Application of Ikaz and direct quadrature for solving leakage in pipeline distribution by using transmission line modelling

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Abstract. A new transient-based advance towards single leak detection is proposed which requires a measurement station with an end at the pipe system. The method use the frequency response and gives adequate results using low frequency bandwidth. This research apply Empirical Mode Decomposition (EMD) as the method denoising the noisy pressure transient signal before the signal further analyze using instantaneous frequency analysis. Therefore EMD is the way to decompose into Intrinsic Mode Function (IMF) from the signal. However it is difficult to select suitable IMF. Thus the paper proposed the implementation of Integrated Kurtosis-based algorithm Z-filter technique for that allows automatic selection of relevant and appropriates IMF. This work demonstrated the synthetic pressure transient signal generates using transmission line modelling (TLM) in order to test the effectiveness of Ikaz as the autonomous selection of IMF. This paper implement the Direct Quadrature as the instantaneous frequency analysis. A straight fluid network was designed using TLM fixing with higher resistance at some point act as a leak and connecting to the pipe feature (junction, pipefitting or blockage). The analysis results using Ikaz revealed that the method can be utilized as an automatic selection of intrinsic mode function (IMF) with lower than 2% error. Ikaz is recommended and advised to be implemented as automatic selection of intrinsic mode function (IMF) through DQ analysis.

1. Introduction
Non-revenue water is a difference between volume of water that have been produced before and after reach the consumer. This is because due to the leakage inside the piping along the system and as we all know water loss is considered as a global problem and major issues of water management. In 2010, statistical shows that the average percentage of non-revenue water in Malaysia was 29.4%, a figure which resulted in major financial, supply and pressure losses as well as excessive energy utilization [1]. Therefore, the result can lead us towards negative impact of services and environment. High non-revenue water gives bad impression to the water supply services. It reflects the problem of instability of water supply infrastructure [2]. Besides, cost repairing damage pipe network also can increases. Other than that, the things that could jeopardize the environment due to non-revenue water problems is water ponding on the metal road which damages the structure and road components.

So there are lots of ways on how to reduce and control the non-revenue water [3]. Most commercialize method is passive control where the problem usually reported by customer or noted by company own staff. The method can be justified in areas with plentiful or low cost supplies. Second is active leakage control and it consist of two method which are regular survey and leakage monitoring. Regular monitoring is a process by listening to the leak of pipework and fitting, reading metered flow
into temporarily zoned area to identify high volume night flow. Leakage monitoring is flow monitoring into zones or districts to measure leakage and to prioritize leak detection activities [4]. Nonetheless the conventional leak detection equipment is often expensive and more adapted method need to be chosen in developing country. Hence the method of commercialize need to be drawback somehow.

Leak detection analysis need to be invented in order for the industries to detect the leakage and take action. Nevertheless, problem we need to deal with is the industrial demand. The cost of the equipment must cheaper so that they can save the money. Sensitivity must be more effectiveness and accuracy. The process analysis must be taken repeatability in order to monitor the pipe network system. Some method had been used previously to analyze the data leakage. For example the acoustic method which is the technologies of recognizing and extracting wave characteristics [5]. The method with high-pressure and long distance leak test loop is designed and established by similarity analysis with field transmission pipelines. The acoustic signals collected by sensors denoise by wavelet transform to eliminate the background noises, and time-frequency analysis is used to analyze the characteristics of frequency domain. Aside from that, pressure transient method also can analyze the leak detection of leakage[6]. For example inverse-transient analysis can give essential leak detection provide that, among other considerations, an accurate transient model of the system exists [7]. The advantages of inverse-transient analysis is more details and the number of complexities in a system can be devastating.

Empirical Mode Decomposition (EMD) is a method to measure nonstationary and nonlinear data [8]. This method is intuitive, direct, posteriori, and adaptive, with the basis of the decomposition based on and derived from the data. Empirical Mode Decomposition method with which any complicated data set can be decomposed into a finite and often small number of Intrinsic Mode Functions (IMF). An Intrinsic Mode Function is defined as any function having the same numbers of zero-crossing and extrema, and also having symmetric envelopes defined by the local maxima and minima respectively. The Empirical Mode Decomposition as for the pre-processing is denoising the signal to obtain the real signal. Then the signal going through Intrinsic Mode Function to expand the data in a basis derivation[9]. Previously the selection is difficult because the signals can only be determined by the expert users. However today with the invention of Integrated Kurtosis-based Algorithm Z-filter (IKAZ) can easily ascertain the degree of data scattering with respect to the data centroid for a dynamic signal analysis. [10]

A direct quadrature method for the solution of Volterra integral equations with periodic solution is proposed. This method is based on an exponentially fitted quadrature rule of Gaussian type, whose parameters depend on the problem, in order to reproduce the behavior of the analytical solution [11]. The error of the quadrature rule is examined and a convergence analysis of the direct quadrature method is given. Some numerical experiments are presented for comparison with other existing methods [12]. The transmission-line modeling (TLM), otherwise known as the transmission-line matrix method, is a numerical technique for solving field problems using circuit equivalents. It is based on the equivalence between Maxwell’s equations and the equations for voltages and currents on a mesh of continuous two-wire transmission lines [13]. The main feature of this method is the simplicity of formulation and programming for a wide range of applications. As compared with the lumped network model, the TLM is more general and performs better at high frequencies where the transmission and reflection properties of geometrical discontinuities cannot be regarded as lumped [14]. The sequence of this method where transmission line modeling will generate the signals of the data. The signals then will be denoising by using Empirical Mode Decomposition and revealed the sequence of intrinsic mode function from high frequency segment into the lower frequency segment. Purpose of this paper is to introduce the Ikaz as automatic selection of the right intrinsic mode function (IMF). After going through Intrinsic Mode Function the signal will be analyze by using Direct Quadrature method. As the result we can get to know the distance of the leakage occur in the piping network system.
2. Methodology

2.1. Simulated Pressure Transient Signal
In this research, with the different pipe length, water pressure and a number of leaks fitted on the pipeline model, two simulated pipeline models were constructed. The first model (Figure 1(a)) simulated was a pipe with the leak and without a leak. The model decomposed of Medium High-Density Polyethylene (MDPE) pipe, which is divided into 3 section by the valve and junction (Figure 1(a)). The total range of pipe for the first model is 49 meter with water pressure 4 bars. The second model (Figure 1(b)) with MDPE pipe, which is divided into 4 section by valve and 2 junctions. As for the second model, the number of the leak is 2 with total distance and water pressure acting on the pipe is 53 meter with 4 bars. The resistance of the junction for simulated signal without the leak is set to be 3000 meanwhile for signal with leak, the resistance is set to be 30,000,000. Both model has same pipe diameter with 60mm respectively.

In order to validate the identification approach, the design of the model was made as simple as possible. Open and close the valve (Figure 1) will cause water hammer pulse which then propagates through the system. The system was applied time-varying valve as detailed describe by Beck et al [13]. The software gives users to set the geometry, length, and diameter of the pipes. By key in the higher value of resistivity at the junction on order to simulate the leak feature, then some of the pressure wave generated by the valve will be reflected. The location of the leak and pipe outlet can be determined by knowing the range of the reflection point from the end of the pipe and the speed of sound that pressure waves travel through the medium.

![Figure 1. Pipe network model a) First model b) Second model](image)

In this research, water is used as simulated fluid as the medium flow in both pipeline model. It was assumed that water has Standard Temperature and Pressure (STP). Since the material is MDPE and pipe diameter is 60mm respectively, the speed of sound is equal to 493 m/s. The range between the valve and the pressure sensor was set to 0.001 meters (Figure 1). Thus it simulates the capture of a time history of signal response of the pressure using a pressure sensor attached very close to the valve. The software also allows the users to put any numbers of flow and pressure data as the output from the system.

2.2. Added White Gaussian Noise
Each of signal response generates from TLM software is added by white Gaussian noise on order to make the signal very close to the real pressure transient signal. The key parameter when deciding to generate white noise signal response is the value of Signal to Noise Ratio (SNR). If the added noise is too weak to bring the changes of extrema of the signal[15]. In opposite, if the added noise is too strong, the EMD/EEMD method will derive meaningless results which are mainly controlled by the added noise.
and scarcely associated with the original signal [16]. According to Zhang et al [17], it appropriates for EMD/EEMD method to set SNR between the original signal and added noise is approximately 37dB. Hence, the value of SNR is set to be 37dB [17]. As presented in Figure 2 below, the graph shows the signal response from TLM with added noise. The red line indicated the original response from TLM without noise and the light blue line mean the signal response with added noise. The signal response from TLM with added noise then going to analyse using Direct Quadrature (DQ) and Integrated Kurtosis Algorithm for Z-notch filter technique (IKAZ) as the automatic selection of intrinsic mode function (IMF). As for the result of analysis will show the characteristic of the pipeline that has been indicated the pipe feature (leak, blockage and pipefitting)[6].

![Figure 2(a). Original Signal response](image)

![Figure 2(b). Signal response with added white Gaussian noise.](image)

3. Results and Discussion
Figure 3 shows the signal response with added noise for the first model of pipe network. While figure 4 illustrate the signal response from second model of pipe network with added noise. By using Direct Quadrature (DQ) that contained of Empirical Mode Function (EMD), the instantaneous frequency and phase angle of the original signal was obtained.
The step of analysis starting with the signal response was decompose into Intrinsic Mode Function (IMF) [18]. EMD deteriorate the signal response into 13 levels of IMF. Figure 5 shows the amplitude versus time for the first 12 levels of IMF. First level of IMF is a group of higher frequency signals which is the noise signal. Final level of IMF was a reverse for the lower frequency signals. To prevent further analysis the first and second signal is avoided because these level have noise frequency signals. In the meantime IMF level 7 and the residue contain basic respond of the network. All the IMF were then discarded. The rest which is IMF level 3 until level 6 have been merge to produce a signal without noise [19]. Therefore, to identify level of IMF that suitable for going through final step of Direct Quadrature, Integrated Kurtosis Algorithm for Z-filter technique to kurtosis ratio (Ikaz-Kurtosis) was implemented. Since the EMD deteriorate the signal response into 13 levels of IMF, the Ikaz-Kurtosis ratio was applied to compute the coefficient of each level.
Figure 5. Intrinsic Mode Function (IMF) from level 1-1

(a) 

(b) 

Figure 6. Ikaz-Kurtosis ratio coefficient for first pipeline model. a) No leak signal b) With leak signal

(a) 

(b) 

Figure 7. Ikaz-Kurtosis ratio coefficient for second pipeline model a) No leak signal b) With leak signal
Figure 6 (a & b) and 7 (a & b) represent the Ikaz-Kurtosis coefficient histogram for the first and second pipe network module for with and without leak response respectively. The X-axis shows the IMF level. Meanwhile, Y-axis show the value of the Ikaz-Kurtosis ratio coefficient. From the observation, the maximum and highest value of Ikaz-Kurtosis ratio coefficient were the most suitable IMF level for going through the post-processing and the final step of Direct Quadrature analysis. This is because the level of IMF that contain the most value of Ikaz-Kurtosis ratio consist of the IMF selection criterion which is clear and narrow spikes. The less the value of Ikaz-Kurtosis ratio, the obscure of clear and narrow spikes which are the main selection criterion of IMF. Furthermore, the IMF level that contains the highest value of Ikaz-Kurtosis ratio coefficient was reserved on level 3 until level 6. As explained before the levels have been combined again to produce a signal without noise [19]. Therefore, the level is relevant and appropriate for further analysed. As presented in figure 6 (a) the IMF level 6 has the highest Ikaz-Kurtosis ratio meanwhile 6 (b) reserved on IMF level 4. The figure 7 (a) show IMF level 5 that was contain the highest coefficient followed by IMF level 6 for figure 7 (b).

Figure 8(a). Instantaneous characteristic of DQ analysis for 1st model signal with no leak

Figure 8(b). Instantaneous characteristic of DQ analysis for 1st model signal with leak
Figure 9(a). Instantaneous characteristic of DQ analysis for 2\textsuperscript{nd} model signal with no leak

Figure 9(b). Instantaneous characteristic of DQ analysis for 2\textsuperscript{nd} model signal with leak

Figure above shows the instantaneous characteristic of the signal for first and second model of pipeline network. In the interval a and b represented as a signal without and with leak. The presence of reflection is clearly highlighted by the instantaneous frequency. Peak of the analysed signal match up with the time taken for the wave to travel along the pipe network to the reflection point and return to the measurement point. The distance of the reflection point is calculated by multiplying the time delay parallel to the peak by the speed of sound in the pipe network. (Speed = 493 m/s) and having this value to account for the return journey. As shown in figure 8 (a) and (b), the existence of reflection corresponding to outlet signature is clearly seen by 48.98m at both figure. Meanwhile, the reflection corresponds of leak signature seen in figure 8 (b) was measured by 15.00m. Figure 9 (a) and (b) illustrated the reflection with the signature outlet that measured with 43.26m at both. The reflection with signature of leak 1 and 2 was measured by 14.18m and 36.26m respectively as shown in figure 9 (b). There are some errors when compared the experimental positioned and simulated positioned. The difference between simulated and analyse position is tabulated in Table 1.
Table 1. Comparison between simulated and experimental

| Water Pressure | Signal Response | Pipe Feature | Simulated Position (m) | IMF contain Maximum Ikaz-Kurtosis ratio Coefficient | Analyse Position (m) | Error % |
|----------------|-----------------|--------------|------------------------|-----------------------------------------------|----------------------|--------|
| First Pipeline Model Leak Data | Leak | 15 | | 15.00 | 0.0 | |
| | Outlet | 48 | 4 | 48.98 | 2.0 | |
| No Leak Data | Outlet | 48 | 4 | 48.98 | 2.0 | |
| Second Pipeline Model Leak Data | Leak 1 | 14 | 5 | 14.18 | 1.3 | |
| | Leak 2 | 36 | 5 | 36.26 | 0.7 | |
| | Outlet | 43 | | 43.26 | 0.6 | |
| No Leak Data | Outlet | 43 | 5 | 43.26 | 0.6 | |

As shown in Table 1 above, first pipe network model contains signature of leak with water pressure of 4 bar, the position of leak show 0% error and outlet signature position show 0.9% error. While for no leak data presented 0.9% error for outlet signature position. Besides, second model have two leak signature with water pressure of 4 bar, position of signature leak 1 and 2 show 0.1% and 0.2% error and outlet position signature show 0.2% error. Meanwhile leak signal response presented 0.2% error for position of outlet signature. From the final part DQ analysis, it is obviously shown that the location of pipe feature that is leak and pipe outlet appear at the same position compared to each original position and simulated position. It also proves that DQ analysis can detect and positioning the transient event happened in the non-stationary pressure transient signal.

4. Conclusion
This paper discussed about self-decision method for IMF selection through Direct Quadrature (DQ) analysis. The result proves that Ikaz-kurtosis ratio is suitable and advisable self-decision method for IMF selection to utensil in Direct Quadrature analysis. The development of automated self-decision of IMF through DQ has been built and statistically analysed by suing Ikaz-kurtosis ratio, issue of IMF selection was solved. Therefore degree of automation for Direct Quadrature was improvised to identify leakage in live water distribution system by using pressure transient signal.

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References
[1] J. M. Alkasseh, M. N. Adlan, I. Abustan, H. A. Aziz, and A. B. M. Hanif, "Applying minimum night flow to estimate water loss using statistical modeling: a case study in Kinta Valley, Malaysia," Water resources management, vol. 27, pp. 1439-1455, 2013.
[2] B. D. Pickard, J. Vilagos, G. K. Nestel, R. Fernandez, S. Kuhr, and D. Lanning, "Reducing non-revenue water: a myriad of challenges," Florida Water Resour. J, pp. 26-32, 2008.
[3] M. Farley, "Non-Revenue Water–International Best Practice for Assessment, Monitoring and Control," in 12th Annual CWWA Water, Wastewater & Solid Waste Conference, 2003.
[4] M. Taghvaei, S. Beck, and W. Staszewski, "Leak detection in pipelines using cepstrum analysis," Measurement Science and Technology, vol. 17, p. 367, 2006.
[5] L. Meng, L. Yuxing, W. Wuchang, and F. Juntao, "Experimental study on leak detection and location for gas pipeline based on acoustic method," *Journal of Loss Prevention in the Process Industries*, vol. 25, pp. 90-102, 2012.

[6] H. M. Yusop, M. Ghazali, M. Yusof, M. P. Remli, and M. 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*, 2017, p. 012091.

[7] A. F. Colombo, P. Lee, and B. W. Karney, "A selective literature review of transient-based leak detection methods," *Journal of Hydro-environment Research*, vol. 2, pp. 212-227, 2009/04/01/ 2009.

[8] N. E. Huang, "Review of empirical mode decomposition," in *Wavelet Applications VIII*, 2001, pp. 71-81.

[9] H. M. Yusop, M. Ghazali, M. Yusof, M. Piremli, and B. Karollah, "The use of transmission line modelling to test the effectiveness of I-kaz as autonomous selection of intrinsic mode function," in *IOP Conference Series: Materials Science and Engineering*, 2017, p. 012070.

[10] M. Z. Nuawi, M. J. M. Nor, N. Jamaludin, S. Abdullah, F. Lamin, and C. Nizwan, "Development of integrated kurtosis-based algorithm for z-filter technique," *Journal of applied sciences*, vol. 8, pp. 1541-1547, 2008.

[11] R. O. Fox, F. Laurent, and M. Massot, "Numerical simulation of spray coalescence in an Eulerian framework: direct quadrature method of moments and multi-fluid method," *Journal of Computational Physics*, vol. 227, pp. 3058-3088, 2008.

[12] A. Cardone, L. G. Ixaru, B. Paternoster, and G. Santomauro, "Ef-Gaussian direct quadrature methods for Volterra integral equations with periodic solution," *Mathematics and Computers in Simulation*, vol. 110, pp. 125-143, 2015/04/01/ 2015.

[13] S. Beck, H. Haider, and R. Boucher, "Transmission line modelling of simulated drill strings undergoing water-hammer," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 209, pp. 419-427, 1995.

[14] M. N. Sadiku and L. C. Agba, "A simple introduction to the transmission-line modeling," *IEEE Transactions on Circuits and systems*, vol. 37, pp. 991-999, 1990.

[15] M. F. Ghazali, "Leak detection using instantaneous frequency analysis," University of Sheffield, 2012.

[16] J. Lin, "Improved ensemble empirical mode decomposition and its applications to gearbox fault signal processing," *International Journal of Computer Science*, vol. 9, pp. 194-199, 2012.

[17] J. Zhang, R. Yan, R. X. Gao, and Z. Feng, "Performance enhancement of ensemble empirical mode decomposition," *Mechanical Systems and Signal Processing*, vol. 24, pp. 2104-2123, 2010.

[18] M. Ghazali, W. J. Staszewski, J. Shucksmith, J. B. Boxall, and S. B. Beck, "Instantaneous phase and frequency for the detection of leaks and features in a pipeline system," *Structural Health Monitoring*, vol. 10, pp. 351-360, 2011.

[19] M. Ghazali, S. Beck, J. Shucksmith, J. Boxall, and W. Staszewski, "Comparative study of instantaneous frequency based methods for leak detection in pipeline networks," *Mechanical Systems and Signal Processing*, vol. 29, pp. 187-200, 2012.