Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Analyzing Instantaneous Frequency Characteristics of Various Features in Water Pipelines via the Hilbert Transform Method

Nor Azinee Said[1], Mohd Fairusham Ghazali[1,2,*], Mohd Fadhlan Mohd Yusof[1], Muhammad Aminuddin Pi Remli[1], Muhammad Hanafi Yusop[1]

[1] Advanced Structural Integrity and Vibration Research (ASIVR), Faculty of Mechanical and Automotive Engineering Technology, University Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[2] Centre for Research in Advanced Fluid & Processes, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia

ARTICLE INFO

Article history:
Received 13 August 2024
Received in revised form 10 December 2024
Accepted 18 December 2024
Available online 10 January 2025

Keywords:
Empirical Mode Decomposition (EMD); Hilbert Transform (HT); transient based method; pipe features; water pipelines

ABSTRACT

Non-revenue water (NRW), caused by water loss in distribution systems, poses a significant challenge to water utilities, particularly in developing nations. Addressing this issue is crucial for financial stability and operational efficiency. This research focuses on applying the empirical mode decomposition (EMD) with the Hilbert transform (HT) method for time-frequency analysis of transient pressure waves in pipeline systems. A transient signal is observed when there is a sudden change in pressure within a pipeline caused by a surge in pressure or the act of opening and closing a valve. The decomposition method is utilized to analyze the transient signal and eliminate the presence of noise that interferes with the signal. This paper presents an approach to investigate the behavior signal of different features in water pipelines. The proposed method combines empirical mode decomposition with Hilbert transform, offering an effective solution. In order to verify the efficacy of the EMD-HT presented in this paper, laboratory experimental tests were done on pipeline systems exhibiting various features, such as leakage, elbow, and junction. The finding shows that the proposed methodology can identify distinct characteristics of various pipe features in water pipelines.

1. Introduction

Non-revenue water (NRW) is the difference between the volume of water the system distributes and the volume billed to customer [1,2]. Physical and commercial losses represent two primary components of NRW. NRW also poses a significant challenge for water utilities in developing nations. This issue affects the financial viability of utilities due to income loss and higher operational expenditures [3]. According to a report published by the International Water Association (IWA) and the AWWA Water Loss Control Committee in 2003 [4], it has been estimated that in the United States, 5 billion kWh of power generated annually is attributed to water waste resulting from leakage or non-payment by customers. It is evident that a significant proportion of water, ranging from 25% to

---

[*] *Corresponding author.*
E-mail address: fairusham@umpsa.edu.my

https://doi.org/10.37934/arfmts.126.1.8697

50%, is lost due to leakages in the transmission process from treatment plants to consumers. Therefore, it is imperative to minimize water loss throughout transmission via pipeline systems. Hence, in recent decades, leak detection methods have emerged as a prominent subject of discussion among researchers worldwide.

Various techniques can be employed to identify pipeline leaks, from essential visual inspections to advanced imaging equipment. The current methodologies employed by water industries to identify and pinpoint water leaks are labor-intensive and often lack precision. Even though the water industry relies mostly on acoustic equipment for leak detection (such as aquaphones, geophones, and noise correlators), there are several alternative technologies available as well, including thermography cameras, ground-penetrating radar, tracer gas, and video monitoring [5]. However, these approaches have yet to be persuasive as a successful solution. The transient-based method has become more popular among researchers due to its better representation and higher accuracy than acoustic methods. These advantages include enhanced sensitivity, increased accuracy, non-invasiveness, adaptability, and the ability to monitor leaks in real time.

Transient-based methods (TBM) use pressure waves and their characteristics as they travel through a pressured fluid [6]. TBM is effective at finding faults in pipe leakage due to its ability to detect fluctuations in pressure that occur when there is a leak. Additionally, TBM can locate the exact leak location by analyzing pressure wave data. Four main types of TBM are pressure transient analysis, inverse transient analysis (ITA), transient reflection method (TRM), system response method (SRM), and transient damping method (TDM) [7]. TRM can be used with various pipe materials and sizes and is the easiest method to implement. It determines whether or not there is a leak in the pipeline and identifies the leak's location in the pipeline by employing reflection information in the pressure signal [8]. TRM has been widely studied in leak detection applications, especially for detecting leakages or faulty pipes along the pipeline system [9].

Since there are various methods to analyze transient-based methods, this research focuses on the application of the instantaneous frequency analysis method for transient reflection in water distribution networks. It acknowledges the existence of other methods for analyzing transient reflection but explicitly emphasizes the significance of pressure transient signals in this study. The signal's instantaneous frequency was analyzed using the Hilbert Transform (HT) [10]. Once the intrinsic mode functions (IMFs) have been obtained through empirical mode decomposition (EMD) operations and their respective importance rankings have been determined through correlation analysis, it becomes imperative to analyze each IMF individually. This analysis allows for identifying and understanding the transient behaviors exhibited by various system components, such as devices and faults, in terms of their influence range and intensity. To more accurately depict non-stationary signals, the notion of instantaneous frequency was introduced in the HT algorithm and then integrated with the EMD algorithm, referred to as the EMD-HT technique in this investigation for the analysis of transient signals [11-15]. The utilization of instantaneous frequency renders HT more appropriate and advantageous for analyzing non-stationary signals than conventional techniques like Fourier transform and wavelet analysis, primarily designed for stationary signals [16]. The EMD-HT methodology has the potential to mitigate water loss and safeguard infrastructure integrity through its capacity to identify and pinpoint leaks in water pipelines.

This study utilizes the combination method of the EMD-HT algorithms for the time-frequency analysis of transient pressure waves. This research paper examines the instantaneous frequency characteristics of multiple attributes in water pipelines by utilizing the Hilbert transform method. The objective is to investigate the behavior signal of different features in water pipelines using the Hilbert transform method. The method and application procedure presented in this paper are validated and verified through preliminary laboratory tests. The pipe features considered for this investigation include leakage, elbows, and junctions. Finally, the test results are analyzed and discussed in the paper.

2. Methodology

2.1 Experiment Setup

To demonstrate and validate the different types of pipe features (leakage, elbow, and junction) based on EMD-HT, transient pressure data were acquired from laboratory experiments. In this experiment, as shown in Figure 1, the details of the data-gathering tools and different pipe features that were used for testing are shown. The experimental pipeline configuration comprises several components: a water tank, pump, solenoid valve, piezoelectric pressure sensor, and MDPE pipe. These elements are combined to form a pipeline system with a total length of 158.27 meters. The experiment utilized a medium-density polyethylene (MDPE) pipe with an exterior diameter of 60 mm, an internal diameter of 55 mm, and a mean thickness of 2.6 mm.

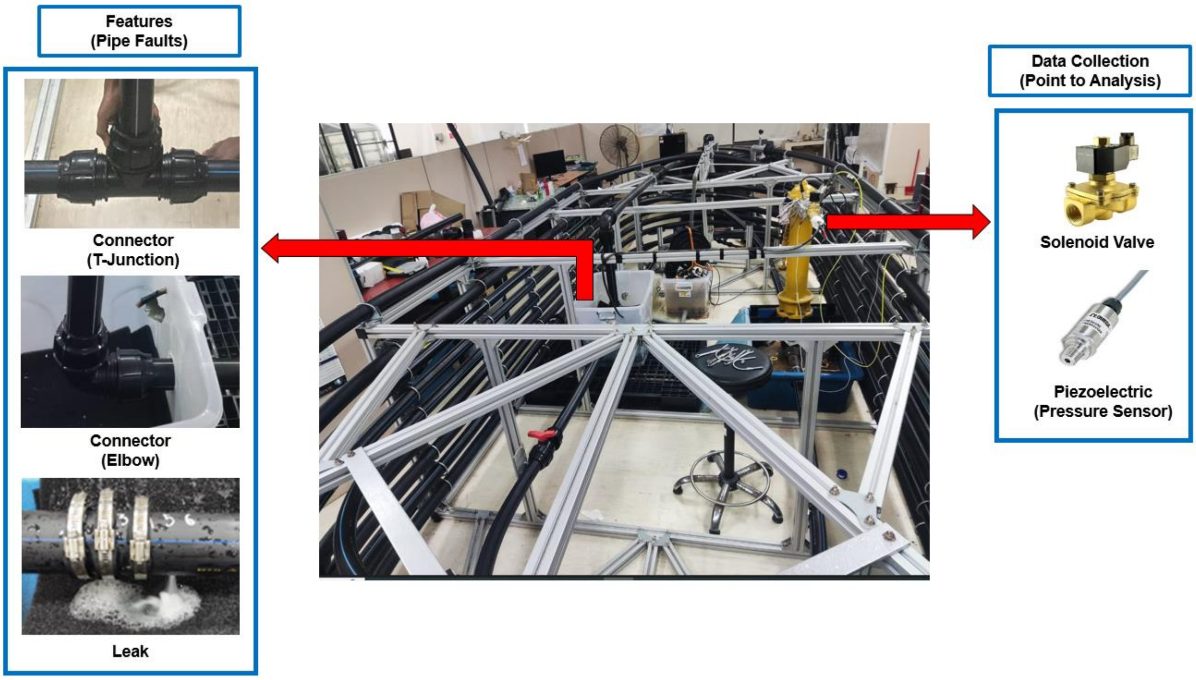


Fig. 1. Schematic of experimental test rig

The water tank and pump were positioned significantly away from the fire hydrant to prevent signal contamination from noise. The solenoid valve's job is to create the "water hammer" effect when it is connected to a fire hydrant. This effect makes the water distribution system more durable by reducing pressure surges while it is working. The free surface tank where the pipe's water is released is retained and connected to the pipe's outlet. Implementing this measure is meant to reduce the occurrence of sudden expansion phenomena caused by pressure waves while also reducing the damage that the waves due to the transducer's data. The measured speed of sound from the experimental apparatus is 497 m/s. Figure 2 displays the schematic diagram view for the test rig design for the experimental test system. Table 1 and Table 2 show the specification of system settings and parameters used for testing.

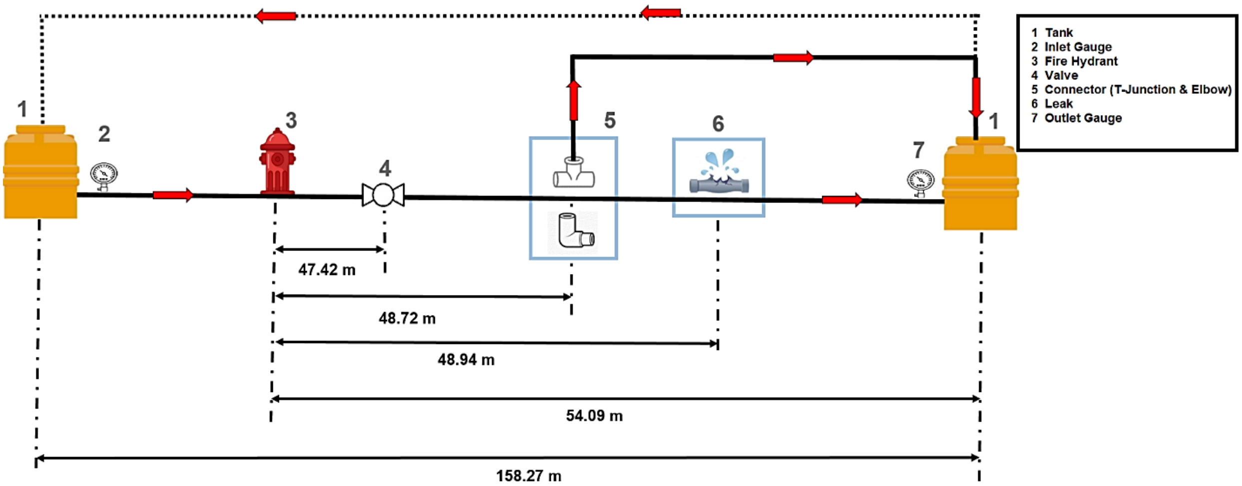


Fig. 2. Schematic diagram view for test rig for experimental test system

Table 1
Setting for geometric information

Number	Fault and Instrument	Distance from sensor (m)
1	Pressure Sensor (Piezoelectric)	1.29 m
2	Leakage	48.94 m
3	Junction	48.72 m
4	Elbow	48.72 m
5	Outlet	54.09 m

Table 2
Experiment test condition

Basic Properties	Value
Pipe Material	Medium-Density Polyethylene (MDPE)
Pipe diameter (mm)	60 mm (Outside) 55 mm (Inside)
Pressure Transient Sensor Model	PCB Piezoelectric 113B27

A water hammer is a phenomenon that generates a pressure surge, causing a wave to propagate down the pipeline system. The transient signal generated during the propagation of waves will result in both reflections when encountering features and blockages inside the pipeline. The pressure sensor and solenoid valve depicted in Figure 1 have been deliberately placed 10 meters from the electric pump to mitigate noise interference during the data-gathering process. The noise observed results from turbulent flow, a characteristic of the wave when water is released from the pump outlet. As the flow moves from the pump, it gradually transitions towards a laminar or steady-state condition. This event also creates friction against the wall of the pipe. Hence, a distance of 10 meters between the pump and the sensor is sufficient for noise reduction. This method is frequently employed in the procedures used for detecting pipeline leakage. The concept was derived from applying pressure transient flow in water pipeline networks [15].

Once the pump is activated, the water will be released and pressurized within the pipe, increasing the water pressure. When the pressure threshold is reached, the solenoid valve will rapidly open and close within a millisecond interval to generate water hammer and pressure signals. When encountering any features, the signal will propagate through the pipeline network and generate a reflection signal. The pressure sensor will record these reflection signals as pipeline information. The raw signals are then transformed directly into DASYLab. The data will be transferred into Matlab for further analysis using signal processing techniques. Following the EMD as a pre-processing technique, the HT serves as a post-processing method.

2.2 Data Pre-processing

There are many things that can cause noise in the signal that the pressure sensor receives, such as the environment, the operation of the pump, pipe vibration, and pipe friction. At this phase, the signal processing method is very important for getting rid of unwanted signals and analyzing data to pull out features. Figure 3 displays a flow chart illustrating the process of data collection and analysis. The pressure sensor signal will be transferred into Matlab software. The data will be decomposed using the EMD approach through coding in the Matlab programming language. The decomposition process yields multiple components known as intrinsic mode functions (IMFs). The number of components is based on the data characteristics. If the amplitude is high, the corresponding component will also increase. However, of all the components, only selected IMFs will be used to perform instantaneous frequency analysis (IFA) using HT. The behavior of leaks, elbows, and junctions can then be distinguished.

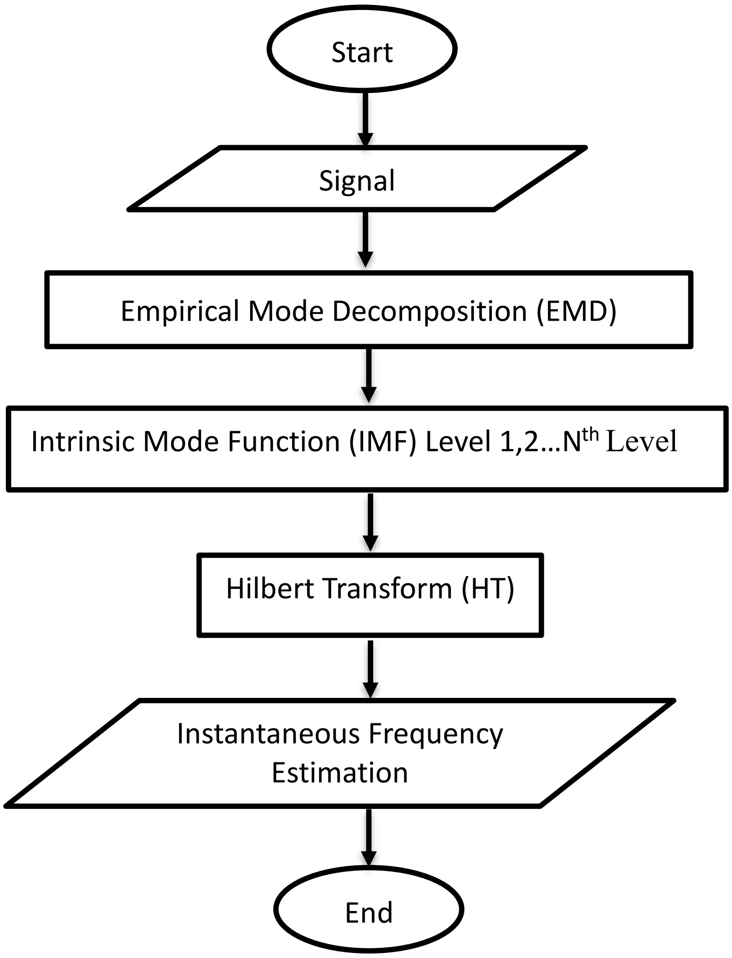


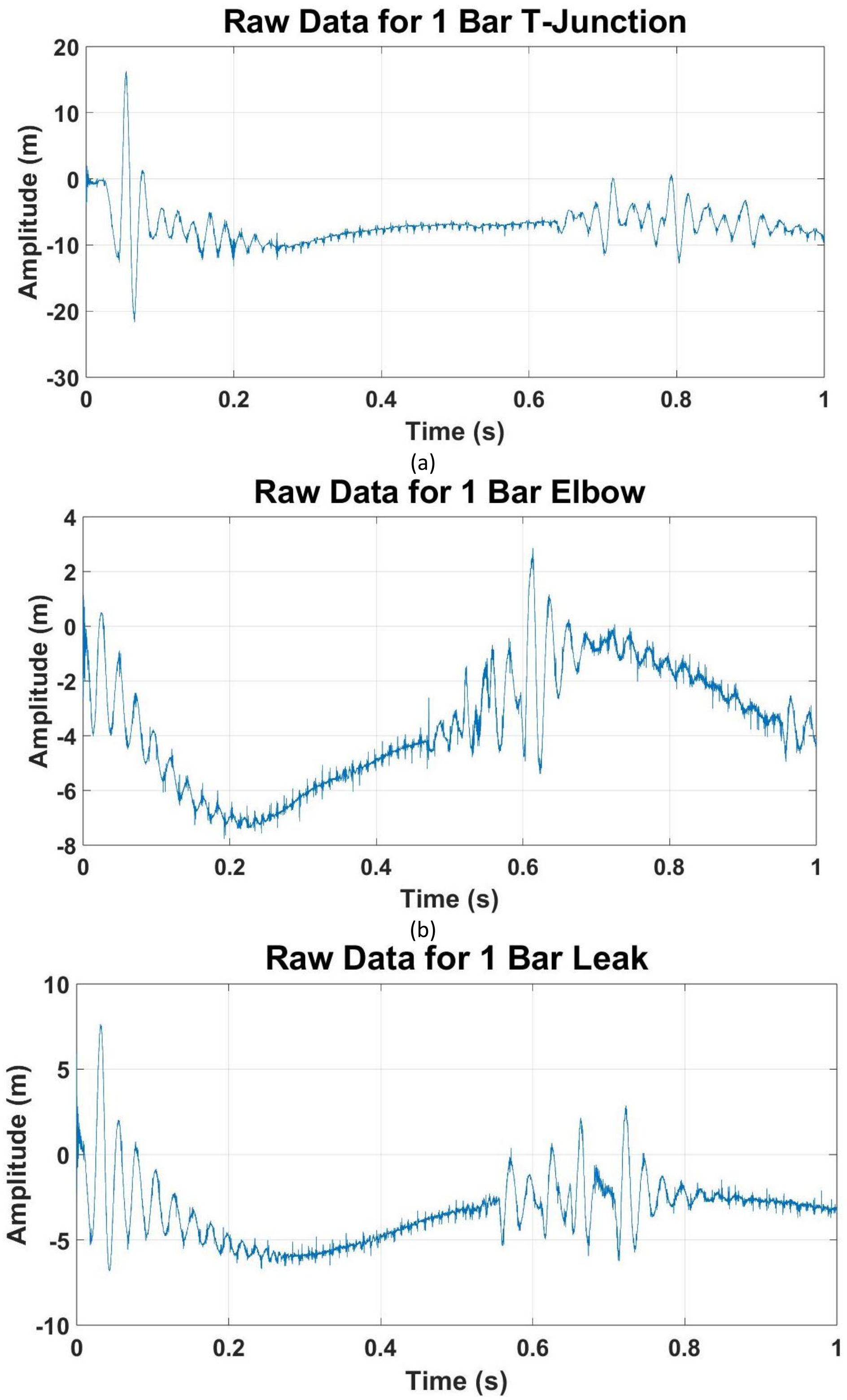
Fig. 3. Data collection and analysis

3. Results and Discussion

The data collection process in this study was conducted using a pressure sensor and Matlab software. Matlab software was used to record the pressure transient signal within the pipeline. The transient pressure waves propagate along the pipeline system in both directions, away from the burst's origin, at the speed of sound within the water distribution system. The signal was recorded for 50,000 samples based on a sampling frequency of 10,000 Hz. The data was acquired for three seconds to verify that the obtained signal missed no information about the pipeline system. The movement exhibited a notable increase at the 10,000th sample, indicating the precise moment when the solenoid valve was activated. The raw data presented in Figure 4 yielded relatively little meaningful information regarding pipelines, primarily due to significant noise. However, it is difficult to differentiate the features by using these raw signals because the signals are almost the same shape. Therefore, a thorough analysis needs to be done to determine the characteristics of the features for leakage, junction, and elbow.

Figure 4(a), Figure 4(b), and Figure 4(c) illustrate the signal response of the T-junction, elbow, and leak (1 mm) data captured during a laboratory experiment with a pressure of 1 bar inside the pipeline. The initial peak amplitude in the signal response, as depicted in Figure 4, corresponds to the opening and closing of the solenoid valve. This action generates pressure transients that propagate and reflect throughout the pipe system. The data is then analyzed using empirical mode decomposition (EMD) as a pre-processing procedure, followed by the Hilbert transform (HT) as a post-processing step. After undergoing the EMD process, the data is decomposed into a series of intrinsic mode functions (IMFs), as shown in Figure 5.

Figure 5 depicts the amplitude versus time relationship for the first 12 levels of IMF. The first level of IMF comprises higher-frequency signals, considered noise signals. Conversely, the last group is reserved for lower-frequency signals. The first and second levels of IMF are excluded from further analysis due to the presence of noise-frequency signals. However, IMF level 7 and the residue component contain essential network responses. Consequently, these IMF components are discarded. The remaining IMF levels, specifically IMF level 3 to IMF level 6, are combined to generate a noise-free signal [17]. The EMD approach will decompose a signal consisting of non-stationary and non-random components. The Empirical Mode Decomposition (EMD) method is a theoretical approach that aims to decompose the original signal into several intrinsic mode functions (IMFs) based on the characteristics of the signal. Figure 5 depicts the outcomes of the decomposition procedure using the Empirical Mode Decomposition (EMD) approach. The original signal has been effectively segregated and partitioned into many independent component functions (IMFs). After the best IMF component was selected, HT analysis was applied to the selected signal to analyze the approximation of instantaneous frequency.

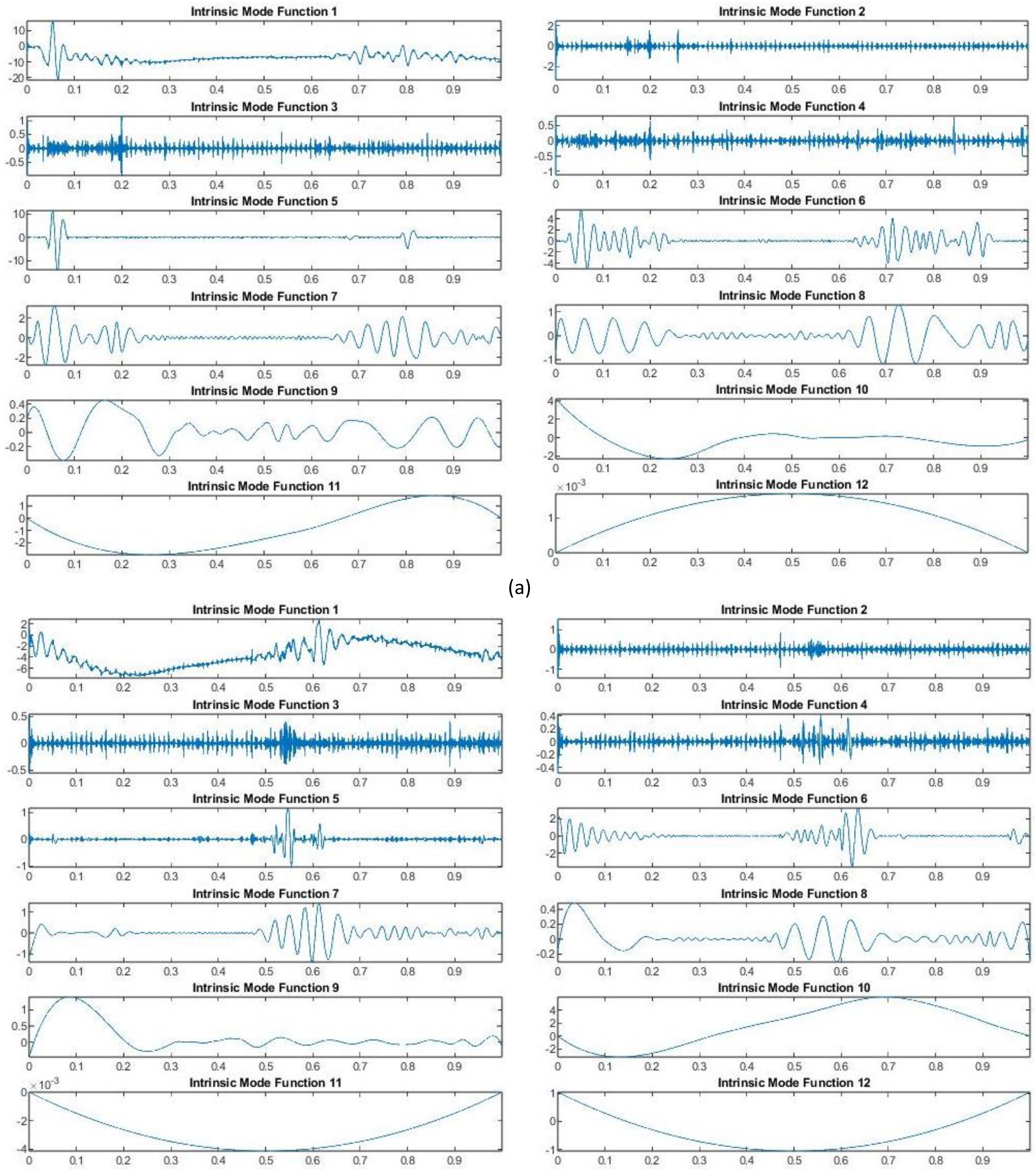


(a)

(b)

(c)

Fig. 4. Original signal response for (a) 1 bar T-Junction, (b) 1 bar Elbow, (c) 1 bar Leak (diameter: 1 mm)

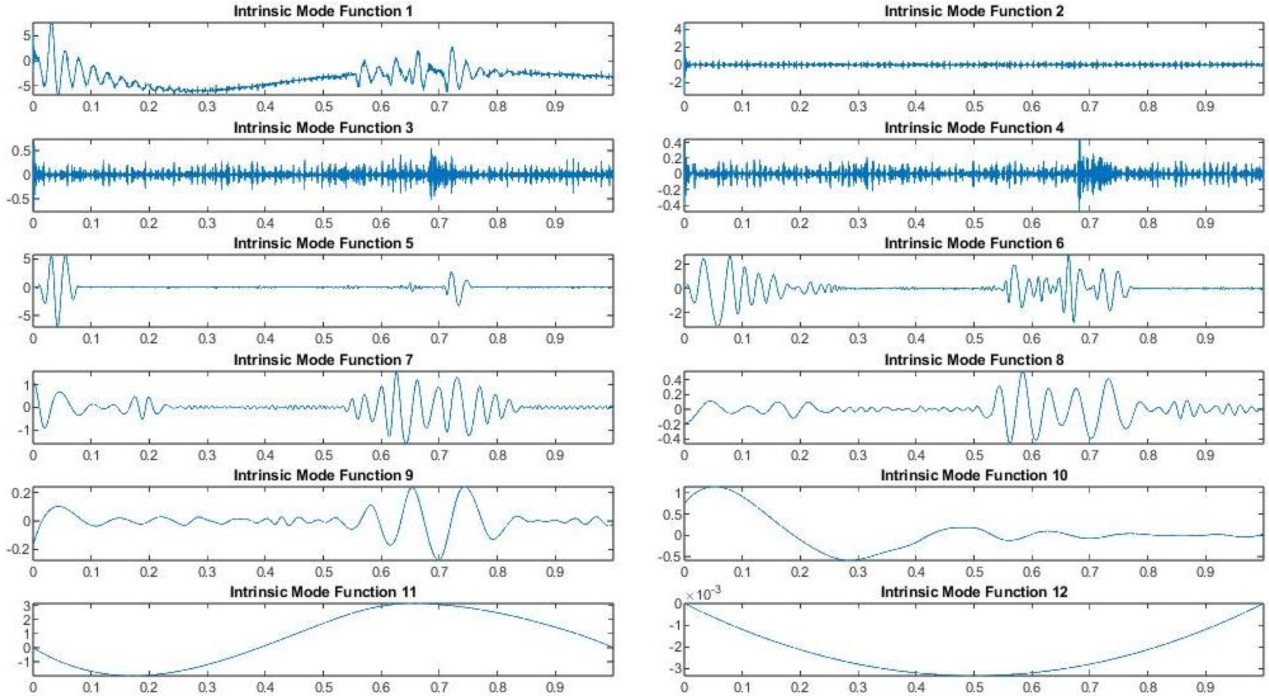


(a)

Intrinsic Mode Function 1
Intrinsic Mode Function 2
Intrinsic Mode Function 3
Intrinsic Mode Function 4
Intrinsic Mode Function 5
Intrinsic Mode Function 6
Intrinsic Mode Function 7
Intrinsic Mode Function 8
Intrinsic Mode Function 9
Intrinsic Mode Function 10
Intrinsic Mode Function 11
Intrinsic Mode Function 12

(b)

Intrinsic Mode Function 1
Intrinsic Mode Function 2
Intrinsic Mode Function 3
Intrinsic Mode Function 4
Intrinsic Mode Function 5
Intrinsic Mode Function 6
Intrinsic Mode Function 7
Intrinsic Mode Function 8
Intrinsic Mode Function 9
Intrinsic Mode Function 10
Intrinsic Mode Function 11
Intrinsic Mode Function 12



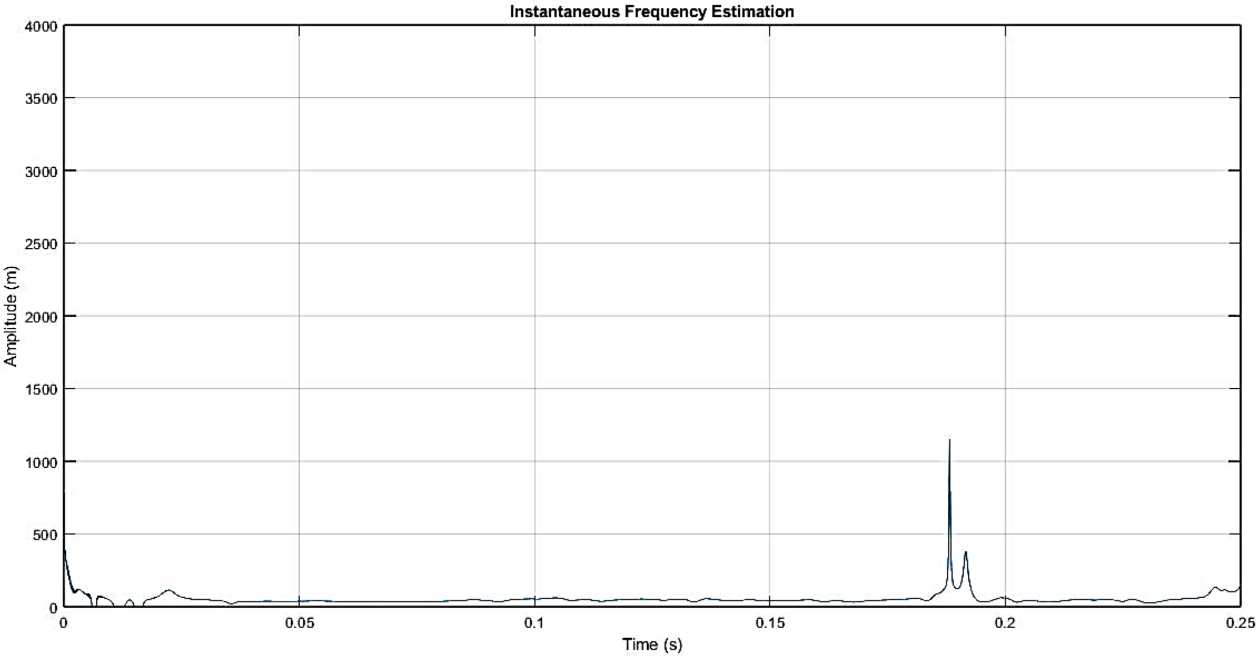
(c)

Fig. 5. IMF level 1-12 after EMD process for (a) 1 bar T-Junction, (b) 1 bar Elbow, (c) 1 bar Leak (diameter: 1 mm)

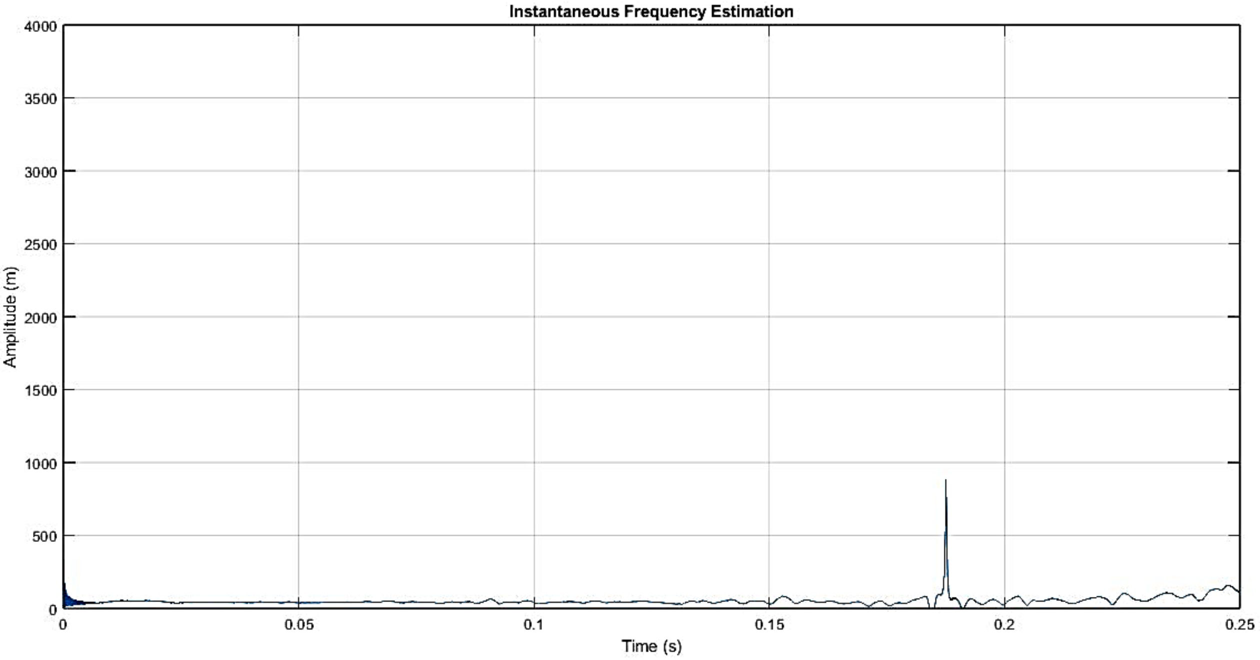
In this phase, the nonstationary nature of the signal, where the frequency value changes dynamically over time, is considered. Characterizing the signal in terms of its instantaneous frequency becomes more beneficial in such cases. Instantaneous frequency refers to the frequency that accurately represents the local behavior of the signal. By using the HT, the instantaneous frequency of the original signal was obtained. Figure 6 shows the instantaneous characteristics of the signal. Instantaneous frequencies clearly highlight the presence of a reflection. The peak of the analyzed signal matched up with the time taken for the wave to travel along the pipe network to the reflection point and return to the measurement point [18]. Figure 6 shows the instantaneous frequency of the signal. It can be clearly seen in the results from the HT analysis that there is a peak, which is the signature of the reflection points corresponding to the leak and the end of the pipe.

Figure 6(a) and Figure 6(b) depict a minor presence of contamination on the spike. These minor spikes, displaying relatively small increases in signal strength, signify subtle deviations in the signal at points where pipelines curve (elbows) or merge or diverge (junctions). Gradual changes in their amplitude indicate nuanced variations in flow patterns or conditions within these locations. At elbows, where flow is likely to be interrupted, small spikes show small changes or irregularities. This could mean that there is turbulence or a change in fluid dynamics because of the way the pipeline is curved. At junctions, these spikes may indicate alterations in pressure or flow rates, providing insight into changes in pipeline behavior. Recognizing these minor spikes pinpoints areas susceptible to disturbances, facilitating targeted maintenance or optimization efforts to ensure smooth flow and integrity within the pipeline system.

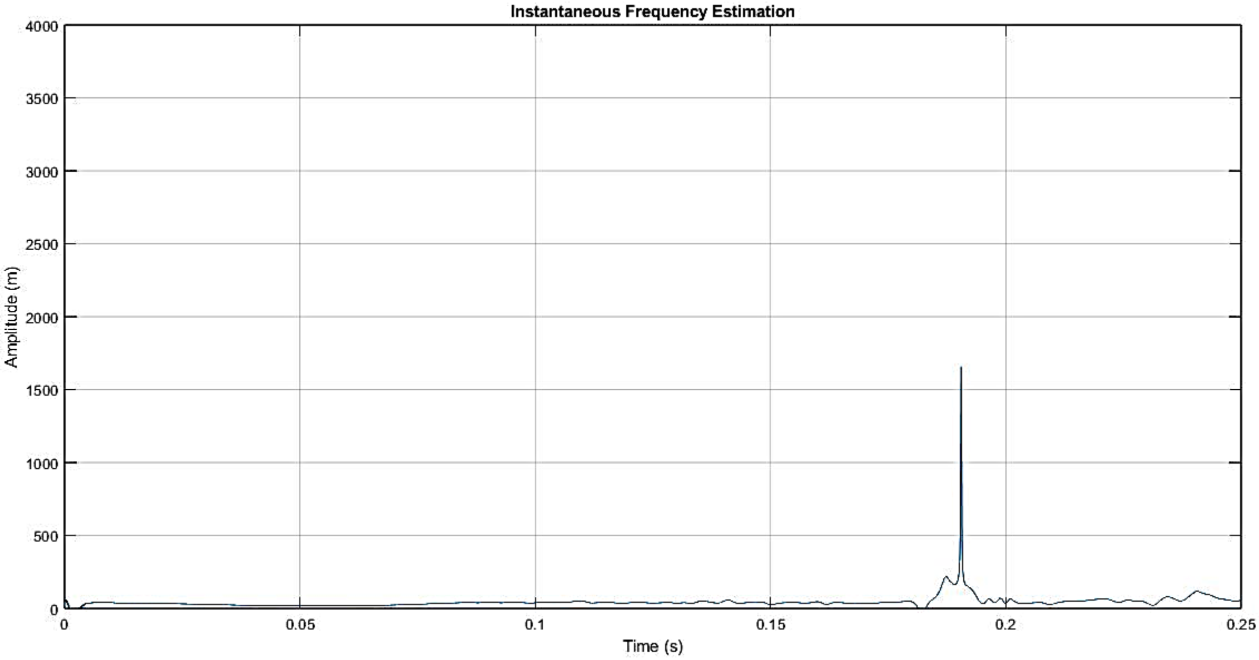
The outcome depicted in Figure 6(c) exhibits a high spike compared to Figure 6(a) and Figure 6(b). These spikes are abrupt, substantial increases in signal amplitude that are clearly distinct from the regular signal pattern. Their pronounced, transient nature signifies critical anomalies or major deviations in the system, usually indicating a leak. These spikes serve as prominent markers, quickly drawing attention to potential problem areas and allowing for immediate localization and action to address the leak. Their sharp and significant appearance signals a drastic change in the signal. This makes them an important indicator of the need for urgent investigation and remediation, ensuring a timely response and mitigation of any potential risks or damages within the pipeline system. So, this concludes that all features appeared after using HT analysis. Therefore, the accuracy of all characteristics shows that the EMD-HT methods can be relied on to find pipe features, whether they are used in a controlled laboratory setting or a real water distribution network. Overall, these techniques are reliable for identifying features in water pipelines.



(a)



(b)



(c)

Fig. 6. Instantaneous Frequency Estimation versus time (s) graph for (a) 1 bar T-Junction, (b) 1 bar Elbow, (c) 1 bar Leak (1 mm)

4. Conclusions

This work presents a time-frequency analysis methodology for identifying features in pipeline systems. The integration of the EMD-HT algorithms is employed in the examination of non-stationary and nonlinear pressure wave signals. Subsequently, the decomposed IMF signals can be utilized to evaluate pipeline conditions. The paper provides a comprehensive explanation of the application technique of the proposed approach.

Additionally, the study includes preliminary experimental testing on a basic pipeline system to validate the method. Additionally, the identification of features is effectively accomplished using the EMD-HT method. This study's proposed method effectively separates and reduces unwanted signals in the first transient pressure wave data that was recorded.

Consequently, this approach significantly diminishes or eliminates the impact of system uncertainties and flow instabilities on the subsequent analysis. The study's conclusions and findings could make a big difference in the field of transient-based pipe detection by allowing it to be used on increasingly complex pipeline systems in the real world. The results presented in this study also indicate the need for more validation and necessary enhancements to extend the proposed method to practical applications in the future.

Acknowledgement

This research work is completely financed by University Malaysia Pahang by the provision of funds and facilities. The author also acknowledges the support by the University Malaysia Pahang Al-Sultan Abdullah (UMPSA) for providing the internal grant RDU223311 and PGRS220389.

References

[1] Farouk, Abdelrahman M., Rahimi A. Rahman, and Noor Suraya Romali. "Non-revenue water reduction strategies: a systematic review." *Smart and Sustainable Built Environment* 12, no. 1 (2023): 181-199. https://doi.org/10.1108/SASBE-04-2021-0071

[2] Frauendorfer, Rudolf, and Roland Liemberger. *The issues and challenges of reducing non-revenue water*. Asian Development Bank, 2010.

[3] Ortega-Ballesteros, Andrés, Francisco Manzano-Agugliaro, and Alberto-Jesus Perea-Moreno. "Water utilities challenges: A bibliometric analysis." *Sustainability* 13, no. 14 (2021): 7726. https://doi.org/10.3390/su13147726

[4] American Water Works Association. *Leaks in water distribution systems: a technical/economic overview*. American Water Works Association, 1987.

[5] El-Zahab, Samer, and Tarek Zayed. "Leak detection in water distribution networks: an introductory overview." *Smart Water* 4, no. 1 (2019): 1-23. https://doi.org/10.1186/s40713-019-0017-x

[6] Elshaboury, Nehal, Eslam Mohammed Abdelkader, Abobakr Al-Sakkaf, and Ghasan Alfalah. "Teaching-learning-based optimization of neural networks for water supply pipe condition prediction." *Water* 13, no. 24 (2021): 3546. https://doi.org/10.3390/w13243546

[7] Xu, Xinge, and Bryan Karney. "An overview of transient fault detection techniques." *Modeling and monitoring of pipelines and networks: Advanced Tools for Automatic Monitoring and Supervision of Pipelines* (2017): 13-37. https://doi.org/10.1007/978-3-319-55944-5_2

[8] Brunone, Bruno, and Marco Ferrante. "Detecting leaks in pressurised pipes by means of transients." *Journal of Hydraulic Research* 39, no. 5 (2001): 539-547. https://doi.org/10.1080/00221686.2001.9628278

[9] Yussof, Nurfarah Anisah Mohd, and Hann Woei Ho. "Review of water leak detection methods in smart building applications." *Buildings* 12, no. 10 (2022): 1535. https://doi.org/10.3390/buildings12101535

[10] Yusop, Hanafi M., M. F. Ghazali, M. F. M. Yusof, and W. S. W. Hamat. "Development of Intelligent Leak Detection System Based on Artificial Pressure Transient Signal Using Integrated Kurtosis-Based Algorithm for Z-Filter Technique (I-Kaz)." *Journal of Mechanical Engineering (JMechE)* 4 (2017): 84-102.

[11] Cheng, Junsheng, Dejie Yu, Jiashi Tang, and Yu Yang. "Application of frequency family separation method based upon EMD and local Hilbert energy spectrum method to gear fault diagnosis." *Mechanism and Machine Theory* 43, no. 6 (2008): 712-723. https://doi.org/10.1016/j.mechmachtheory.2007.05.007

[12] Sun, Jilong, Ronghe Wang, and Huan-Feng Duan. "Multiple-fault detection in water pipelines using transient-based time-frequency analysis." *Journal of Hydroinformatics* 18, no. 6 (2016): 975-989. https://doi.org/10.2166/hydro.2016.232

[13] PiRemli, Muhammad Aminuddin, Mohd Fairusham Ghazali, W. H. Azmi, and M. Y. Hanafi. "Transient-based leak detection and monitoring of water pipes using complementary ensemble empirical mode decomposition (CEEMD) method." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 83, no. 2 (2021): 135-148. https://doi.org/10.37934/arfmts.83.2.135148

[14] Yusop, Hanafi M., M. F. Ghazali, M. F. M. Yusof, MA Pi Remli, and M. H. Kamarulzaman. "Pipe leak diagnostic using high frequency piezoelectric pressure sensor and automatic selection of intrinsic mode function." In *IOP Conference Series: Materials Science and Engineering*, vol. 257, no. 1, p. 012091. IOP Publishing, 2017. https://doi.org/10.1088/1757-899X/257/1/012091

[15] Stańczyk, Justyna, and Ewa Burszta-Adamiak. "Development of methods for diagnosing the operating conditions of water supply networks over the last two decades." *Water* 14, no. 5 (2022): 786. https://doi.org/10.3390/w14050786

[16] Huang, Norden E., Zheng Shen, Steven R. Long, Manli C. Wu, Hsing H. Shih, Quanan Zheng, Nai-Chyuan Yen, Chi Chao Tung, and Henry H. Liu. "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis." *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 454, no. 1971 (1998): 903-995. https://doi.org/10.1098/rspa.1998.0193

[17] Amin, M. M., M. F. Ghazali, M. A. PiRemli, A. M. A. Hamat, and N. F. Adnan. "Leak detection in medium density polyethylene (MDPE) pipe using pressure transient method." In *IOP Conference Series: Materials Science and Engineering*, vol. 100, no. 1, p. 012007. IOP Publishing, 2015. https://doi.org/10.1088/1757-899X/100/1/012007

[18] Yusop, Hanafi M., M. F. Ghazali, M. F. M. Yusof, and W. S. W. Hamat. "Improvement of Cepstrum Analysis for the Purpose to Detect Leak, Feature and Its Location in Water Distribution System based on Pressure Transient Analysis." *Journal of Mechanical Engineering (JMechE)* 4 (2017): 103-122.