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A Review of Vibration Detection Methods Using Accelerometer Sensors for Water Pipeline Leakage

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ABSTRACT Water pipeline leakage detection is still an important issue, particularly for the development of smart cities. Thus, this paper reviews water pipeline leakage detection techniques, which can be classified into three different categories, namely, software-based, hardware-based, and conventional methods. We compare the advantages and disadvantages for all the methods in the groups and thoroughly discuss the hardware-based method, which is our focus. Specifications on water pipeline testbeds used in the previous works are also highlighted. Since many recent techniques are based on accelerometer or vibration sensors, a comparative study that includes the cost and accuracy in identifying the pipeline leaks is presented. The theoretical computation of the vibration induced from our water pipeline testbed is also demonstrated and compared with the actual vibration data collected from the experimental works using three different sensors, namely, MPU6050, MMA7361, and ADXL335.

INDEX TERMS Water pipeline, pipeline leakage, vibration leak detection, accelerometer, pipeline test bed.

I. INTRODUCTION

A smart environment is one of the characteristics that enabled smart city. When we discuss smart environment considerably lies on water [1], energy [2], [3] and air pollution [4], [5] management. Prior to the water utilities, pipeline networks are essential for transporting water from one destination to another. Large quantities of water transport from reservoir to consumer meaning that small of water losses, it can have considerable economic impacts because of the environmental burden associated with wasted energy and the potential risk to public health. Leaks may occur due to aging pipelines, corrosion, and excessive pressure resulting from operational error and the rapid closing or opening of valves. To prevent future water losses and public risks, many techniques have been proposed with different applications for detecting the occurrence and sizes of a leakage in water pipeline systems [6]. Systematic leakage control programs have two main components: i) water audits and ii) leak detection surveys. Water audits measure the volume of water that moves in and out of the water pipeline system and can be used to help identify which segments and portions of the water pipeline network are leaking. However, water audits do not provide any information about the exact locations of leakage in a pipeline system. A leak detection survey must be conducted to identify the sizes and locations of leakage. Generally, the costs associated with leakage include i) pumping, treating and transporting clean water, which results in significant economic losses; ii) reductions in pipeline pressure due to leakage, which results in associated energy costs and poor service delivery; and iii) fining companies with high levels of leakage, which is performed by industry regulators.

The problem statement of this study is divided into three main parts: leakage detection methods, single axis analysis, and localisation of the leak point. Leakage detection methods can be broadly categorized into software-based [7]–[13],

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Year	Method
1850s	Manual Sounding
1880s	Deacon Mater Waste Metering
1920s	Helical Vane Meters
1930s	Step Testing
1965	Ground Microphone
1978	Leak Noise Correlator
1980s	Electronics Step Tester (DMA's)
1990s	Acoustic Loggers Ground Penetrating Radar
2002	Digital Correlator
2006	Internal Noise Leak Indicator
2008	Acoustics Leakage Detection
2010	Transient Leakage Detection
2013	Vibration Leaks Detection
2014	Vibration Leaks Detection (Accelerometer sensor)
2015	Vibration Leaks Detection (V-Type Ultrasonic sensor)
2016	Leakage detection bi-wire sensors (Capacitance sensor)
2017	Multiple-model algorithm (Pressure and flow sensors)
2018	Temperature gradient between pipe and soil

FIGURE 1. Several leak detection methods organized according to their historical appearance.

conventional [14] and hardware-based [13], [15]–[19]. The software-based method uses various computer software for the leaks detection analysis. The second category, conventional method is a traditional method that uses experience personnel who walked along the pipeline system to identify unusual pattern on the pipe, smell substances or listen to noise generated from the leaking hole. The third category is hardware-based, which uses visual observation or appropriate measurement. This method can be grouped into two; non-contact and contact measurement techniques.

A considerable amount of literature has been conducted investigating various acoustic leakage detection methods [20]–[23]. These studies detected leaks in the water pipeline system from the noise generated from the leaks hole. The acoustic technique has been widely used in the water industry and produced effective results for leak detection and localisation on the pipeline system [24]. The pipeline inspection technique involved with minimum intervention and above-ground disruption. However, the acoustic leak detection method has several limitations. Vitkovsky *et al.* [25], Misiunas Vitkovsky *et al.* [26], and Lee *et al.* [27] concluded that due to the viscoelastic, which is soft and elastic material, the plastic pipe will absorb the noise sound that is generated from the leak and thus the noise sound wave becomes weak. The disadvantages of the acoustic method are the difficult to place acoustic sensors in the right location at the water pipeline and difficult to detect the quiet leaks, which produced no sound. Due to this fact, researchers have shown a strong interest on the vibration technique for the leakage detection. The vibration signal from the water pipe is measured using an accelerometer or ultrasound [7]. This paper focuses on the leakage detection method and vibration leakage detection on a plastics water pipeline system. The terms of accelerometer sensor and vibration sensor are interchangeably used in this paper.

In this paper, the contributions are as follows

- Water pipeline leakage detection techniques and categories, namely software-based, hardware-based and conventional
- Specifications on water pipeline testbeds
- A comparative study of vibration sensors for water pipeline leakage detection
- Validation of water pipeline testbed using vibration sensors

This paper is organized in nine sections. Section I discusses the introduction of the water pipeline leakage and the problem statement. Leakage detection techniques are reviewed in Section II. Section III discusses the leak detection technique using software based methods, which included hydrostatics, mass balance, pressure point analysis (PPA), statistical analysis model method and transient based method. The hardware-based method listed conventional, visual observation, tracer gas injection, infra-red thermography, ground penetrating radar (GPR), Acoustic, pipeline inspection gauge (PIG) and vibration explained in the Section IV. Section V discussed the comparison of leakage detection methods. While, flow rate induced vibration, is discussed in Section VI. Section VII discusses the water pipeline test bed specifications for experimental testing and Section VIII explains the vibration sensors for plastic pipeline leakage detection. The conclusions of the review of vibration detection methods for water pipeline leakage in Section X.

II. LEAKAGE DETECTION TECHNIQUES

In recent decades, water companies have increased the efficiency of their distribution systems because of the increasing demands of the public and industry for treated water. Consequently, in most countries, engineers and researchers have developed leak detection techniques to address leakage problems in water pipeline systems. The historical appearances of different leakage detection techniques are outlined in Fig. 1.

The first detection method based on listening was introduced in the 1850s [28]. The manual sounding method involves placing a wooden listening rod on the accessible contact points of the water pipeline system and fittings, such as main valves or hydrants. The listening rod is used to detect the sound resulting from leaking water and from pressurized pipes where it functions similarly to the stethoscope used by doctors to listen to the heart. When a noise is detected, leaks are pinpointed by listening at the ground surface directly above the pipeline at small intervals along the water pipeline system. The use of traditional methods, such as listening devices, is straightforward and inexpensive. However, listening methods are time consuming and have questionable effectiveness. Furthermore, sound does not travel along non-metallic pipes such as asbestos cement pipes.

In the 1970s, the process of detecting and locating leaks was improved by the development of leak noise correlation. The underlying concept of this method is similar to that of listening-based methods, which rely on the noise generated by leaks in the pipeline system. However, a fundamental difference of the leak noise correlation method is the use of a correlation technique to analyze the noise detected by the sensor. Later in 1980s, leak monitoring and detection systems were introduced [29]. A leak monitoring network system is divided into discrete sectors of districts that are each known as a District Meter Area (DMA) and cover between 1500 and 3000 connections. DMAs require the installation of flow rate meters at every important points throughout the water pipeline system to record the velocity of water flow at each sector of the district. These meters enable continuous monitoring of the water that flows in each district. These data are compared with legitimate usage flow to determine the amount of leakage in the pipeline system. If the difference between the night water flow and legitimate usage flow is nearly zero, leakage is negligible. Therefore, leaks can be detected based on changes in the water flow rate. An experienced operator of the water pipeline system can determine whether flow decreases in the pipeline system is due to new leaks.

Since 2010, a transient analysis method is used to analyze the water pipeline conditions from internal sensors, which are flowrate, pressure and temperature sensors [11], [12], [30]. In 2015, an air-couple V-type ultrasonic leak detection system was proposed for non-contact method on PVC pipe leak detection monitoring [7]. The V-type ultrasonic sensor worked by installing a couple of the ultrasonic transducers (UTs) out of pipeline with specific distance and adjusting the sensor head direction. The UTs in this design are to transmit ultrasonic frequency to pipeline, such as the center frequency of 40 kHz and resolution of around 1 Hz. The vibration of the pipeline is measured from reflection signal from the ultrasonic sensor. The ultrasonic transducer measured vibration frequency induced from the water pipeline system is between 150 and 200 Hz. However, this method is not suitable for measuring vibration signal from the underground pipeline systems. Due to V-type ultrasonic sensor, this method analyzed the vibration data only from a single x-axis, which is an axis parallel to the water pipeline.

The water pipeline leaks detection method using bi-polar wire as a capacitance sensor was introduced in 2016 [31]. The researchers analyzed pipe leaks using the simpler techniques and cheaper hardware. Two different techniques, which are the measurement of capacitance and time of flight of electromagnetic waves in the sensor elements, were studied in terms of the sensitivity to the leakage pipeline and the significance of temperature variations. Predescu *et al.* [32], Rahmat *et al.* [33], Adedeji *et al.* [34], and Han *et al.* [35] conducted software- and hardware-based implementation in detecting water pipe leakage. The researchers controlled the pressure head and water flow using a multiple-model algorithm method at the pumping station. The proposed method used high sensitivity sensors to investigate the leakage detection, and this resulted in the capability to detect leaks in the water network line. Sadeghioon *et al.* [36] considered the multiple-model control algorithm method for the pipeline leakage based on the temperature difference measured between the pipe wall and the soil, and also the pressure inside the pipe. The accuracy of the leakage detection achieved high percentage, approximately 98.45%. Meanwhile, Jahnke [37] also identified the water pipeline leakage based on the temperature difference of soil using a number of thermisters installed at 3m depth from the pipeline with a 0.25m distance.

Generally, practical leak detection techniques interfere minimally with normal operation and should be inexpensive to deploy [14]. Consequently, leak detection and location methods play important roles in the overall management of the integrity of water pipeline systems. Leak detection methods can be classified as very simple to very complex methods that use sensitive measurement equipment or sensors and trained personnel. Leak detection and location methods are based on pressure changes in the water pipeline system, and discharge is a vital research topic for academics and industry. Table 1 discusses several leak detection methods organized according to their methods, authors, sensors type, advantage and disadvantage between 2010 and 2018.

Current methods are divided into three large groups: software-based methods, conventional methods and hardware-based methods, as illustrated in Fig. 2.

Software-based methods use various types of computer software to analyze and detect leaks in pipeline systems. This method is used to measure internal pipeline parameters, including pressure, flow rate and temperature. Conventional methods require experienced personnel who walk along a pipeline and look for unusual patterns near the pipeline based on odors or sounds due to a leak. Hardware-based methods detect leaks by visual observation or using appropriate measurement equipment. In addition to these three groups of transient-based analysis methods, many leak detection techniques are available. However, none of these techniques are completely successful or reliable in all leak detection cases because they can be imprecise, time-consuming or suitable only for limited pipeline segments [14], [24]. Ideally, pipeline operators and owners of the water company aim to employ simple, robust and highly accurate methods for detecting and locating leaks in the water pipeline system [45].

TABLE 1. Several leak detection methods organized according to their historical appearance.

Method	Authors	Sensor type	Advantage	Disadvantage
Transient based analysis	Duan et al. [9]	Pressure and flowrate sensor	- High sensitivity leak detection - Easy to install	- Unable to localise leak point. -High cost
	Ghazali et al. [10]–[12]	Pressure transducer sensor	- High sensitivity leak detection - Easy to install - Able to localise leak point	- High cost
	Wang et al. [13]	Pressure transducer	- High sensitivity leak detection - Easy to install	- Unable to localise leak point. - High cost
Vibration Leak Detection (Piezo Sensor)	Hester et al. [15]	Minisense 100 piezo sensor	- Easy to install - Low cost	- Unable to localise leak point. - Low sensitivity. - Offline analysis data.
Vibration Leak Detection (Accelerometer Sensor)	Masanobu Shinozuka et al. [17]	MEMS accelerometer sensor (SD1221L-002)	- High sensitivity leak detection - Low cost	- Unable to localise leak point. - Offline analysis data. - Hard to install
	Ismail et al. [38]–[43]	Accelerometer MPU6050, ADXL335 and MMA7361	- High sensitivity leak detection. - Easy to install - Low cost. - Able to identify leak point and sizes.	- Offline analysis data.
Vibration Leak Detection (V-Type Ultrasonic)	Chamran et al. [7], [44]	Ultrasonic transducer (MA40S4R)	- High sensitivity leak detection. - Easy to install. - low cost	- Unable to localise leak point. - Not suitable for underground pipeline.
Leak Detection bi-wire sensors (Capacitance sensor)	Giaquinto et al. [31]	Bi-wire sensors (Capacitance sensor)	- Low cost. - Sense water in a continuous path that can be several meters long. - Monitor large areas in real time	- Positive capacitance offset error. - Parasitic effects in the setup. - Sensitivity to temperature variations.
Multiple model algorithms, pressure and flow sensors	Alexandru et al. [32]	Pressure, flow and temperature sensors	- High accuracy. - used existing built-in sensors.	-Slow leakage detection and small leaks hard to detect
	R F Rahmat et al [33]	Pressure and flow sensors	- Can detect leaks - Can identify location of leaks.	- Maximum distance to detect leaks 2 meters - Water flow rate close to 10 litters per minute.
	Kazeem B. Adedeji et al. [34]	Pressure and flow sensors	- Can detect leaks.	- Not capable to identify location of leaks
Multiple model algorithms, pressure and temperature sensors	Ali M. Sadeghioon et al. [36]	Pressure and temperature sensors	- High sensitivity . - High accuracy almost 98.45%. - Able to detect leakage.	- Cannot identify location of leaks.
Temperature gradient between pipe and soil	S I Jahnke et al. [37]	Temperature sensors and fiber bragg grating sensor (FBGS)	- High sensitivity. - Able to detect leakage.	- Rainfall significant effect on soil temperature.

III. LEAK DETECTION USING SOFTWARE-BASED METHODS

Software-based methods use various types of computer software to detect leaks in pipeline systems. These methods are based on monitoring internal pipeline parameters, such as pressure, water flow rate and temperature. The internal hydraulic conditions of a pipeline system can be measured using measurement instruments [45]. The complexity and reliability of the method is very significant, and examples of this method are used hydrostatic testing method, mass balance method, pressure point analysis (PPA) method, statistical analysis method and transient analysis method.

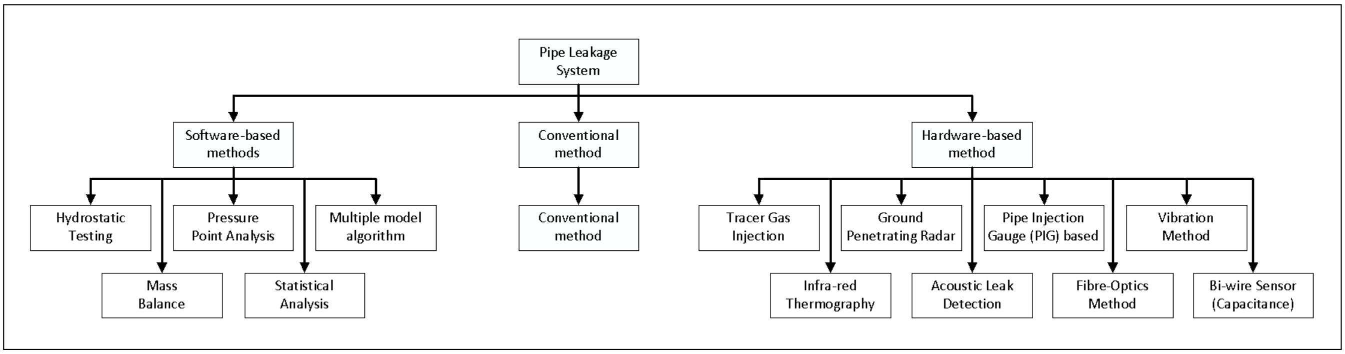

FIGURE 2. Groups of water pipeline system methods.

TABLE 2. Comparison of software-based methods advantage and disadvantage.

Method	Advantage	Disadvantage
Hydrostatics [30]	- Able to identify the condition of the pipeline either leaks or not.	- Difficult to use in an existing pipeline because pipeline must be shut down. - The effects of ambient temperature when obtaining reading from measurement equipment.
Mass Balance [46]–[48]	- Able to identify the condition of the pipeline either leaks or not.	- Main weakness is the assumption of steady state. - Unable to locate leaks in the pipeline system.
Pressure Point Analysis (PPA) [49]	- Able to identify leaks in the pipeline system.	- Unable to locate leaks on the pipeline system. - Indicate false alarms when pressure drop in the pipeline.
Statistical analysis model method [13], [50]	- Suitable for real time applications. - Successfully tested in oil pipeline.	- The noise interferes and some leaks are hidden ni the noise.
Transient Based method [11], [13], [20], [21], [22], [25], [30], [51]–[58]	- Able to identify condition of the pipeline either leakage or not. - Able to locate leaks at a greater distance from measurement point.	- Difficult to identify leakage when the leaks too small or slow.
Multiple model algorithms [32]–[36]	- Accuracy leakage detection more than 80% -rely on built-in sensors	- Slow pipeline leakage detection -difficult to identify small leaks.

Table 2 shows the advantage and disadvantage of different type of software-based method between.

Hydrostatic (or hydro) testing is a traditional method used to detect and locate leaks by examining each length of the pipeline. This method has been used in the water, oil and gas industries to test the integrity of steel pipeline systems [51] which involves sealing the pipeline and pressurizing it with water. The pressure and temperature of the pipeline are measured over a specific time period, usually 24 hours. However, this technique is not easy to use in an existing pipeline system because some sections of the pipeline must be shut down. In addition, temperature measurements of buried pipes require excavation at the pipeline sites to eliminate the effects of ambient temperature when obtaining readings from the measurement equipment.

The mass balance (and volume balance) method is based on conversion of mass in the water pipeline system [46]. As the fluid enters the pipeline section, it either remains in the pipeline section or leaves the pipeline section. The difference between the upstream and downstream water flow measurements is identified as a leak if it is more than the established tolerance [47]. This technique indicates that leak detection does not necessarily produce a high rate of change in the pipeline pressure or water flow in the pipeline [48]. This approach has been commercialized and used in the oil pipeline industry and is very sensitive to the accuracy of the pipeline instrumentation. The main weakness of the mass balance method is the assumption of a steady state. The detection period can be increased to prevent false alarms, delaying the response time for detecting leaks. Another significant disadvantage of the mass method is that it is unable to locate leaks in the pipeline system.

The pressure point analysis method is used to detect leaks by comparing current pressure measurements against running statistical trends of pressure and flow rate measurements over a period of time along the pipeline [49]. This approach is based on several assumptions, including the assumption that decreased in the pressure of the pipeline system indicates the presence of leaks. This method can be used to detect water leaks in the pipeline system but cannot locate leaks. This method shows that significant decreases in pressure in the pipeline system are identified as leaks. However, this method can yield false alarms when the pressure drop in the pipeline does not represent a leak because the leak signature is incorrectly identified [49].

A statistical analysis model method for leak detection systems was developed by Shell and referred to as an Atmos pipe [22]. This method uses advanced statistical techniques to analyze flow rate, pressure and temperature data from the pipeline system. This method is suitable for real-time applications and has been successfully tested in oil pipeline systems [50]. On the other hand, this method is effected from the noise interferes with statistical analyses and that some leaks are hidden in the noise, preventing their detection.

The measurement selection and the characteristics of the generated transient depend on the technique that will be used for further analysis. For example, when closing a valve or stopping a pump, the flow rate and pressure conditions in the pipeline system will be affected, and a pressure wave will be produced. Any changes in the physical structure of the pipeline system, such as changes in pipeline sections, junctions, resistance or leaks, alter the wave. Generally, the wave is partially reflected, partially transmitted and partially absorbed by a given feature. Alterations in a system's flow are linked with pressure responses [52]. The speed at which the wave travels depends on the pipeline and fluid characteristics. Consequently, each water pipeline distribution system will have different transient behaviors that depend on various devices in the system.

The transient waves propagate back and forth throughout the pipeline network and carry information regarding leaks or features within the pipeline system [30]. In addition to its potential low cost and non-intrusive nature, this technique has the potential to locate leaks at a greater distance from the measurement point. However, the transient method can obscure data reflection when strong noise is present in the pressure measurement records or when a leak is too small or slow [53]. Several hydraulic transient-based techniques for detecting leaks are described in the literature, including (i) direct transient analysis [54]; (ii) inverse transient analysis [30], [51]; (iii) impulse response analysis [22], [25]; (iv) transient damping methods [55]; (v) frequency domain response analysis [59]; and (vi) wavelet analysis [20], [60]. The transient increases the damping rate [13] and creates a reflected signal in the resultant trace [52], [56] when a leak occurs in a pipeline system. Therefore, it is important to identify and quantify these effects to detect transient leaks and the locations of leaks [57].

A multiple-model algorithm and flow sensors are one of the methods to detect leakage by analyzing the water flow inside the pipeline [32]–[35]. The implementation of hardware and software in the system follows the latest trend of using the Internet of Things (IoT) to demonstrate such architecture can be used in a real-time process control. The advantage of the system is that the energy efficiency and lifetime of the equipment can be improved by using a multimodel approach. However, the disadvantage is that the flow rate sensor must be installed inside the pipeline so that the water flow can be measured directly, which is a hassle for the existing water pipeline system. Meanwhile, another multiple-model algorithm used the relative pipeline pressure and the temperature gradient between the outside pipe and soil for distinguishing leaks in pipeline networks [36]. This method resulted in approximately 98.45% accuracy over the 6-month field trial.

IV. LEAK DETECTION ON HARDWARE-BASED METHODS

Hardware-based methods using visual observations or appropriate equipment for leak detection and location are used to detect leaks from outside of the water pipeline system. The following methods that have been used visual observation method, tracer gas injection method, infra-red thermography method, ground-penetrating radar (GPR) method, acoustic leak detection method, pipeline inspection gauge (PIG)-based method and vibration method. Table 3 compares the advantages and disadvantages of hardware-based methods.

Visual observation is a traditional and simple method for detecting leaks in water pipeline systems. This method involves employing experienced personnel or workers to detect and localize leaks by flying (e.g. airplane or drone), driving or walking along the water pipeline. However, the experienced personnel will search for abnormal patterns near the pipeline or listen for noise generated by water escaping from a hole in the pipeline system. The effectiveness of this technique depends on the experience of the operator, the size of the leak and the inspection frequency [50]. Occasionally, trained dogs that can smell the release of a substance from the pipeline are used [50].

In the tracer injection technique, a non-toxic, water insoluble gas that is lighter than air gases such as helium or hydrogen gas is injected into the water pipeline system [61]. A highly sensitive gas detector is used to identify leaks and the locations of leaks based on the emission of the gas through the hole in the pipeline system [52]. However, this technique cannot be used for daily leak inspections of pipeline systems because it is time consuming and expensive. Furthermore, this method does not regularly pin-point the locations of leaks or estimate their size. The tracer gas injection method is expensive and entails high maintenance requirements, including an experienced operator for handling equipment.

The infrared thermography method is based on the detection of temperature differences between the surroundings of the pipeline and the pipeline system. Special imaging equipment, such as infrared cameras, is attached to flying vehicles, such as aircrafts or helicopters, which pass over the pipeline system. This method has been used to analyze underground pipeline systems based on the thermal characteristics of the soil [61]. One advantage of this technique is that it can cover large areas without excavation. However, the main limitation of this method is that it can only be used for pipeline systems that transport liquid or gas at a higher temperature than the temperature of the surrounding soil, such as pipeline systems for transporting hot water or steam. Several factors may affect the capabilities of this method, including ambient temperature, solar radiation, cloud cover and the surface conditions of the test area [52]. The disadvantages of this method include the expenses of the tool kit, the need for operators to undergo significant training and obtain experience, and the dependence of the method on weather. In addition,

TABLE 3. Comparison of hardware-based methods advantage and disadvantage.

Method	Advantage	Disadvantage
Visual Observation [48], [50]	- Able to detect leakage on pipeline system. - Able to locate the leaks point.	- Need experience personnel driving or waking along pipeline for listening or smelling leaks.
Tracer gas injection [52], [62]	- Able to identify leakage on the pipeline. - Able to locate the leaks point on the pipeline.	- Not suitable because of time consuming. - Expensive and high maintenance requirement including operator handling.
Infra-red thermography [62]	- Able to cover large area without excavation. - Able to identify leakage on pipeline. - Able to locate leaks point.	- Expenses of the tool kit and need experience operator. - Effected from ambient temperature, solar radiation, cloud cover and surface condition.
Ground-Penetrating Radar (GPR) [22], [25], [49], [53], [54], [63]	- Able to identify and locate leaks on metallic and non-metallic pipeline.	- Selected an appropriate frequency is difficult because different of soil type. - Expenses equipment. - The result difficult to interpret particularly for unmapped pipeline. - The operational range is restricted. - Significant operator training and experience requirement.
Acoustics [6], [8], [64], [65]	- Able to detect leakage on the pipeline. - Accurate method. - Less dependent on operator skill. - Easy to used.	- Contact location is requirement. - Difficult to correlate quiet leaks. - Perform poorly on PVC or large diameter pipe.
Pipeline Inspection Gauge (PIG)	- Able to detect leakage on the pipeline. - Able to locate leaks point on the pipeline.	- Expenses equipment requirement. - Need experience personnel to deploy the system.
Vibration [7], [8], [15], [17], [38]–[44], [66]–[79]	- Improve limitation of the acoustic method in detecting leaks on the PVC pipe. - Able to detect leakage on the pipeline. - Able to locate the leaks point.	- less distance on detect leakage between sensor and leaks point.
Leak Detection bi-wire sensors (Capacitance sensor) [31]	- Cheap. - Sense water in a continuous path that can be several meters long. - Monitor large areas in real time.	- Positive capacitance offset error. - Parasitic effects in the setup. - Sensitivity to temperature variations.
Temperature gradient between pipe and soil [37]	- High sensitivity. - Able to detect leakage.	- Rainfall significant effect on soil temperature.

the method is only accurate when the soil is at near-ambient conditions [49].

In the last few years, the application of ground-penetrating radar (GPR) for detecting leaks in pipeline systems has drawn substantial attention [30], [53], [54]. The GPR technique is based on the generation of electromagnetic radiation from radar that is propagated through the ground and returned to the surface. This method can identify leaks in pipeline systems without digging. The velocity of the wave depends on the dielectric constant at the surface of the pipeline. Different wave reflections are produced due to changes in the subsurface of the pipeline material [22]. One advantage of this method over the acoustic method is that it can be used for both metallic and non-metallic pipeline systems. As previously described, GPR is a time-consuming leak detection technique [47]. However, a recent study indicates that GPR can be conducted at 15-30 km/hr along the main route of transmission depending on its location and traffic [28]. On the other hand, this technique has the following disadvantages: (i) selecting an appropriate frequency is difficult because different types of soil respond differently; (ii) the required equipment is expensive; (iii) the results are difficult to interpret, particularly for unmapped services (pipeline); (iv) the operational range is restricted, and (v) significant operator training and experience are required.

The acoustics leak detection method can be systematically used in water pipeline systems and detects noise that is generated from leaks in the pipeline system. The acoustic technique has been widely used in the water industry and produces effective results for detecting and localizing leaks in pipeline systems [20]. Complicated approaches are used to diagnose pipes by capturing the change in the frequency response function (FRF) of the noise due to a leak or by estimating the time delay between recorded signals with different sensors. The main advantages of this method are: (i) it can detect leaks that other acoustic methods cannot; (ii) it is accurate; (iii) it is less dependent on the operator skill, and (iii) it is easy to use. The main disadvantages of this method are: (i) a contact location is required; (ii) it is difficult to correlate quiet leaks,; and (iii) it performs poorly for PVC/large-diameter pipes due to interfering signals from external sources and excessive signal attenuation. Although the acoustic leak detection method has several limitations, it works well for detecting and locating leaks in metal pipes. However, this method does not perform well when applied to pipes made of soft materials, such as plastic [56], because soft pipes are more ‘elastic’ and can reduce sound waves by 300-600 m/sec. Due to their viscoelastic properties, plastic pipes also absorb sound energy thus weakening the sound waves. Furthermore, the high-frequency noise increases when the sound waves travel along the water pipeline system. Analyzing these noise signals will make this process more complicated [22]. The accuracy of leakage detection is also affected by the presence of air in the pipeline system. The presence of air can reduce the bulk modulus and density of the liquid and lead to a decrease in acoustic velocity. Additionally, theoretical studies have suggested that suspended solid may make the liquid more dense and hence decreases the acoustic velocity [56].

The pipeline inspection gauge (PIG)-based method is a pipeline system industry tool that behaves like the free-moving piston inside the pipeline. Generally, oil and gas companies have used the PIG method to clean, inspect, capture and record geometric information about pipeline systems [79], [80]. Recently, the Water Research Centre in the UK developed a PIG system called Sahara to detect and locate leaks in the transmission mains of a water pipeline system. As described by Chastain-Howley and Mergelas, the Sahara system is the only PIG-based method for leak detection and location. The disadvantages of this method include that it is relatively expensive and that experienced personnel are required to deploy the system.

The vibration method uses measurement equipment to measure the vibrations of a pipeline line system, such as the Micro-Electro Mechanical Sensor (MEMS) [17], [81], ADXL206 triple axis accelerometer sensor [11] or MPU6050 sensor [82]. The sensor is attached in the pipeline system to detect fluid flow and vibration noise [78], [83]. The recorded vibration data are analyzed using computer software and the fuzzy logic algorithm [11], [82], transient analysis, neural network analysis, wavelet analysis [84] or fast Fourier transform (FFT) analysis [85].

To improve the limitations of the acoustic method for a plastic pipeline system, the vibration method is used to detect and locate leaks. When the acoustic and vibration methods are compared for a real plastic water pipeline, the vibration sensor is the most accurate sensor for detecting and locating leaks. Cross-correlation analysis is used to analyze acoustic and vibration data to detect and locate leaks [38]–[43], [65].

Leak detection via bi-wire sensors (capacitance sensors) can be engaged as passive distributed sensing elements (SEs) [31]. The system accurately locates the leaks point by infiltrations into soil or concrete materials using a standard time-domain refractometry signal processing. The study introduced the possibility of using the same kind of SEs with simpler technique and cheaper hardware for triggering the water pipeline in abnormal conditions (leakage). The advantage of the system is that the bi-wires are quite cheap and can sense water in a continuous path at several meters long. The basic principle system can be extended to complex systems and distributed networks of sensing elements that allow for large areas monitoring in real time. On the other hand, the disadvantage of the system is that the parasitic effects are found during the set-up. It is suggested to install bi-wires at a few tens of meters since temperature variation effects on a long wire.

V. COMPARISON OF LEAKAGE DETECTION METHODS

Table 4 illustrates the key attributes of leak detection hardware-based methods, including leak sensitivity, estimated location, false alarms, maintenance requirements and cost. The leak sensitivity is the smallest size of leak in the water pipeline system that can be detected, and a false alarm occurs when a water pipeline leak is incorrectly detected.

Statistical and transient-based methods are generally considered superior based on their leak sensitivity and number of false alarms. The main disadvantage of most software-based methods is that they cannot locate leaks in the pipeline system because the data analysis method is based on pressure, flow rate and temperature data from the pipeline. In addition, most software-based methods require the installation of transducers and gauges in water pipeline systems and have high false alarm rates when the water pipelines leak.

Maintenance requirements are measured based on the maintenance and level of technical expertise that is required to maintain the system. Cost is measured based on capital expenditures (CAPEX) and on-going operation costs (OPEX). Nearly all hardware-based methods are highly sensitive and can accurately estimate the locations of leaks in water pipeline systems. However, considerable issues exist regarding their implementation, including their high cost and inability to continuously monitor water pipeline systems. However, false alarms and maintenance requirements are the main issues associated with this method because false alarms can increase the costs associated with repairing and maintaining the water pipeline.

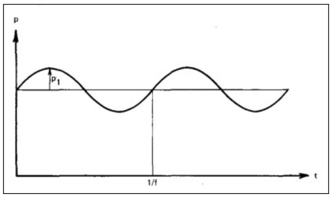

FIGURE 3. The time varying internal pressure of tube.

VI. FLOW RATE INDUCED VIBRATION

The time varying internal pressure, $P = P_0 + P_1 \sin \omega t$ of a tube is shown in Fig. 3. The P_0 represents the nominal pressure while P_1 repeats the amplitude of the pressure variation, where the frequency, $f = \omega 2\pi$. The pressure in the pipeline will be giving the force from the inside of the pipe, the pipe will be expended and this will induce the vibration. Fig. 4 illustrates the simple expressions derived from the sketch of the cross-section pipe. The pipe can be considered thin walled (thickness, t) and the wavelength of the pressure variations is much longer than the diameter. As the static

TABLE 4. Key attribute of hardware-based leak detection methods.

Method	**Leak Sensitivity**	**Location Estimate**	**Operational Change**	**Availability**	**False Alarm**	**Maintenance Requirement**	**Cost**
Conventional Method [28]	High	No	No	Yes	Medium	Medium	High
Software-Based Methods							
Hydrostatics [30]	High	No	No	Yes	High	High	High
Mass Balance [46]–[48]	Low	No	No	Yes	High	Low	Low
Pressure Point Analysis (PPA) [49]	High	No	No	Yes	High	High	High
Statistical analysis model method [13], [50]	High	No	No	Yes	Medium	Medium	High
Transient Based method [11], [13], [20]–[22], [25], [30], [51]–[58]	High	No	No	Yes	Medium	Medium	High
Multiple model algorithm and flow sensors [32]–[36]	High	Yes	No	Yes	Medium	Medium	High
Hardware-Based Methods							
Visual Observation [48], [50]	High	Yes	No	Yes	Medium	Low	Medium
Tracer gas injection [52], [62]	High	Yes	No	Yes	Low	High	High
Infra-red thermography [62]	High	Yes	No	Yes	Medium	High	High
Ground-Penetrating Radar (GPR) [22], [25], [49], [53], [54], [63]	High	No	No	Yes	High	Medium	High
Acoustics [6], [8], [64], [65]	High	Yes	No	Yes	High	Medium	High
Pipeline Inspection Gauge (PIG)	High	Yes	No	Yes	Medium	Medium	High
Vibration [7], [8], [15], [17], [38]–[44], [66]–[79]	High	Yes	No	Yes	Medium	Low	Low
Leak Detection bi-wire sensors (Capacitance sensor) [31]	High	Yes	No	Yes	High	High	Medium

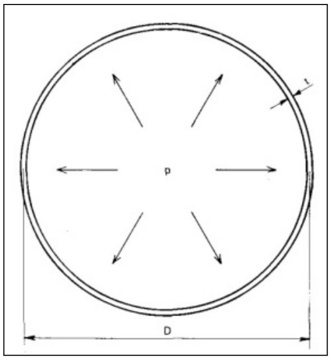

FIGURE 4. The simple expressions can be derived from the sketch of the cross-section pipe.

stresses and strains is introduced by the nominal pressure, P_0 are irrelevant for derivation of the vibration value are considered only dynamic stresses and strain [65].

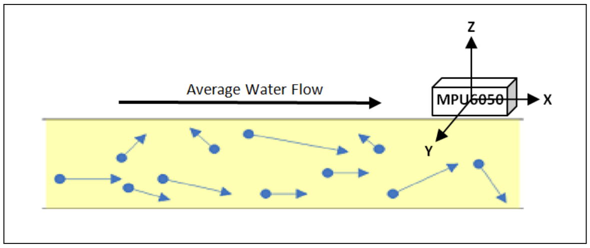

FIGURE 5. Microscopic view of the water flow in a pipeline.

Water molecules averagely traveled in the main direction of the water flow, as depicted in Fig. 5. However, many molecules collided against the pipe wall. Due to the first law of thermodynamics, certain amount of the kinetic energy produced by the molecules will dissipate to heat as the turbulent eddies, but most of the kinetic energy will convert into potential energy in the form of pressure [30]. The vibration

TABLE 5. Comparison characteristics of the specification of the test bed system.

Sensors type	Water leakage detection method	Shape of testbed	Pipe material	Diameter of pipe	Size of leak
Hitachi – metal (H35C) [92]	Vibration	Square (600 x 600cm)	PVC	1.5 inches (38.1mm)	2 x Ball valve
ADXL203, inlet pressure and flowrate sensor [69], [70]	Pressure, flowrate and vibration	Straight 40 feet (1219.2cm)	PVC	Â¿ inches (19.05mm)	2.54mm
Outlet pressure sensors (Force Sensitive Resistance, FSR) [66]	Pressure	U-shape (1200cm)	PVC	40mm	10mm
MMA7361 [41], [67]	Vibration	Asymmetrical Out – 36 x 18 feet (1097.28 x 548.64cm) In – 12 x 6 feet (365.76 x 182.88cm)	PVC	Out – 2 inches (50.8mm) In – Â¡ inches (12.7mm)	-
MPU6050, ADXL335 and MMA7361 [38]–[43]	Vibration	Straight 10m	ABS	25mm	1 and 3mm

in the pipeline resulted from the energy conversion cycle is proportional to the average flow rate within the pipeline [11].

In fluid dynamics, the Bernoulli's principle states that for an inviscid flow of a non-conducting the increased in the speed of the fluid occurs simultaneously with a decrease in pressure in the fluid's potential energy [9], [14]. Bernoulli's principle [10], [13] thus says that a rise in the pressure of flowing fluid must always be accompanied by a decrease of the speed, and vice versa.

The values of the v and w velocities fluctuate in original fluid energy range as long as there is no external force. Therefore, the relationship between the fluid energy and the velocity is presented by

$$|U(t)| = \sqrt{(u^2 + v^2 + w^2)} \tag{1}$$

The equation of the velocity fluctuation frequency, v and w are shown in (2) and (3).

$$v = \sqrt{(2(\Delta\rho_v g \Delta_z)/\rho)} \tag{2}$$

$$w = \sqrt{(2\Delta\rho_v/\rho)} \tag{3}$$

The flow velocity, u in the main stream direction is given by

$$u = \sqrt{(2\Delta\rho)_u/\rho)} \tag{4}$$

The equation in (1) is translated from (2) to (4) and can be expressed as

$$|U(t)| = \sqrt{(2/\rho(\Delta\rho_u + \Delta\rho_v + \Delta\rho_w - \Delta\rho_z))} \tag{5}$$

Therefore, we consider ρ_v and ρ_w are related to the pipeline vibration, which is proportional to the water flow energy. Moreover, v and w fluctuated irregularly with time; the velocity fluctuation frequency appears as the vibration frequency. The frequency characteristic is scattered over a wide range. In particular, the output frequency response is accentuated at resonant frequency of the pipeline system, which comprises components of various materials and shapes [15].

The single axis has been investigated by many researchers where the axis is parallel with the pipeline, which is often the x-axis [7], [12], [15], [44], [65], [71], [73], [85]–[88]. Therefore, the aim of this study is to investigate the vibration measurement for three axes (x-, y- and z-axis). The x-axis of the accelerometer has the same direction with the pipeline and the water flow in the pipeline [12]. The position of the x-axis of the sensor is placed in parallel with the water pipeline system and the y- and z-axes are crossed 90 degrees angle with the x-axis, as illustrated in Fig. 5. The vibration of the water pipeline is measured with the triple axes accelerometer sensor. All the three axes data are collected and analyzed to find the condition of the pipeline system.

VII. WATER PIPELINE TEST BED SPECIFICATIONS

Table 5 summarizes the comparison of the characteristics of the test bed system for different water pipeline leakage detection systems. The characteristics include leakage detection method, shape of test bed, pipe material diameter of pipe and size of leaks.

Water pipeline test bed systems were developed to test methods or techniques for detecting pipeline leaks. Some research conducted the test bed systems in the laboratory. Test bed systems are designed according to the parameter measurements and the type of pipeline. However, the design shape and sensor placement affect the results collected by the sensors. Studies of the design of test bed systems have been focusing on plastics pipes because the existing method (acoustic) cannot accurately detect leaks from plastic pipes [56]. The test bed system was designed and developed to validate the non-invasive acceleration-based damage detection concept and to assess water distribution systems using a wireless MEMs sensor network (Hitachi-Metal H35C). The test bed system was constructed using 40 PVC pipes with a diameter of 1.5 inches (3.8 mm) and two valves labeled A (outlet) and B (simulated rupture). The entire test bed system, which has an overall size of 600 cm x 600 cm. Valve A and valve B are used to control water pressure inside the water distribution system and to emulate a rupture, respectively. The vibration and pressure data are analyzed using the correlation pressure and an accelerometer as well as FFT analysis to detect leaks in the water pipeline system [89].

The 40-feet-long plastic water pipeline was designed and developed for the test bed system at an outdoor field. Two sizes of leaks were simulated on the test bed: a 0.1-inch diameter hole and a hole formed using a ball valve that resulted in a leak that varied in size [62], [63]. The sizes of the holes and leaks in the water pipeline test bed composed of 3/4-inch pipe, the intact test best water pipeline, simulated 0.1-inch leak and ball valve used for the simulated leak. The system included an accelerometer (ADXL206) and flow rate sensor to detect leaks and obtain location data for analysis.

The test bed bench test system was designed and developed to test the capabilities of the proposed non-invasive (to the pipeline) pressure sensor assembly to detect and locate a leak. This system consists of a U-shaped pipeline section composed of 40-mm PVC with a simulated leak in the middle of the test bed system. Water is circulated through the test bed system using a water pump capable of providing water pressure of up to 3 bars. A 10-mm hole is made in middle section of one of the PVC pipe sections. The system uses five force-sensitive resistance (FSR) sensors to detect and locate leaks along the PVC water pipeline [65].

The asymmetrical test bed has dimensions of 36 × 18 feet and is constructed of PVC pressure pipes of 2 inches in diameter with 3 valves and 6 PVC pipes with diameters of 1/2 inch. An acceleration-based sensor (MMA7361) is attached to a commercial water flow meter to measure the water flow rate in the pipeline. This pulse train is connected to a customized wireless sensor node that provides the base station with real-time flow rate measurements. The vibration data are analyzed using time-correlation to detect leaks in the PVC water pipeline [66].

Another water pipeline test bed system using a vibration technique was designed using an inch diameter of ABS pipe with a length of approximately 10 meters. This test bed is an enhancement of the design from the PVC pipe experiment because it uses ABS pipe to measure leak vibration noise [38]–[43]. The test bed water pipeline has a water pump to provide water flow and pressure in the pipeline, and the end of the pipeline is connected to two ball valves. The water is circulated in the test bed system on command using a water pump capable of providing pressures of 0.6 to 1.6 kgf/cm2 and water flow rate of 10 to 25 liter/sec. The function of the valve is to control the pressure and water flow in the pipeline system. An acceleration sensor (MMA7361, MPU6050 and ADXL335) is attached to the ABS water pipeline system to collect vibration data. The vibration data are analyzed using the signal analysis method to detect leaks and determine the sizes of the leaks.

VIII. VIBRATION SENSORS FOR PLASTIC PIPELINE LEAKAGE DETECTION

The acoustic method has been used for many years in the water industry to detect leaks and has recently been applied for locating underground pipes [18] and blockages (sediment depositions) in pipeline networks [90]. The acoustic method uses a sound sensor, such as a hydrophone or microphone sensor, to measure the noise resulting from leakage in a water pipeline. However, this method has limitations because measuring leakage and locating leaks in plastic pipeline systems are difficult and because quiet leaks are difficult to correlate [22]. The specific problems of detecting leaks in plastic pipelines using acoustics have recently received increasing attention by the research community. Romano *et al.* [91] validated these findings by conducting an experimental study in a custom test rig in which simultaneous measurements were obtained using a hydrophone (acoustic), geophone (velocity) and accelerometers (acceleration). Moreover, quality measures for the data have been proposed and tested experimentally as a metric of the prominence of the peak in the cross-correlation function related to leak noise. The results of these analyses indicated that the accelerometer is the best sensor for detecting and locating leaks in plastic pipelines [65].

The vibration method uses vibration sensors to detect vibrations from leaks in plastic pipelines. The sensors used to measure vibration signals are commercial accelerometer transducer or accelerometer breakout sensors. The accelerometer transducer is manufactured by Brüel and Kjaer [92] (type 4384). This sensor is called a piezoelectric charge accelerometer and has a sensitivity acceleration of $\pm 10\ g$ [65], [89]. The frequency range for acceleration measurement is between 0.1 and 12600 Hz at temperatures from -74 to 250 degC. The breakout accelerometer sensor is used to measure the vibrations of noise leakage in a plastic water pipeline. The following sensors were used for the accelerometer: ADXL203 [62], ADXL335 [93], MiniSense 100 Piezo [93], condenser microphone [92], MEMs (Hitachi – metal H34C) [93] and MMA7361 [94]. These sensors have different sensitivities for measuring the vibration signals (acceleration) from leaks.

Table 6 compares the sensors that have been used in plastic water pipelines based on the number of axes, sensitivity, power consumption and cost. These sensors have different characteristics for detecting the acceleration of noise vibrations from leaks. The accelerometer sensors that depend on the number of axes and the sensitivity of the sensor over gravity are superior to other sensors. As the number of axis, increasing the accuracy of the sensor will be increased. For example, if the x-axis unable to identify the condition of the water pipeline another two axis will be analyze.

The two sensors illustrated in Table 6 which only one axis are the MiniSense 100 Piezo sensor and the condenser microphone. The sensitivity of the MiniSense 100 Piezo sensor is ±1 g for measuring the vibration of plastic water pipelines. This sensor is a resistance-based sensor, and the limitations of the sensors for lower frequency measurements are between 0.65 and 65 Hz. The selected external resistance will affect the lower frequency measurements of the sensor. The resistances of the sensor are 10 $M\Omega$, 100 $M\Omega$ and 1 $G\Omega$, and the greater resistance to lower frequency is 0.65 Hz. However, the

TABLE 6. Comparison characteristics of the breakout accelerometer sensor.

Type of sensor	Num. of axis	Sensitivity	Power consumption	Data output	Cost	Accuracy
MiniSense 100 Piezo [15]	1	±1g	-	Analogue	Low	Low
IEPE accelerometer [71], [72]	1	1V/g		Analogue	Low	Low
Condenser microphone [98]	1	-	-	Analogue	Medium	Medium
V-type ultrasonic [7], [44]	1	-	-	Analogue	Low	Medium
ADXL203 [69], [70]	2	±5g	700uA/5V	Analogue	High	Medium
ADXL335 [15], [40], [42], [42], [43]	3	±3g	180uA/1.8V	Analogue	Low	Low
Hitachi Metal (H34C) [92]	3	±3g	360uA/3V	Analogue	Medium	Low
MMA7361 [41], [42], [67], [73]	3	±3g	47uA/1.71V	Analogue	Low	Low
MPU6050 [38]–[40], [42], [43]	3	Up to ±16g	500uA/3V	Digital	Low	High

condenser microphone is used to design vibration sensors by using sound conversion from plastic water pipelines. This sensor was designed based on a mathematical model with a wide range of frequency measurements [95]. The main disadvantage of these two sensors is that they only measure one axis with low sensitivity.

The ADXL206 accelerometer is used to measure the vibration signals in a water pipeline system. By analyzing the vibration data, the sensor can detect and identify leaks and the locations of leaks in plastic water pipelines [96]. However, this sensor is limited because it can only measure two axes. The best sensors can measure three axes because the plastic pipeline moves in three dimensions when the water flow is accelerated in the pipeline. One major disadvantage of this sensor is that it is very expensive to set-up, with a cost of more than five hundred USD. The set-up cost can increase the production costs when the sensor system design includes multiple sensors.

The triple axis of the accelerometer sensor is ADXL335, Hitachi-Metal H34C, MMA7361 and MPU6050 sensors. These sensors have different sensitivities for measuring acceleration (vibration) signals from plastic water pipelines. Josiah Hester 2013 placed accelerometer measurement sensors on a plastic water pipeline to measure vibration signals using the ADXL335 sensor. Acceleration (vibration) data were obtained at 125 Hz, and the data were transmitted over a serial connection to a collection server [18]. MMA7261 is the lowest power consumption sensor and lowest cost sensor [94]. The main limitations of these sensors are their sensitivities for detecting the acceleration of leak noise vibrations in plastic water pipelines.

To avoid the limitations of these sensors, our research proposed using the MPU6050 sensor to detect and measure the acceleration (vibration) signals produced from vibration leak noise in a plastic water pipeline system. The sensitivity of this sensor can be varied from $\pm 2\ g$ to $\pm 16\ g$ by programming using the Arduino UNO. The sensitivity of this sensor is higher ($\pm 16\ g$) for measuring the acceleration signal and for transmitting data over the ZigBee network. The advantage of this sensor is that it can be used to measure acceleration with three axis numbers with lower power consumption and lower cost. Lower power consumption is necessary for developing wireless node sensors and long-time running sensors with lower power consumption and a minimal battery supply. For example, two AA batteries are used to run the full system of wireless sensor nodes.

IX. WATER PIPELINE TESTBED USING VIBRATION SENSORS VALIDATION

We have developed a water pipeline testbed with a length of 10-m and the outer diameter of 25-mm Acrylonitrile-Butadiene-Styrene (ABS) pipe, as presented in [38] and [39]. The vibration induced from the water pipeline is then theoretically computed and then compared with the experimental results from three different sensors, which are MPU6050, MMA7361 and ADXL335.

Referring to [66], the equation governing

$$\frac{d^2y}{dt^2} = -CP'(x) \tag{6}$$

where $(d^2\ y)/dt^2$ is the pipe acceleration (vibration),
C is constant,
γ is specific weight of the beam,
g is acceleration of gravity ($9.81\ m/s^2$),
$P'(x)$ is pressure fluctuations.
The minus sign comes from a decreased pressure along the direction of flow.

Here, the water-filled pipe is modeled as a one-dimensional beam, and the specific weight of the beam γ is defined as weight per unit volume which is mathematically given as;

$$\gamma = \rho g \tag{7}$$

where ρ is density of the water-filled pipe (beam)

That C is constant derived as

$$C = \frac{A\gamma}{g} \tag{8}$$

whereby A is a cross sectional area of the beam

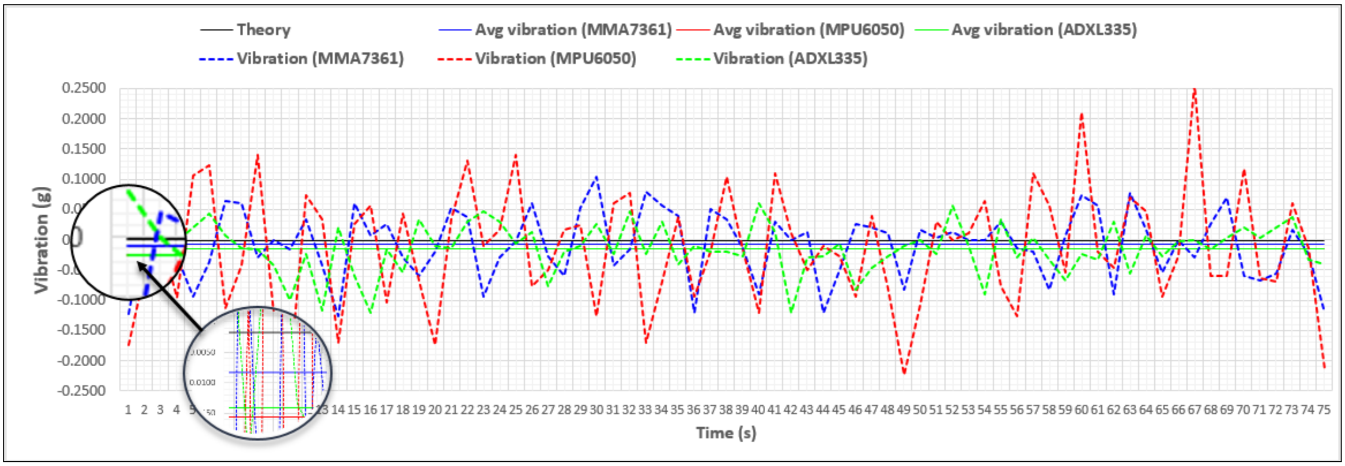

FIGURE 6. Experimental and theoretical vibration data for MMA7361.

The notation W is the weight of water-filled pipe and the value is referred to the standard table of 40 PVC plastic pipe in Appendix A, given $W = 0.9\ kg/m$ for 25-mm ABS pipe. The mass of the water-filled pipe M is computed as

$$M = \frac{W}{g} \tag{9}$$

The cross area of the pipe A can be calculated as

$$A = \pi \frac{d^2}{4} \tag{10}$$

Referring to the table of schedule 40 PVC plastic pipe data in Appendix A, the outer diameter of 25-mm ABS pipe is given 33.4 cm (0.0334 m).

Then, the volume V is obtained by using the relationship between the area of the pipe A and a unit length of the pipe $L = 10$ m. Therefore, the volume V is determined

$$V = \frac{A}{L} \tag{11}$$

The density of the beam ρ can then be calculated as

$$\rho = \frac{M}{V} \tag{12}$$

Based on the parameters of our testbed [38], [39], C equals to 0.00917 and substitute C into Eq. (8)

$$P'(x) = -0.00917 \frac{d^2y}{dx^2} \tag{13}$$

Given Bernoulli Equation is $\frac{P}{\rho} + \frac{v^2}{2} + gz = constant$

$$\left(\frac{P_2 - P_1}{\rho g}\right) + \left(\frac{v_2^2 - v_1^2}{2g}\right) + (Z_2 - Z_1) = 0 \tag{14}$$

Pitot tube pipe $z_1 = z_2$ and $v_2 = 0$, then

$$P_2 - P_1 = \frac{v^2 \rho}{2} \tag{15}$$

where $P'(x)$ and v

$$P'(x) = P_2 - P_1 \tag{16}$$

$$v = \frac{Q}{A} \tag{17}$$

Substitute Eq. (17)) into (15), then

$$P'(x) = \frac{Q^2 \rho}{2A^2} \tag{18}$$

When Q is 24.45 lpm ($0.0004075m3/s$), then

$$P'(x) = 1.537Pa = 1.5673\ x10^{-5} kgf/cm^2$$

Find vibration, $\frac{d^2y}{dx^2}$, substitute $P'(x)$ into Eq. (13

$$\frac{d^2y}{dx^2} = -\frac{P'(x)}{0.00917} = -\frac{1.5673x10^{-5}}{0.00917} = -0.00171g$$

Fig. 6 presents the results of MMA7361, MPU6050 and ADXL335 collected from several experiments and are validated with the calculated vibration, $-0.00171\ g$.

TABLE 7. Performance for MMA7361, MPU6050 and ADXL335.

Parameter	MMA7361	MPU6050	ADXL335
Average	-0.0083	-0.0156	-0.0141
Standard Deviation (SD)	0.0554	0.0989	0.04

Table 7 shows the performance of the three sensors in terms of average and standard deviation. It is clearly seen that MMA7361 demonstrates average vibration close to the theoretical value compares with the others. Because of the noise from environment may induced some vibration, MMA7361 seems has less sensitivity to noise. Nevertheless, for the distribution of vibration data, ADXL335 exhibits the lowest standard deviation while MPU6050 shows the worst results for both average and standard deviation. Due to the characteristics of ADXL335, it probably has high accuracy in identifying the water pipeline leakage.

TABLE 8. Schedule 40 PVC plastic pipe data.

Nominal Pipe Size In.	Nominal Pipe Size mm	Pipe O.D. In.	Pipe O.D. mm	Wall Thickness In.	Wall Thickness mm	Weight of Pipe Lbs./Ft.	Weight of Pipe kg/m	Weight of Pipe Filled With Water Lbs./Ft.	Weight of Pipe Filled With Water kg/m
1/8"	(3)	.405	(10.3)	.068	(1.7)	.04	(.06)	.06	(.09)
1/4"	(6)	.540	(13.7)	.088	(2.2)	.07	(.11)	.11	(.17)
3/8"	(10)	.675	(17.1)	.091	(2.3)	.10	(.14)	.18	(.26)
1/2"	(15)	.840	(21.3)	.109	(2.7)	.15	(.20)	.25	(.40)
3/4"	(20)	1.050	(26.7)	.113	(2.9)	.20	(.30)	.40	(.60)
1"	(25)	1.315	(33.4)	.133	(3.4)	.30	(.40)	.70	(.90)
1 1/4"	(32)	1.660	(42.1)	.140	(3.5)	.40	(.60)	1.00	(1.50)
1 1/2"	(40)	1.900	(48.2)	.145	(3.7)	.50	(.70)	1.40	(2.00)
2"	(50)	2.375	(60.3)	.154	(3.9)	.60	(.90)	2.00	(3.00)
2 1/2"	(65)	2.875	(73.0)	.203	(5.1)	1.00	(1.50)	3.10	(4.51)
3"	(80)	3.500	(88.9)	.216	(5.5)	1.30	(2.00)	4.50	(6.70)
3 1/2"	(90)	4.000	(101.6)	.226	(5.7)	1.60	(2.40)	5.90	(8.70)
4"	(100)	4.500	(114.3)	.237	(6.0)	1.90	(2.80)	7.40	(11.00)
5"	(125)	5.563	(141.3)	.258	(6.5)	2.80	(4.10)	11.40	(17.00)
6"	(150)	6.625	(168.3)	.280	(7.1)	3.30	(4.90)	15.40	(23.00)
8"	(200)	8.625	(219.1)	.322	(8.2)	5.30	(7.80)	26.90	(39.90)
10"	(250)	10.750	(273.0)	.366	(9.3)	7.50	(11.10)	41.60	(61.80)
12"	(300)	12.750	(323.8)	.406	(10.3)	10.00	(14.90)	58.50	(87.00)

X. CONCLUSION

This paper has reviewed the water pipeline leakage detection techniques and categorized them into software-based, hardware-based and conventional methods. A software-based method uses various types of computer software to analyze the measured data from internal pipeline parameters, such as pressure, flow rate and temperature. Meanwhile, a hardware-based method detects leaks by visual observation or using right measurement equipment. On the other hand, a conventional method or traditional method relies on experienced personal walking along the pipeline and looking for unusual patterns of odor or noise near the pipeline. Prior to the hardware-based group, specifications on water pipeline testbeds and vibration sensors used for plastic water pipeline have been also discussed in the paper. Various vibration sensors have been compared in terms of number of axis, sensitivity, power consumption, data output, cost and accuracy in identifying the pipe leaks. In addition to that, the theoretical computation of the vibration induced from our water pipeline testbed has been presented. The vibration data collected from the experimental work using MPU6050, MMA7361 and ADXL335 have been validated with the computed vibration. Future work is to propose procedures for water pipeline leakage using three-axis vibration sensor

APPENDIX A

See Table 8.

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