak and no leak condition is normally distributed and independent therefore t-test [89] can be used to compare the samples.

Pooled sample variance:

$$S_p^2 = \frac{(n-1)S_X^2 + (m-1)S_Y^2}{n+m-2}.$$

Let $X_1, \cdots, X_n$ and $Y_1, \cdots, Y_m$ be two independent samples from normal distributions with the same population variance. The test statistic for testing

$$H_0 : \mu_X = \mu_Y \text{ vs. } H_1 : \mu_X \neq \mu_Y$$

$$T = \frac{\bar{X} - \bar{Y} - (\mu_X - \mu_Y)}{S_p\sqrt{1/n + 1/m}} \sim t_{n+m-2}.$$

Reject H_0 if $|T| > t_{\alpha/2,n+m-2}$.

We compared XYZ (No leak) with X'Y'Z' (leak) values, our vibration interpretation technique (VIT) algorithm whose pseudocode is shown in (Algorithm 1), use pooled sample variance and t-test, the results are discussed in the next section. Typical setup for the entire system is shown in Figure 4.5.

4.7 Results Analysis

The results of this test are shown in Table 4.4. It detected that there is a leak when there was a leak with 87.9% accuracy and that there is no leak when there is no leak

Algorithm 1 Vibration Interpretation Technique

procedure LEAK DETECTION
    top:
    $xyz \leftarrow$ values of xyz
    $\bar{x} \leftarrow$ *mean of* x
    $\bar{y} \leftarrow$ *mean of* y
    $l \leftarrow 0$
    if $\bar{x} \neq \bar{y}$ **then return** False
        $l \leftarrow 0$ ▷ leak not detected
        goto *top*.
    $j \leftarrow patlen$
    if $\bar{x} \approx \bar{y}$ **then**
        $l \leftarrow 1$
        $l \leftarrow l + 1$ ▷ possible leak detected
        goto *loop*.
    goto *top*.
    loop:
    if $l > 1$ **then** ▷ leak confirmed.
        close;
    goto *top*.

with 96.3% accuracy. A framework [90], [91] to evaluate prediction systems was proposed by Shepperd and MacDonell (SM) based on Standardised Accuracy (SA), an unbiased statistic, to test the likelihood of the result relative to the baseline technique of random 'predictions' (guessing), and effect size calculations. The results interpretation described in this paper is based on the SM framework. The Standardised Accuracy (SA) is relative to random prediction based on 1000 permutations. To establish practical significance, the Effect Size is also considered [92], [93]. Thus, the SA of each approach and the effect size is shown by Table 4.3. These results are interpreted as follows using the SM framework: From the SA, it is evident that VIT is 78% better than random predictions. In this paper, the effect size is measured as Δ [92]. The effect size of VIT relative to random prediction is interpreted as a 'medium' effect size.

TABLE 4.3: SA and effect size Δ

Technique	**Criteria**	
	SA (%)	Δ
VIT	78.28	0.442

Our results show that VIT outperforms random guessing with also a superior effect size Δ.

TABLE 4.4: Results of comparing XY with X'Y' values

	True Positive	**False Positive**
Leak	87.9%	3.7%
No Leak	96.3%	12.1%

The false positives may be observed in Figure 4.6. Basing on the size of the contribution of either A or B to the sampled data, the results could be positive or falsely negative. For example; if 'A' dominates the result will be *No leak*, while that in-fact would be the start of a leak. We tried to minimise this by sampling at least twice before confirming a leak (see Algorithm 1) line 15.

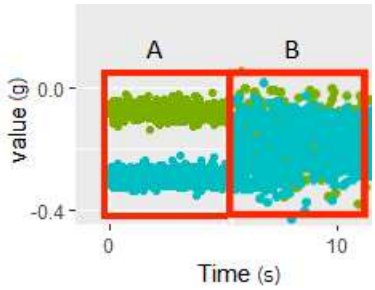


FIGURE 4.6: Scatter plot of XY (A) and X'Y' (B) values

4.8 Conclusion

VIT uses vibrations of the pipeline to determine the existence of a leak, hence, the soil type does not play a large role in the leak detection. The water monitoring and leak detection system discussed has not been implemented and tested. Looking at the effect size, Δ VIT offers results that have practical significance and therefore farmers could adopt the use of vibration interpretation techniques to detect water leaks in their farms' irrigation systems. The results from the data analysis show a significant difference in the *leak* and *No leak* conditions. Therefore in conclusion,the data analysis technique used is able to detect that there is a leak with high accuracy as shown by the results in Table 4.4.

Chapter 5

Conclusions and Future Work

This chapter is a synopsis of the thesis, highlighting the contributions and limitations of the work done. A summary of the work done is below, followed by a discussion of the contributions made by the study, constraints and possible improvements for the future works.

5.1 Summary of Work Done

The work done as a part of this master thesis is outlined briefly in this section.

1. **A systematic literature review of the vibration interpretation techniques used for water leak detection in buried pipes was conducted.**

   The literature review includes the following:

   1. Several databases were scanned for peer-reviewed studies on VITs used for leak detection in buried water pipelines. The search resulted in 65 papers, of which 25 were selected after removing duplicates and applying the inclusion criteria.
   2. A narrative review of the selected studies.
   3. Results have been submitted for publication.

   From the meta-analysis of the selected papers, it was evident that a lot of research has been conducted on the use of vibration interpretation techniques for leak detection, however not many focused on leak detection in small-diameter, end-user pipelines.

2. **Presented a vibration interpretation method using qualitative data analysis to classify leaks**

   As a need for leak detection in end-user premises was identified in the SLR, the predictability of leaks in small diameter pipelines was investigated.

   1. Vibration data from an experimental water pipeline setup was obtained and analysed to identify the leak and no leak situations.
   2. Proposed the use of VITs for leak detection in irrigation pipelines in Botswana.
   3. The results were presented at the IEEE Africon 2019 conference (Published [94]).

5.2 Contribution of This Thesis

The work done in this thesis contributes in the following ways:

1. A systematic literature review of carefully selected studies, showing that the application of VITs is significant for leak detection.
2. The meta-analysis showed that although leak detection using vibration analysis is widely studied, case studies on end-user pipelines have not been highly focused on.
3. A solution for detecting leaks in water pipelines for agricultural uses in Botswana was given using VITs and IOTs in a LoRaWAN architecture was discussed and tested.

5.3 Limitations and Possible Future Work

This thesis focuses on leak detection methods and a solution that detects the presence of leaks with high accuracy is presented. However, it should be noted that there are some drawbacks. This section discusses these limitations and possible improvements for continuing research.

5.3.1 Limitations to Approach and Analysis

The approach proposed in this thesis was used for analyzing leak data from small diameter plastic pipelines. A prototype of the proposed network was not created and tested. The algorithm was not tested on pipelines of different diameters and materials. The usability of the method in real-time has not been tested.The limitations to the analysis are as follows;

1. The dataset conditions such as noise, water pressure and flow rate were unknown. These conditions may affect the results differently as they were not tested.
2. The proposed algorithm was not tested in real-time. A prototype was not made and tested on pipelines to determine the accuracy in natural conditions.
3. The data collected was from a small-scale laboratory set up. The results may differ for a large scale network.

5.3.2 Possible Future Work

In this study, a method of leak detection and its implementation has been proposed. The following is a list of improvements for future work based on the current study;

1. The VIT Algorithm may be affected by natural conditions such as noise, pressure and flow rate. This needs to be tested to determine its performance and accuracy in real-time.
2. In the dataset used for analysis, the sensors were placed 2m from the leakage point for every scenario. The sensor placement for effective leak detection in the network was not studied.

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