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Analysis and Procedures for Water Pipeline Leakage Using Three-Axis Accelerometer Sensors: ADXL335 and MMA7361

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ABSTRACT Previous studies have proposed vibration of the water pipeline using accelerometer sensors as a mechanism to detect leaks. Nevertheless, they only relied on a single x-axis data, no single study investigates all the axes of the sensors. Therefore, this paper aims to investigate a vibration technique to detect leakage on plastic water pipeline using wireless accelerometer sensors, namely, 6DOF accelerometer sensor (i.e., MPU6050) and breakout accelerometer sensors (i.e., ADXL335 and MMA7361) across the x-, y-, and z-axis. A 25-mm diameter of acrylonitrile butadiene styrene (ABS) pipe with a length of approximately 10 m was developed as the water pipeline testbed. All of the accelerometer sensors measured the vibration on the water pipeline across the x-, y-, and z-axis, over ZigBee networks. The vibration signals were then compared between the three sensors and analyzed by extracting the signal features in time and frequency domains. The sensors were examined based on three different cases, which are no pipe leakage, a 1-mm leak, and a 3-mm leak. All three sensors demonstrated a significant difference between no leak and leak conditions when the water pressure is in the range of 0.6–1.2 kgf/cm^2 for both time and frequency domains. For different leak size cases, ADXL335 can distinguish the 1-mm and 3-mm holes from the three-axis data. On the contrary, MPU6050 can identify similar leak size cases only from the y- and z-axis data. Overall, ADXL335 has the best performance compared with MPU6050 and MMA7361 in detecting water pipeline leakage, which includes the sizes of the leaks. Based on the empirical results, this paper finally proposes a procedure analysis for each sensor on improving the accuracy of water pipeline leakage detection.

INDEX TERMS Leakage detection, vibration leakage detection, accelerometer, three axes, x-axis, y-axis, z-axis, MPU6050, ADXL335 and MMA7361.

I. INTRODUCTION

The water industries in many countries have been identified with the problem of limited water resources, and counter measures are taken to foster better water management system [1]. These efforts come from an effective water utilisation, reduction of wastage and control policies to realise management strategies. Water loss from the main distribution system is remained as one of the main issues facing not only by the developing country and also by the developed country around the world. Old pipes are one of the main factors to the water loss as water transmission and distribution networks continue to deteriorate with time [2]. Water treatment processes that produce clean water for human consumption are expensive, and it is in the government's interest to maintain a pipeline system that prevents the generation of non-revenue water (NRW). NRW is observed when the amount of water produced by the water treatment centre is higher than the amount of water recorded in metered bills [3], [4].

In modern society, pipeline networks are essential for transporting water from one destination to another area, particularly rural. Somehow, leaks may occur due to aging pipelines, corrosion, and excessive pressure resulting from operational error and the rapid closing or opening of valves [5]. To prevent future water losses, many techniques have been proposed with different applications to detect leaks in the pipeline system or network. Systematic leakage control has two main components: i) water audits and ii) leak detection surveys. Water audits measure the volume of water that moves in and out of a water pipeline system and can be used to identify which segments and portions of the water pipeline network are leaking. However, water audits do not provide any information about the exact location of leaks in the pipeline system. A leak detection survey must be conducted to identify the sizes and the locations of the leaks. Generally, the costs associated with the leakage include i) pumping, treating and transporting clean water, which results in significant economic losses; ii) reductions in pipeline pressure, 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 [4].

Most researchers [6]–[9] used the vibration data to determine the location of the leak point on the water pipeline system. Two vibration sensors are positioned on the water pipeline and a cross correlation method is used to identify the location of the leaks. Nevertheless, previous studies [6]–[9] have not applied the vibration technique to detect the conditions of the water pipeline and the sizes of the leaks. They only used the internal water pressure data to determine the conditions of the water pipeline whether leakage or no leakage. Until recently, there has been limited evidence that the vibration sensor can be used to identify the conditions of the water pipeline and the sizes of the leaks using three-axis. As of date, previous studies [6]–[9] have only examined the single axis to identify the location of the leaks, which is the x-axis is paralleled with the water pipeline and water flow in the pipeline.

The study is an extension of our previous works by analysing the vibration signal from the accelerometer sensor was attached outside the pipeline that effects three axes (x-, y- and z-axis) is crucial to predicting the leakage, leaks sizes and proposed procedure analysis on the water plastic pipeline, which focused on one type of accelerometer sensor, MPU6050. However, much uncertainty still exists about other three-axis accelerometer sensors. Thus, this research paper aims to propose procedure analysis for plastic water pipeline leakage detection using sensors, namely ADXL335 and MMA7361. The first research objective is to develop three-axis accelerometer sensors and the data will be collected over wireless ZigBee networks. Secondly, to compare and evaluate the performance of three-axis accelerometer sensors by extracting their signals in time and frequency domains. Based on the results, a procedure is proposed for ADXL335 and MMA7361 on identifying the conditions of the plastic water pipeline including the size of leaks. Since previous studies [6]–[9] only focused on the x-axis vibration and MMA7361 accelerometer sensor, the present study makes several contributions in the water pipeline leakage detection work as follows

- Performance comparison and analysis for different types of accelerometer sensors, namely MPU6050, ADXL335 and MMA7361 subject to the extraction of x-, y- and z-axis data using time- and frequency-domains
- New procedures analysis using three axes are proposed for ADXL335 and MMA7361 on improving the detection of leaks with regards to the empirical findings

This paper is organised in eight sections. Section I discusses the introduction of the water pipeline leakage and the problem statement, objective and contribution of the paper. Leakage detection techniques are reviewed in Section II. Section III discusses the system design and architecture for three accelerometer sensors such as MPU6050, ADXL335 and MMA7361. Then, the experiment setup for data collection from water pipeline testbed system is explained in the Section IV. Section V discusses the result and analysis from three accelerometer sensors in detection leakage on the water pipeline with three condition, which are no leaks and leaks (1- and 3-mm) condition. Meanwhile, the proposed procedure for three accelerometer sensors such as MPU6050, ADXL335 and MMA7361 is discussed in Section VI. The conclusion of the review of vibration detection methods for water pipeline leakage in Section VII. Section VIII discusses the recommendations for future work.

II. REVIEW PREVIOUS WORK

The current methods for water pipeline leakage detection system can be broadly categorised into three large groups: software-based methods, conventional biological methods and hardware-based methods. Software-based methods use various types of computer software to analyse and detect leaks in pipeline systems. This method is used to measure internal pipeline parameters, including pressure [10], flow rate [11]–[14] and temperature [10], [15], [16]. Conventional methods require experienced personnel who walk along a pipeline and look for unusual patterns near the pipeline based on odours 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 and time-consuming or suitable only for limited pipeline segments [17]. 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 [18].

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 [19]. 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 [20], because soft pipes are more 'elastic' and reduce sound waves by 300-600 m/sec. Due to their viscoelastic properties, plastic pipes also absorb sound energy (weakening the sound waves). However, the high-frequency noise increases when the sound waves travel along the water pipeline system. Analysing these noise signals will make this process more complicated [21]. The accuracy of leakage detection is also affected by the presence of air in the pipeline system. To improve the limitations of the acoustic method for a plastic pipeline system, the vibration method is used to detect and locate leaks. When acoustic and vibration methods are compared for a real plastic water pipeline, the vibration sensor is the most accurate sensor in detecting and locating leaks [7]. A cross-correlation analysis is used to analyse acoustic and vibration data to detect and locate leaks [7].

III. SYSTEM DESIGN AND ARCHITECTURE

This section discusses on a system design and architecture of the water pipeline testbed used in this research. The hardware development is explained, which includes system design and architecture, 6DOF sensor - MPU6050, breakout XYZ accelerometer sensors - ADXL335 and MMA7361, a sensor node, ZigBee pro wireless module and a development of wireless sensor node. The development of the testbed system comprises of Acrylonitrille Butadience Styrene (ABS) pipe, pressure transducer, flow rate sensor, water pump and two manual valves. A software development in the sensor node with two different techniques is described, which are serial (I^2C) and analogue acceleration data reading between the accelerometer sensor and Arduino controller board. A procedure on sensor node design and development is explained. The experiment setup is discussed to measure the vibration signal from the pipeline system under three different states, namely inertial, normal and abnormal. An inertial condition is a noise signal generated by the water pump and outlet manual valves. Meanwhile, the normal and abnormal conditions are for no leaks and leaks cases, respectively.

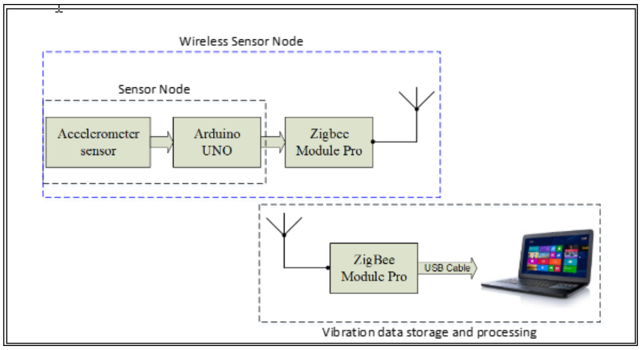
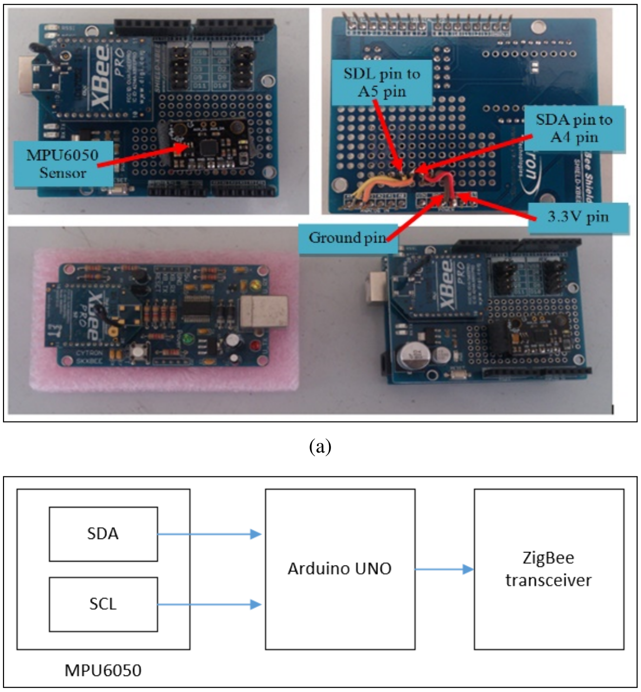


FIGURE 1. A block diagram of the wireless sensor system [22]–[25].

A block diagram of the wireless sensor system used in this study is illustrated in Fig. 1. Three main components, namely, accelerometer sensors, Arduino UNO controller board, ZigBee module are employed in the water pipeline testbed. The sensor nodes are developed with accelerometer sensor and Arduino UNO controller board. The wireless sensor node is connected to ZigBee wireless transceiver for sending vibration data through wireless to a storage and processing unit.

Three different accelerometer sensors, namely, MPU6050, ADXL335 and MMA7361 are investigated in measuring the vibration of the water pipeline systems (i.e. testbed). The vibration signal from the accelerometer sensor is converted from a vibration signal to an electronic signal, which are digital (6DOF SENSOR - MPU6050) and analogue (ADXL335 and MMA7361). The data from the sensor is processed by Arduino UNO from analogue to digital signals before the data is sent to the ZigBee wireless transceiver module. The ZigBee wireless transceiver sends the vibration data to the data storage and processing unit. The processing software, which is MATLAB, is used to analyse the vibration data offline.



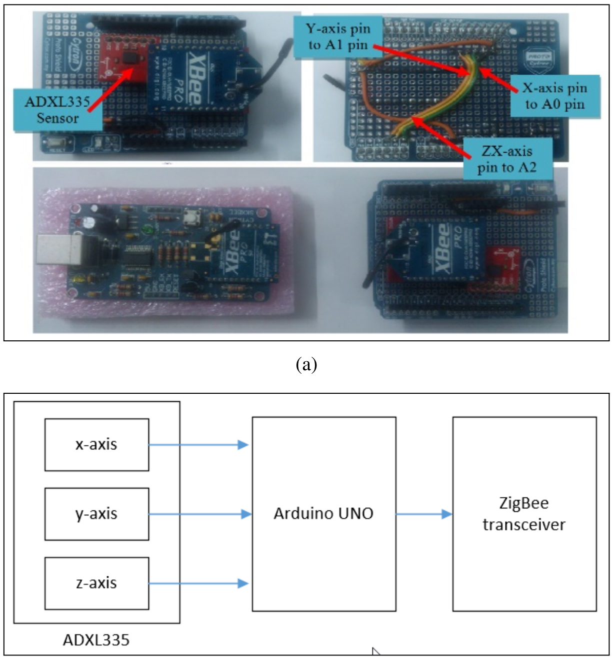
(a)

(b)

FIGURE 2. MPU6050 sensor node [23]. (a) The wiring of the MPU6050 sensor to the Arduino ZigBee prototype shield. (b) A Block diagram of the MPU6050 wireless sensor Node.

A wireless sensor node consists of three main modules, which are Arduino controller board, accelerometer sensors and ZigBee transceiver, as depicted in Fig. 2(b). The wiring of the MPU6050, ADXL335 and MMA7361 sensors to the Arduino ZigBee prototype sensor is depicted in Fig. 2(a) to 2(b), 3(a) to 3(b) and 4(a) to 4(b) respectively.

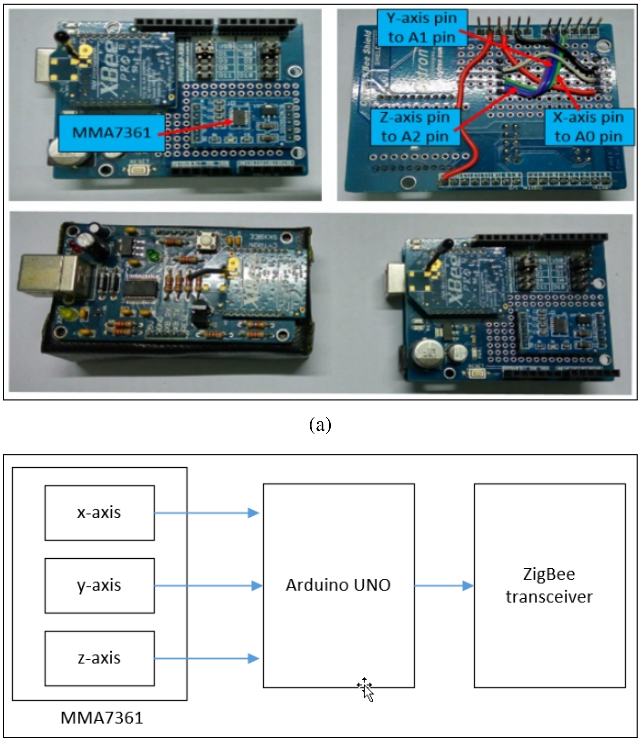
Fig. 5 shows the flow chart of the water pipeline system development. The initial step is to study the specification of the 6DOF sensor - MPU6050 and breakout triple axis



(a)

(b)

FIGURE 3. **ADXL335 sensor node. (a) The wiring of the ADXL335 sensor to the Arduino ZigBee prototype shield. (b) A Block diagram of the ADXL335 wireless sensor Node.**



(a)

(b)

FIGURE 4. **MMA7361 sensor node. (a) The wiring of the MMA7361 sensor to the Arduino ZigBee prototype shield. (b) A Block diagram of the MMA7361 wireless sensor Node.**

accelerometer sensor - ADXL335, particularly for the vibration data reading from the sensors. The sensor transmits the vibration data from the accelerometer via ZigBee networks. The programming in the Arduino controller board is set to a sensitivity of ±16g and ±20000/sec for the 6DOF sensor - MPU6050 sensor. Next, the sensor connection is designed on the Arduino ZigBee prototype board using fritzing software. Then, the connection on the Arduino ZigBee prototype board is connected. The Arduino UNO board is then programmed in order to access data from the sensor. After that, the sensor collects the vibration data and sends them to a laptop over ZigBee where the vibration data is recorded and analysed via Universal Serial Bus (USB) port. The vibration signals are analysed offline using time domain analysis and Fast Fourier Transform (FFT) for the conditions of the water pipeline system including the sizes of the leaks. The bandpass filter is applied to filter the noise frequency produced from the water pump and also from the initial vibration of the sensor.

IV. EXPERIMENT SETUP

The experiments are set up based on the fluid dynamics. The Bernoulli's principle states that for an inviscid flow of a non-conducting fluid which is an increased in the speed of the fluid occurs simultaneously with a decrease in pressure [26], [27]. Bernoulli's principle [28], [29] says that a rise of the pressure in a flowing fluid must always be accompanied by a decrease of the speed, and conversely, if an increase in the speed of the fluid resulted in a decrease in the pressure. The following sub section will explain the equipment and procedures used to conduct the experiments.

A. WATER PIPELINE TESTBED SYSTEM

The water pipeline monitoring testbed system is built to analyse the water pipeline stability. The measurement is to identify the normal pipe and also the leakage condition of the water pipeline system. The vibration data is collected on the pipeline system using the contact technique. Fig. 6 illustrates the system architecture of the water pipeline monitoring system used in this work. The prototype of the pipeline system includes the water pump, flow rate meter, pressure meter, leak pipes and two manual valves. The function of a water pump is to generate the water flow and the water pressure in the pipeline system. The water system is designed to recycle the water intake during the experiments conducted.

Fig. 7 show the overall water pipeline system. The water pump installed provides the maximum water flow of 24 litre/sec, and a maximum pressure of 1.6 kgf/cm^2 in the pipeline system. When all valves are fully opened, the condition is called as free flow condition; the pressure gauge is 0.1 kgf/cm^2. At this particular state, the water pressure is at the maximum of 24 litre/sec.

V. RESULTS AND ANALYSIS

This section validates the water pipeline testbed system used in this research via experimental and theoretical work. The validation between the experimental and theoretical data for MMA7361 is discussed. Due to experimental setup result, the testbed system is possible to use for experiment in identifying the conditions of the water pipeline including the

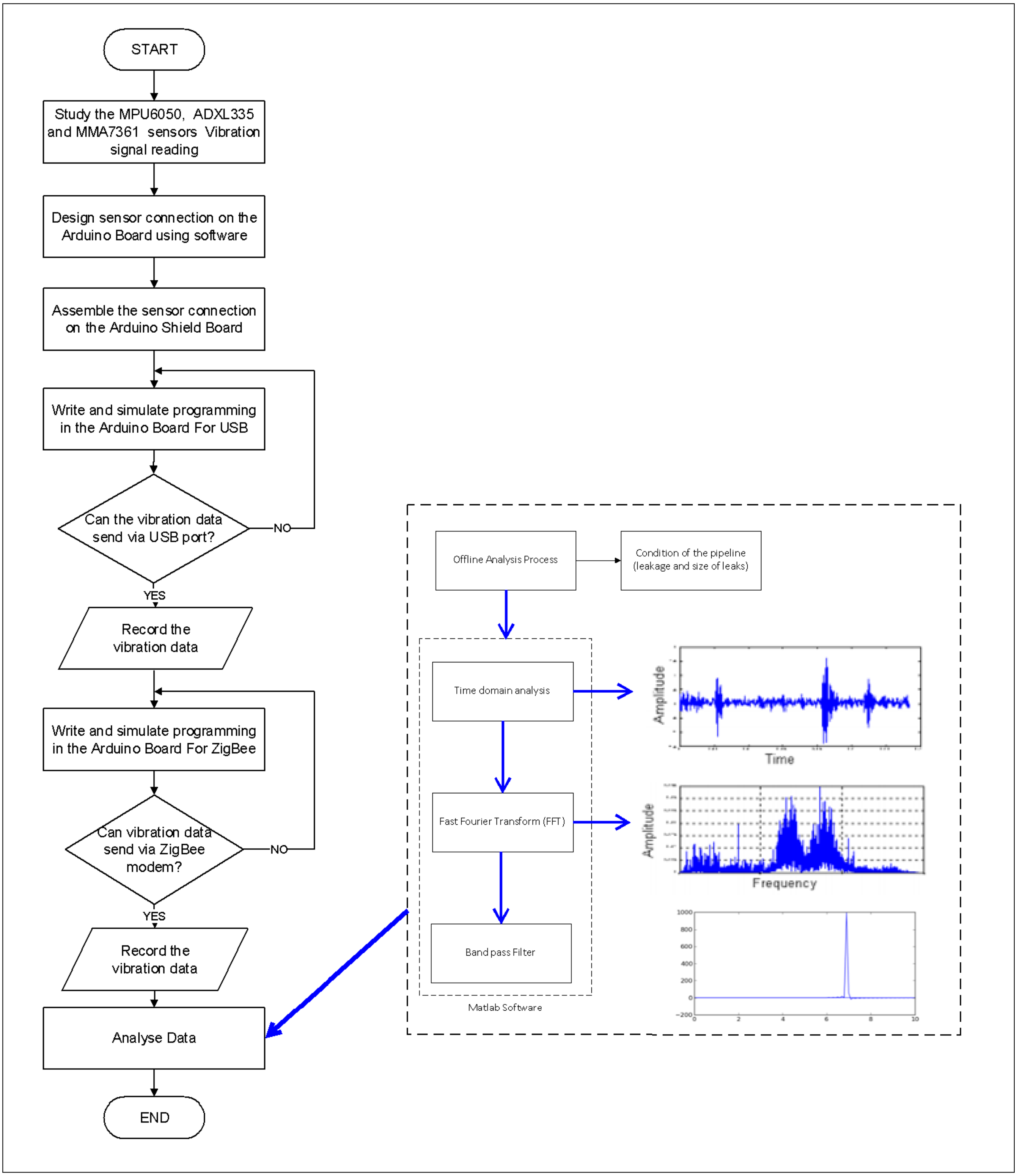


FIGURE 5. **Flow chart of the system development.**

sizes of the leaks. The result of the time domain analysis is discussed for several cases in relation to the water pipeline conditions. The purpose of the time domain analysis used in this study is to investigate the conditions of the pipeline, normal (no leak) or abnormal (1mm and 3mm leaks). The performance of the accelerometer sensors using fast Fourier

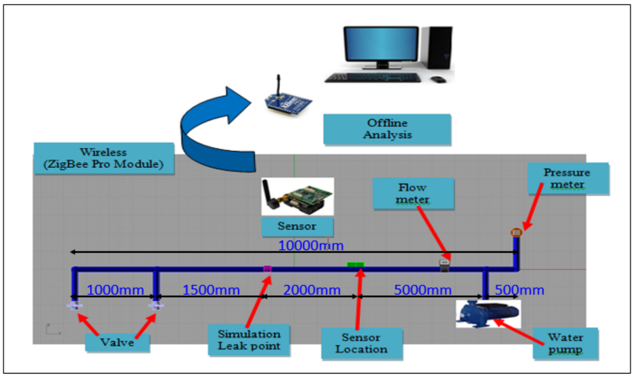


FIGURE 6. Water pipeline system architecture [22]–[25].

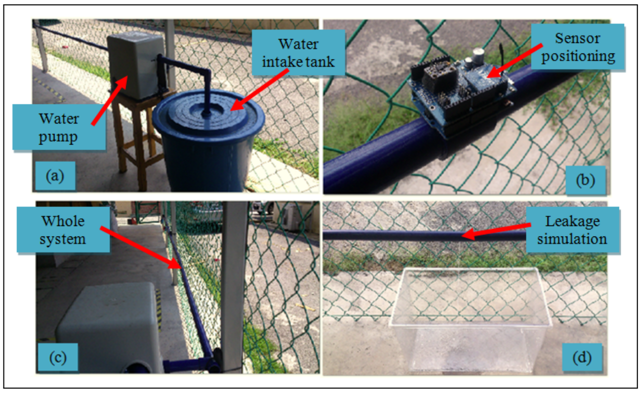


FIGURE 7. Water pipeline testbed system [22]–[25].

transform (FFT) in identifying the conditions of the water pipeline including the sizes of the leaks. On the other hand, the noise frequency is produced from the accelerometer sensors in initial condition, in which the testbed system is in OFF condition and the noise frequency produced from the water pump is investigated. The conditions of the pipeline of either normal (no leak) or abnormal (1mm and 3mm leaks) is investigated using time domain and fast Fourier transform (FFT) analysis. The performance analysis of the accelerometer sensor with different sizes of the leaks from three-axis which are x-, y- and z-axis are summarised in Tables 1 and 3.

A. TIME DOMAIN ANALYSIS

Fig. 8 to 10 illustrate the vibration data versus time for accelerometer sensors such as MPU6050, ADXL335 and MMA7361, respectively at x-, y- and z-axis. The vibration data is analysed by using time domain analysis in 30 second for all axis. Fig. 8 shows the vibration data of the MPU6050 accelerometer sensor with the average vibration for x-, y- and z-axis is 0.0208g, 0.0695g and 1.1351g. The standard deviation (STD) of the vibration data for the x-, y- and z-axis is 0.0733g, 0.1461g and 0.0834g. Due to the result, the y-axis shows the highest value of STD compare with x- and z-axis. The y-axis vibration data can significantly predict the leakage on the water pipeline system.

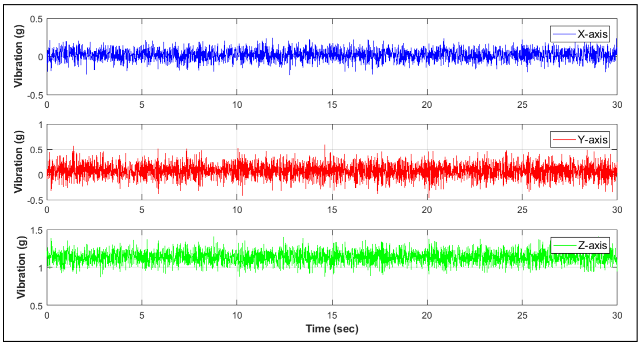


FIGURE 8. Average vibration (g) versus Time (sec) for x-, y- and z-axis by MPU6050.

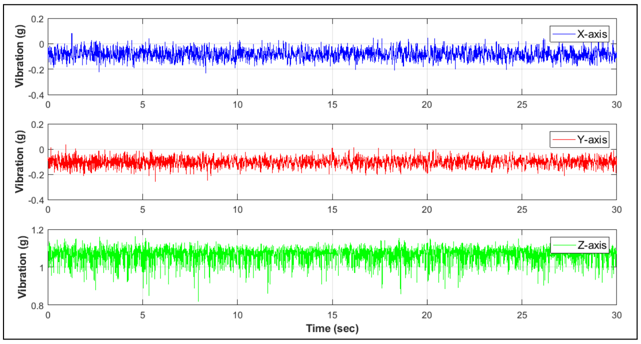


FIGURE 9. Average vibration (g) versus Time (sec) for x-, y- and z-axis by ADXL335.

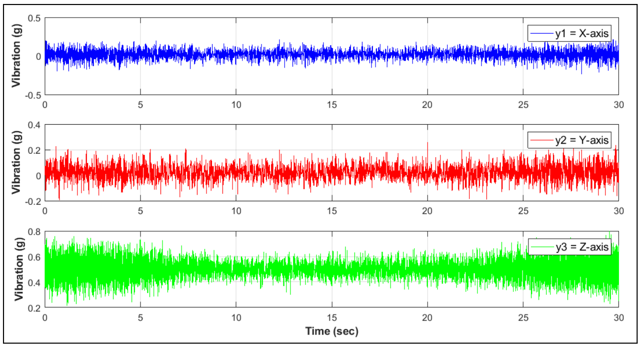


FIGURE 10. Average vibration (g) versus Time (sec) for x-, y- and z-axis by MMA7361.

Fig. 9 illustrates the vibration data from the ADXL335 accelerometer sensor with average vibration for x-, y- and z-axis is -0.0837g, -0.1033g and 1.0656g. The STD of the vibration data for the x-, y- and z-axis is 0.0419g, 0.0357g and 0.0425g. Based on the results, the STD of x- and z-axis is slightly different compared with y-axis. There is a slightly significant different between x- and z-axis. However, both x- and z-axis are significant different to y-axis vibration data.

Fig. 10 indicates the average of vibration data for x-, y- and z-axis from MMA7361 are -0.0396g, 0.0102g and 0.5000g. The STD of the vibration data for x-, y- and z-axis is 0.0764g, 0.0637g and 0.0971g, respectively. Due to the STD result, there is a significant difference between x-, y- and z-axis. MPU6050 demonstrates that y-axis is significant in detecting

TABLE 1. Summary of the water pipeline conditions for varing pressure (0.6 to 1.2 KGF/CM^2) at 1.5M.

Sensors	X-Axis				Y-Axis				Z-Axis			
	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2
MPU6050	L1>NL	L1>NL	L1>NL	L1>NL	L1<NL	L1>NL	L1<NL	L1<NL	L1>NL	L1>NL	L1>NL	L1>NL
	L3>NL	L3>NL	L3>NL	L3>NL	L3<NL	L3<NL	L3<NL	L3<NL	L3>NL	L3>NL	L3>NL	L3>NL
	L3>L1	L3>L1	L3<L1	L3>L1	L3<L1	L3<L1	L3>L1	L3<L1	L3<L1	L3<L1	L3>L1	L3<L1
ADXL335	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL	L1>NL
	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL
	L3>L1	L3>L1	L3<L1	L3<L1	L3>L1	L3>L1	L3<L1	L3>L1	L3>L1	L3>L1	L3>L1	L3<L1
MMA7361	L1>NL	L1<NL	L1<NL	L1>NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL
	L3>NL	L3<NL	L3>NL	L3<NL	L3>NL	L3>NL	L3>NL	L3>NL	L3<NL	L3>NL	L3>NL	L3>NL
	L3>L1	L3>L1	L3>L1	L3<L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1

the conditions of the water pipeline and not for ADXL335 and MMA7361.

Table 1 summarises the key findings of the three accelerometer sensors across all pressure for different axes at 1.5 m. The cases of no leak, 1 mm and 3 mm leaks are represented as NL, L1 and L3 in the table when comparing with the Bernoulli principle, respectively. The grey and white boxes indicate the true and false results. The average vibration data was analysed and calculated from three thousands of vibration data. Ideally, the average vibration of leak must be higher than that of no leak [22], [30], [31].

Based on Table 1, the ADXL335 can significantly distinguish the conditions of the water pipeline and the sizes the leaks across all axes for the varying pressure. On the other hand, the MPU6050 sensor is only able to identify the conditions of the water pipeline including the sizes of the leaks at x- and z-axis; not for y-axis. However, the MMA7361 sensor is able to identify the conditions of the water pipeline only when the size of the leak is 3 mm for both y- and z-axis. It is difficult for the MMA7361 sensor to differentiate the sizes of the leaks when the pipeline in burst condition except for low water pressure, 0.6 kgf/cm^2 and x-axis.

Based on the findings, the best performance of the accelerometer sensor in detecting the condition of the water pipeline (either no leak or leaks) including the sizes of the leaks (either leak 1-mm or 3-mm) across all axes is ADXL335 using the time domain analysis.

B. FAST FOURIER TRANSFORM (FFT) ANALYSIS

Next, the study will investigate the vibration data using Fast Fourier Transform (FFT) analysis to identify the conditions of the water pipeline system, which includes the sizes of the leaks. Firstly, the vibration data will be analysed to differentiate the noise frequencies of accelerometer sensor, water pump and output ball valve. Secondly, the FFT analysis will be discussed subject to the conditions of water pipeline as well as the leaking sizes.

1) ACCELEROMETER SENSOR NODE FREQUENCY

Fig. 11 to 13 illustrates the vibration frequency at the initial condition for all the sensors across x-, y- and z-axis. The initial condition is known as the noise frequency in this study. The purpose of identifying the initial noise frequency is to filter out the unwanted signal frequency, which is produced from the accelerometer sensor itself. All sensors have demonstrated identical noise frequency, which is 23.4 Hz across all axes, as marked in the Fig. 11 to 13.

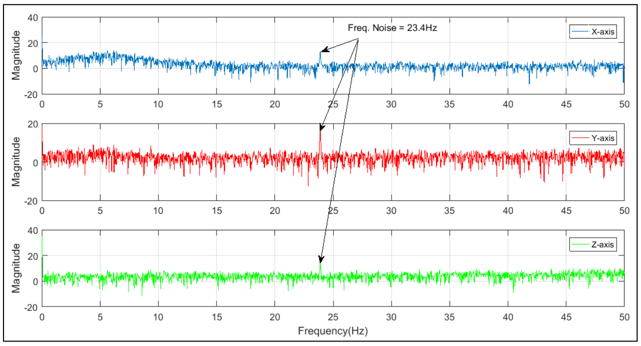


FIGURE 11. FFT analysis for initial vibration data MPU6050 sensor.

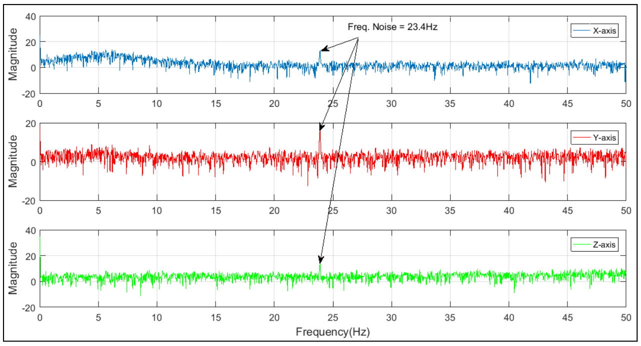
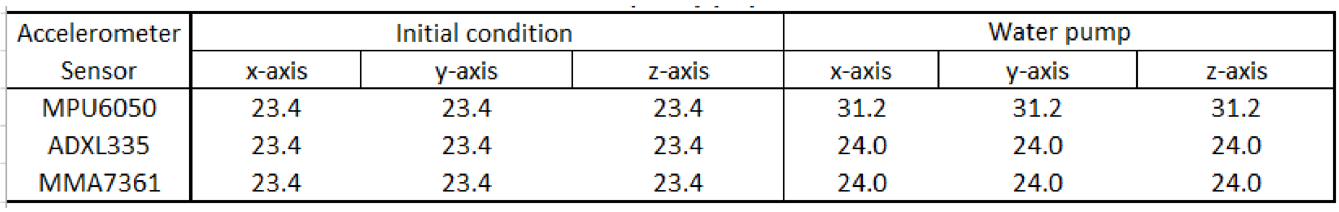


FIGURE 12. FFT analysis for initial vibration data ADXL335 sensor.

2) WATER PUMP FREQUENCY

The vibration data of the water pump is measured to identify the noise frequency for the water pump. The vibration data is collected by attaching the accelerometer sensors at the water pump motor. Fig. 14 to 16 presents the Fast Fourier Transform (FFT) analysis for the vibration data of water pump for

TABLE 2. The frequencies in Hz of the initial condition for the accelerometer sensors and the noise frequencies for the water pump.



Accelerometer Sensor	Initial condition			Water pump		
	x-axis	y-axis	z-axis	x-axis	y-axis	z-axis
MPU6050	23.4	23.4	23.4	31.2	31.2	31.2
ADXL335	23.4	23.4	23.4	24.0	24.0	24.0
MMA7361	23.4	23.4	23.4	24.0	24.0	24.0

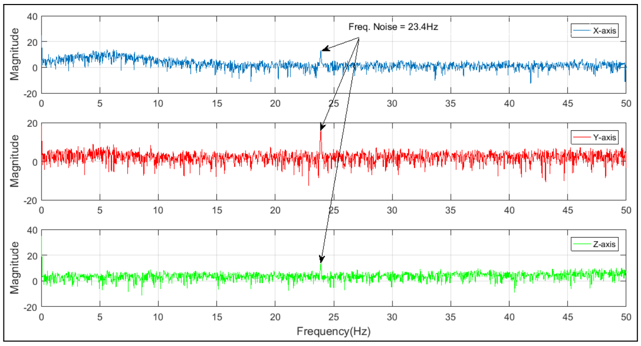


FIGURE 13. FFT analysis for initial vibration data MMMA7361 sensor.

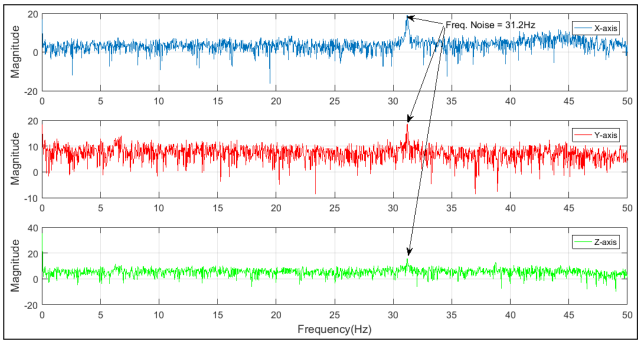


FIGURE 14. FFT analysis for water pump vibration data MPU6050 sensor.

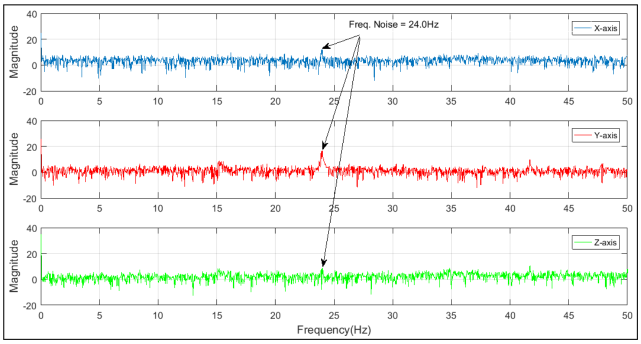


FIGURE 15. FFT analysis for water pump vibration data ADXL335 sensor.

MPU6050, ADXL335 and MMA7361, respectively. Based on this figure, the noise frequency found is 31.2 Hz for MPU6050 while 24.0 Hz for both ADXL335 and MMA7361.

The initial frequency is measured for identifying the noise frequency produced from the water pump. This noise frequency is filtered from the FFT analysis and only shows the corresponding leakage frequency. Table 2 summarises the frequencies of the initial condition of the accelerometer sensors and the noise frequency for the water pump. The initial condition frequency for all the sensors at three different axes is found identical, which is 23.4 Hz. This is more likely because all the three sensors used the same Arduino ZigBee shield and the same power supply. On the contrary, the MPU6050 sensor has greater noise frequency for the water pump than ADXL335 and MMA7361 sensors, as can be seen in Table 2. This is likely due to the MPU6050 sensor produces the acceleration data in a serial data transmission ($I^2\ C$) to Arduino UNO. On the other hand, the ADXL335 and MMA7361 sensors produce the acceleration data in analogue and hence the Arduino UNO converted the analogue signal to digital before transmitting it to data storage.

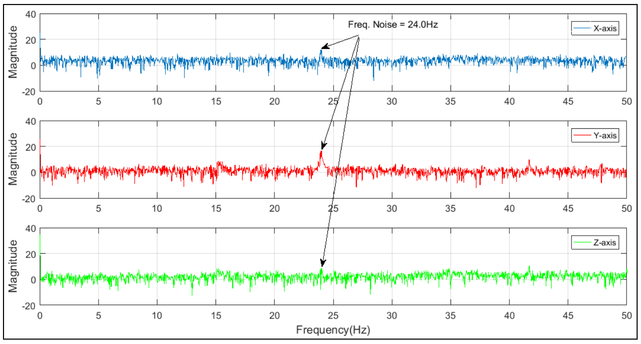


FIGURE 16. FFT analysis for water pump vibration data MMMA7361 sensor.

Table 3 summarises the key findings of the three accelerometer sensors based on the FFT analysis for several water pressures across all axes at 1.5 m. The terms NL, L1 and L3 represent no leak, 1-mm and 3-mm leaks, respectively. The grey and white boxes indicate the true and false results, that are in agreement with [32]–[35]. The important test in this study is whether the three acceleration sensors can identify the sizes of the leaks on the water pipeline testbed. Based on the frequencies, MMA7361 can identify the conditions of the water pipeline and only the 3-mm leak (not 1-mm leak) across all axes and water pressure. However, MMA7361 can only differentiate the 1-mm and 3-mm leaks when the water pressure is 1.2 kgf/cm^2 and not for other water pressure level.

TABLE 3. A summary of the water pipeline conditions at 1.5 M for the water pressure between 0.6 to 1.2 KGF/CM^2.

Sensors	X-Axis				Y-Axis				Z-Axis			
	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2
MPU6050	L1>NL	L1<NL	L1>NL	L1<NL	L1>NL	L1<NL	L1>NL	L1<NL	L1>NL	L1<NL	L1>NL	L1<NL
	L3>NL	L3<NL	L3>NL	L3<NL	L3>NL	L3<NL	L3>NL	L3<NL	L3>NL	L3<NL	L3>NL	L3<NL
	L3>L1	L3<L1	L3>L1	L3=L1	L3>L1	L3>L1	L3>L1	L3=L1	L3>L1	L3<L1	L3>L1	L3<L1
ADXL335	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL	L1<NL
	L3<NL	L3<NL	L3<NL	L3=NL	L3<NL	L3<NL	L3<NL	L3<NL	L3<NL	L3<NL	L3<NL	L3<NL
	L3=L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3<L1	L3>L1	L3>L1	L3>L1
MMA7361	L1=NL	L1<NL	L1<NL	L1>NL	L1>NL	L1<NL	L1<NL	L1>NL	L1=NL	L1<NL	L1<NL	L1>NL
	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL	L3>NL
	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1	L3>L1

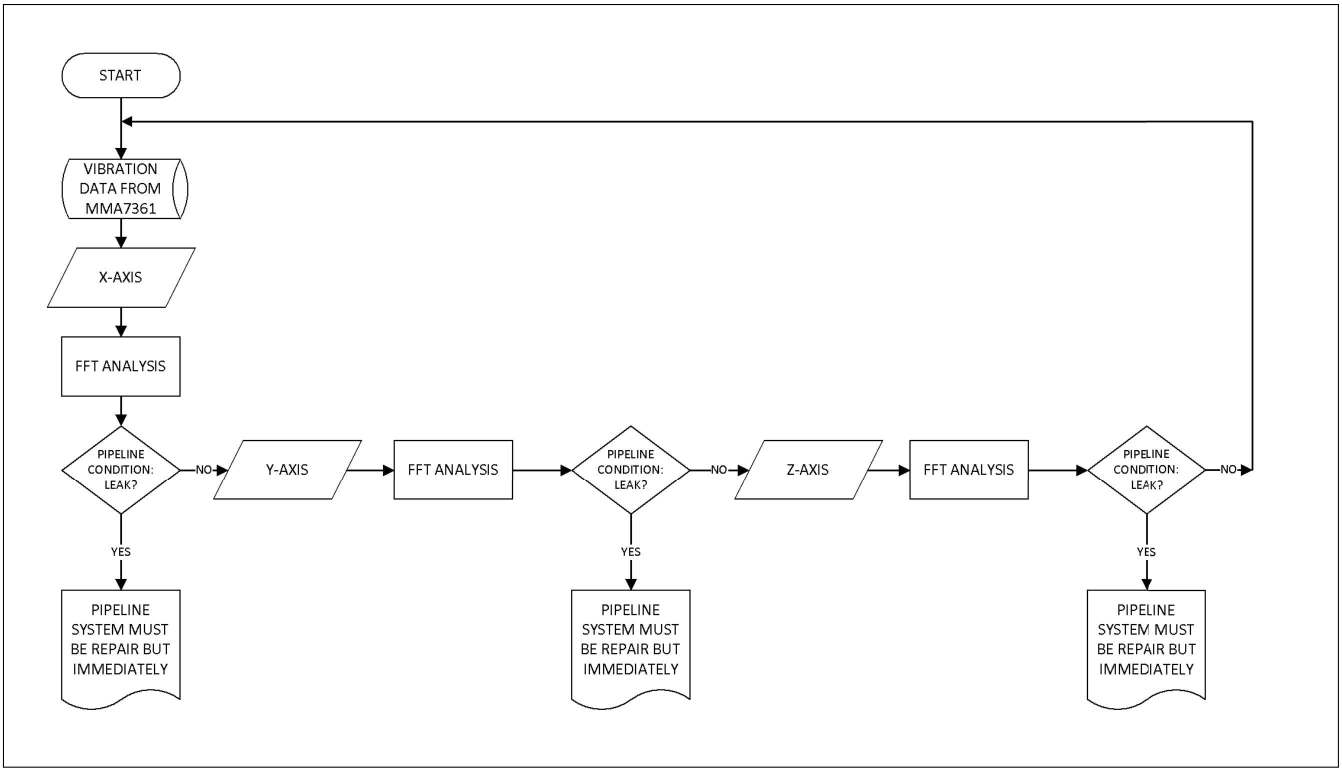


FIGURE 17. A proposed procedure of water pipeline leakage detection for MMA7361.

Meanwhile, MPU6050 have difficulties to identify the conditions of the water pipelines and the sizes of the leaks at water pressure above 0.8 kgf/cm^2, but not at the water pressure of 0.6 kgf/cm^2. On the contrary, the ADXL335 sensor has shown inconsistent trend in recognising the normal and abnormal conditions for all axes and water pressure. This is probably because the limitation on the sensitivity specification of the sensor, which is lower compared to both MPU6050 and MMA7361.

For MMA7361, the conditions of the water pipeline system can only be determined when the leaking size is greater than 3mm across all axes and distance. Nevertheless, the conditions of the water pipeline including all the leaking sizes (i.e. 1mm and 3mm) can only be detected for the shortest distance of 0.5m. Table 3 demonstrates that ADXL335 is not feasible to identify the conditions of the water pipeline for all the experiment settings when the FFT analysis is applied. However, the ADXL outperforms others in the time domain analysis.

VI. PROPOSED PROCEDURE ANALYSIS

This section will propose the procedure analysis to distinguish the conditions of the water pipeline and the sizes of the leaks across three-axis ffor all the measured sensors.

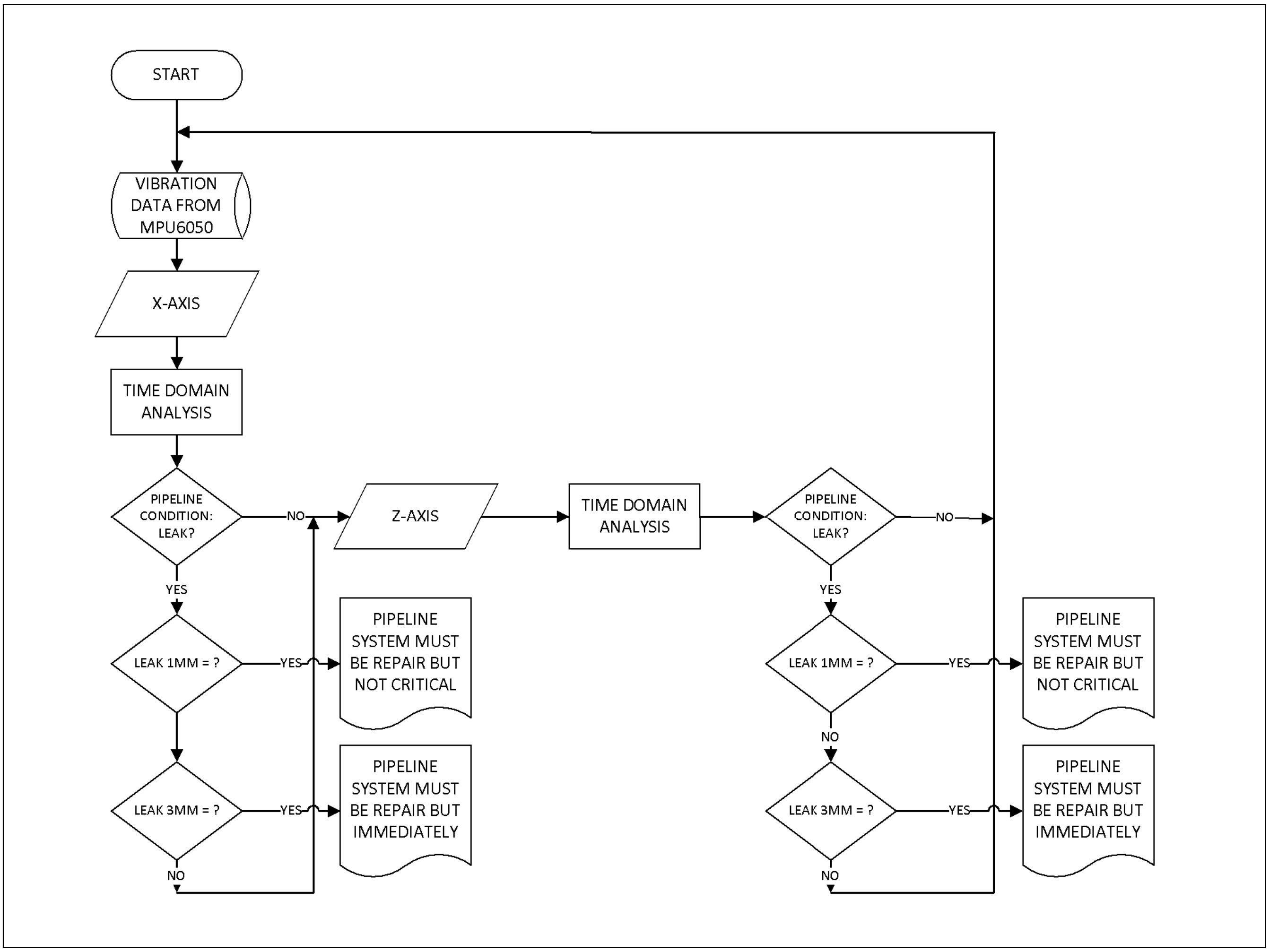


FIGURE 18. A proposed procedure of water pipeline leakage detection for MPU6050 [23].

Based on the results in Table 3, MMA7361 can identify the conditions of the water pipeline using FFT analysis across all pressure and axes when the size of the leak is 3-mm. However, all the leaks can be identified when the water pressure is 1.2 kgf/cm^2 across all axes.

Fig. 17 demonstrates a proposed procedure analysis to identify the conditions of the water pipeline and the sizes of the leaks for MMA7361 using FFT analysis. Firstly, the vibration data from all the axes of MMA7361 are collected and transmitted. Secondly, the FFT analysis is used to identify the conditions of the water pipeline from the x-axis data when the leaking size is greater than 3-mm. If the leakage of the water pipeline is detected, the pipeline must be repaired immediately because the leaking size is greater than 3-mm. If the x-axis data is unsatisfactory to detect the conditions of the water pipeline, the y- and z-axis will be analysed respectively to detect the conditions and the sizes of the leaks.

Next, the proposed procedure analysis for MPU6050 is using time domain analysis. Based on the results in Table 1, the conditions of the water pipeline system can be identified across all pressure using two axes (i.e. x- and z-axis). The vibration data at x-axis can identify the sizes of the leaks at all pressure except for 1.0 kgf/cm^2. Nevertheless, the z-axis can identify this circumstances at 1.0 kgf/cm^2. Surprisingly, the y-axis has a difficulty to differentiate the conditions of the water pipeline as well as the sizes of the leaks for all water pressure except for 0.6 kgf/cm^2. Due to this fact, the procedure is designed only for x- and z-axis.

Based on the key findings in this study, a proposed procedure analysis for the identification of the conditions of the water pipeline and the sizes of the leaks for MPU6050 using time domain analysis is shown in Fig. 18. Firstly, the vibration data for x- and z-axis of MPU6050 are collected and transmitted. Secondly, time domain analysis is used to identify the conditions of the water pipeline from the x-axis data. Thirdly, if the conditions of the water pipeline can be detected, the sizes of the leaks will be differentiated whether it is a 1-mm or 3-mm leaks. If the size of the leak is 3-mm, then the pipeline must be repaired immediately. If the x-axis

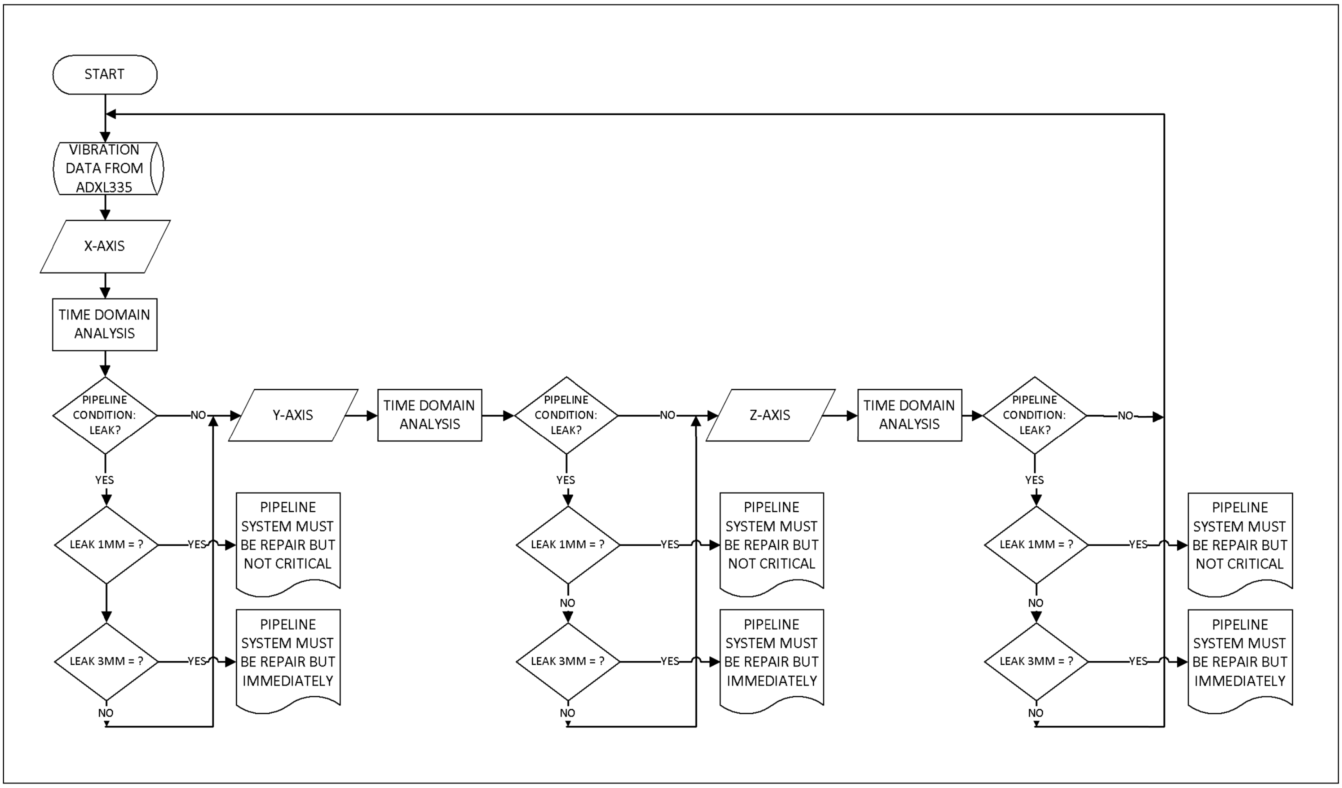


FIGURE 19. **A proposed procedure of water pipeline leakage detection for ADXL335.**

is unsatisfactory to detect the conditions of the water pipeline, the z-axis will be analysed further using the time domain analysis.

Also, the proposed procedure analysis for ADXL335 is using time domain analysis. Based on the results in Table 1, the conditions of the water pipeline system can be identified at the water pressure from 0.6 kgf/cm^2 to 1.2 kgf/cm^2 across all axes. However, the vibration data at x-axis is able to determine the sizes of the leaks for the water pressure between 0.6 kgf/cm^2 and 0.8 kgf/cm^2. Meanwhile, the y-axis can distinguish the sizes of the leaks for all water pressure except for 1.0 kgf/cm^2. On the other hand, the z-axis can only recognise the leaks when the water pressure is below 1.0 kgf/cm^2. The axes can detect the leaks at different water pressure, by considering the vibration data from all the three-axis which can increase the accuracy on detecting the severity of the leaks.

Based on the research findings, Fig. 19 illustrates a proposed procedure analysis for the identification of the water pipeline conditions and the sizes of the leaks for ADXL335 using time domain analysis. Firstly, the vibration data from all the three-axis are collected and transmitted. Secondly, the x-axis vibration data is analysed first using time domain analysis to investigate the conditions of the water pipeline. Thirdly, if the conditions of the water pipeline can be detected, the analysis will continue to differentiate the sizes of the leaks of either 1-mm or 3-mm. If the size of the leak is 3-mm, then the pipeline must be repaired immediately while for the 1-mm leak, the water company can schedule for repair and maintenance. If the x-axis data is unsatisfactory to detect the conditions of the water pipeline, the y- and z-axis will be analysed further. Based on the results, this process can be repeated every two minutes of data collection.

VII. CONCLUSION

The empirical findings in this study have provided new insight whereby more than one axis can increase the efficiency of the sensors, such as MPU6050, ADXL335 and MMA7361. This is because when the x-axis of vibration data is unable to identify the conditions of the PVC water pipeline, other axes can improve the accuracy of the detection. The primary finding in this paper is that the vibration method has made a contribution in distinguishing the sizes of the leaks, when the water pipelines is in abnormal conditions for 1mm and 3mm leaks. The study can increase the accuracy of the pipeline leakage detection with the proposed procedure analysis using accelerometer sensors at three different axes (x-, y- and z-axis). The work demonstrated that the ADXL335 sensor is able to identify the conditions of the water pipelines and the sizes of the leaks by using time domain analysis at water pressure varied from 0.6 to 1.2 kgf/cm^2 for all axes. Meanwhile, the MPU6050 sensor can recognise the conditions of the water pipeline across only x- and z-axis, but not in y-axis, for the water pressure varied from 0.6 to 1.2 kgf/cm^2.

In addition to that, the MPU6050 sensor seems failed to distinguish the cases of water pipeline leakage using FFT analysis regardless of any axis. In contrast, the MMA7361 sensor can be improved by using FFT analysis to identify the conditions of the water pipeline when the size of the leak was greater than 3-mm, but not for a small leak of 1-mm, for all the water pressure and axes. This study has demonstrated that analysis on the vibration data for more than one axis, can increase the performance of the accelerometer sensors specifically on examining the conditions of the water pipeline including the sizes of the leaks.

VIII. RECOMMENDATIONS FOR FUTURE WORK

This research has embarked on many questions for further investigation. It would be interesting to assess the effects of multi-sensors and real time analysis on identifying the conditions of the water pipeline, sizes of leaks and localisation of leaks. Multi-sensors include flowrate, inner and outer pressure, and accelerometer sensors can be integrated to monitor the water pipeline conditions. Meanwhile, wireless sensor network will transmit the collected data to a monitoring and decision system, which is known as Internet of Things (IoT). Further research can also concentrate on the investigation of real-time analysis by using fuzzy logic or Artificial Neural Network (ANN) from online server data. The online decision system will be able to alarm severe conditions of the pipeline and predict the location of the leaks in real-time. Therefore, the findings of this study have several important implications for future practices.

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REFERENCES

[1] R. McKenzie and C. Seago, "Assessment of real losses in potable water distribution systems: Some recent developments," *Water Sci. Technol. Water Supply*, vol. 5, no. 1, pp. 33–40, 2005.

[2] D. Misiūnas, "Failure monitoring and asset condition asssessment in water supply systems," in *Proc. 7th Int. Conf. Environ. Eng.*, no. 2, 2008, pp. 648–655.

[3] Suruhanjaya Perkhidmatan Air Negara. (2016). *Non Revenue Water (NRW)*. [Online]. Available: http://www.span.gov.my/index.php/en/statistic/water-statistic/non-revenue-water-nrw-2016

[4] I. Hasnul, M. Salleh, and N. A. Malek, "Non-revenue water, impact to the service, environment and financial," Ministry Energy, Green Technol. Water, Malaysia, Tech. Rep., 2010.

[5] M. F. Ghazali, S. B. M. Beck, J. D. Shucksmith, J. B. Boxall, and W. J. Staszewski, "Comparative study of instantaneous frequency based methods for leak detection in pipeline networks," *Mech. Syst. Signal Process.*, vol. 29, pp. 187–200, May 2012. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84859434235&partnerID=tZOtx3y1

[6] F. Almeida, M. Brennan, P. Joseph, S. Whitfield, S. Dray, and A. Paschoalini, "On the acoustic filtering of the pipe and sensor in a buried plastic water pipe and its effect on leak detection: An experimental investigation," *Sensors*, vol. 14, no. 3, pp. 5595–5610, Jan. 2014. [Online]. Available: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4004009&tool=pmcentrez&rendertype=abstract

[7] A. M. Sadeghioon, N. Metje, D. N. Chapman, and C. J. Anthony, "SmartPipes: Smart wireless sensor networks for leak detection in water pipelines," *J. Sens. Actuator Netw.*, vol. 3, no. 1, pp. 64–78, Feb. 2014. [Online]. Available: http://www.mdpi.com/2224-2708/3/1/64/htm

[8] H. Kakuta, K. Watanabe, and Y. Kurihara, "Development of vibration sensor with wide frequency range based on condenser microphone—Estimation system for flow rate in water pipes," vol. 6, no. 10, pp. 2267–2272, 2012. [Online]. Available: http://waset.org/publications/8417/

[9] M. Shinozuka, P. H. Chou, S. Kim, H. Kim, D. Karmakar, and F. Lu, "Non-invasive acceleration-based methodology for damage detection and assessment of water distribution system," *Smart Struct. Syst.*, vol. 6, no. 6, pp. 545–559, 2010.

[10] A. M. Sadeghioon, N. Metje, D. Chapman, and C. Anthony, "Water pipeline failure detection using distributed relative pressure and temperature measurements and anomaly detection algorithms," *Urban Water J.*, vol. 15, no. 4, pp. 287–295, Apr. 2018.

[11] A. Predescu, M. Mocanu, and C. Lupu, "Real time implementation of IoT structure for pumping stations in a water distribution system," in *Proc. IEEE 21st Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Oct. 2017, pp. 529–534.

[12] R. F. Rahmat, I. S. Satria, B. Siregar, and R. Budiarto, "Water pipeline monitoring and leak detection using flow liquid meter sensor," in *Proc. IOP Conf. Ser., Mater. Sci. Eng.*, vol. 190, Apr. 2017, p. 012036.

[13] K. B. Adedeji, Y. Hamam, B. T. Abe, and A. M. Abu-Mahfouz, "Leakage detection and estimation algorithm for loss reduction in water piping networks," *Water*, vol. 9, no. 10, p. 773, Oct. 2017.

[14] Q. Han, W. Zhu, and Y. Shi. (2017). "Leak event identification in water systems using high order CRF." [Online]. Available: https://arxiv.org/abs/1703.04170

[15] S. I. Jahnke, "Pipeline leak detection using *in-situ* soil temperature and strain measurements," M.S. thesis, Fac. Eng., Built-Environ. Inf. Technol., Univ. Pretoria, Pretoria, South Africa, Jan. 2018. [Online]. Available: https://www.up.ac.za/media/shared/124/ZP Resources /JahnkeMEng.pdf

[16] N. Giaquinto, A. Cataldo, G. M. D'Aucelli, E. De Benedetto, and G. Cannazza, "Water detection using bi-wires as sensing elements: Comparison between capacimetry-based and time-of-flight-based techniques," *IEEE Sensors J.*, vol. 16, no. 11, pp. 4309–4317, Jun. 2016.

[17] J. B. A. (KeTTHA). (2012). *Water Services Industry Performance Report 2011*. [Online]. Available: www.kettha.gov.my

[18] D. Covas, H. Ramos, and A. B. de Almeida, "Standing wave difference method for leak detection in pipeline systems," *J. Hydraulic Eng.*, vol. 134, no. 12, pp. 1029–1033, Jul. 2008. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-45749109354&partnerID=tZOtx3y1

[19] M. J. Brennan, Y. Gao, and P. F. Joseph, "On the relationship between time and frequency domain methods in time delay estimation for leak detection in water distribution pipes," *J. Sound Vib.*, vol. 304, nos. 1–2, pp. 213–223, Jul. 2007. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0022460X07001423

[20] M. Ferrante and B. Brunone, "Pipe system diagnosis and leak detection by unsteady-state tests. 2. Wavelet analysis," *Adv. Water Resour.*, vol. 26, no. 1, pp. 107–116, 2003.

[21] C. P. Liou, "Pipeline leak detection by impulse response extraction," *J. Fluids Eng.*, vol. 120, no. 4, pp. 833–838, 1998.

[22] M. Ismail, R. A. Dziyauddin, and N. A. A. Salleh, "Performance evaluation of wireless accelerometer sensor for water pipeline leakage," in *Proc. IEEE Int. Symp. Robot. Intell. Sensors (IRIS)*, Oct. 2015, pp. 120–125.

[23] M. I. M. Ismail, R. A. Dziyauddin, N. A. Ahmad, and N. Ahmad, "Vibration detection in water pipelines leakage using wireless three-axis accelerometer sensor," *Int. J. Adv. Sci. Technol.*, vol. 112, pp. 137–150, Mar. 2018.

[24] R. A. Dziyauddin, S. Usman, H. Abdullah, and M. I. M. Ismail, "TRIZ inventive solution in solving water pipeline leakage using accelerometer sensor," *J. Telecommun., Electron. Comput. Eng. (JTEC)*, vol. 10, nos. 1–9, pp. 173–177, 2018.

[25] M. I. M. Ismail, R. A. Dziyauddin, and N. A. A. Samad, "Water pipeline monitoring system using vibration sensor," in *Proc. IEEE Conf. Wireless Sensors (ICWiSE)*, Oct. 2014, pp. 79–84. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84946687641&partnerID=tZOtx3y1

[26] C. S. Jog, *Fluid Mechanics*. Cambridge, U.K.: Cambridge Univ. Press, 2015. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84952773873&partnerID=tZOtx3y1

[27] L. J. Clancy, *Aerodynamics*, 1st ed. Hoboken, NJ, USA: Wiley, 1975.

[28] H. Chanson, *Hydraulics of Open Channel Flow: An Introduction—Basic Principles, Sediment Motion, Hydraulic Modelling, Design of Hydraulic Structures*, 2nd ed. Oxford, U.K.: Butterworth-Heinemann, 2004.

[29] R. Mulley, *Flow of Industrial Fluids: Theory and Equations*. New York, NY, USA: Taylor & Francis, 2004.

[30] J. A. Liggett and L.-C. Chen, ''Inverse transient analysis in pipe networks,'' *J. Hydraulic Eng.*, vol. 120, no. 8, pp. 934–955, 1994.

[31] J. E. Hough, ''Leak testing of pipelines uses pressure and acoustic velocity,'' *Oil Gas J.*, vol. 86, p. 47, Nov. 1988. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-0024108071&partnerID=tZOtx3y1

[32] A. Martini, M. Troncossi, and A. Rivola, ''Automatic leak detection in buried plastic pipes of water supply networks by means of vibration measurements,'' *Shock Vib.*, vol. 2015, Jan. 2015, Art. no. 165304. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84937250311&partnerID=tZOtx3y1

[33] M. Rizwan and I. D. Paul, ''Leak detection in pipeline system based on flow induced vibration methodology in pipeline,'' *Int. J. Sci. Res.*, vol. 14, no. 4, pp. 3326–3330, 2015. [Online]. Available: http://www.ijsr.net

[34] M. M. Campagna, G. Dinardo, L. Fabbiano, and G. Vacca, ''Fluid flow measurements by means of vibration monitoring,'' *Meas. Sci. Technol.*, vol. 26, no. 11, p. 115306, Nov. 2015. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84946082911&partnerID=tZOtx3y1

[35] W. Kaewwaewnoi, A. Prateepasen, and P. Kaewtrakulpong, ''Investigation of the relationship between internal fluid leakage through a valve and the acoustic emission generated from the leakage,'' *Measurement*, vol. 43, no. 2, pp. 274–282, Feb. 2010. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-72149124209&partnerID=tZOtx3y1

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