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# Leak localization using empirical mode decomposition and Teiger-Kaiser energy operator analysis based on pressure transient signal: experimental study

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**Abstract.** Leak detection become crucial part in water management services due to strenuous work in identification of leak location for pipeline networks. This paper focused on leak identification and localization using Teiger-Kaiser Energy Operator (TKEO) as instantaneous frequency analysis (IFA) while Empirical Mode Decomposition (EMD) as decomposition method with implementation of Integrated Kurtosis Algorithm for Z-Filter (Ikaz) to Kurtosis ratio as the automatic selection criterion for intrinsic mode function (IMF). Test rig construct inside laboratory as testing site using 67.90-metre Medium Density Polyethylene (MDPE) pipe. In order to create an artificial leak, pinhole is drill at 19.75-metre distance from point of analysis that is fire hydrant attached with pressure sensor. Experiment conduct by using two variation of pressure that are 2bar and 4bar. As the result, with percentage of error less than 6%, combination of TKEO as IFA and efficiency of Ikaz performed well in locating the position of leak and outlet of pipeline system.

## 1. Introduction

Water as a source of living and important to all field of productions such as agriculture, industry, energy, transport and so on [1]. The problem raise here is how to make sure water supply efficiently to consumer. Moreover, water supply system bring a meaning of the whole system integrate public mains, pipes, chambers, pumping stations, treatment plants, balancing reservoirs, and service or any influences and all others structures, buildings, appurtenances used, equipment, and the lands where the storage, collection, conveyance, treatment, abstraction, distribution and supply of water are located. Water loss can be high influences in distribution of water around the piping systems. Water loss can happen due to the leakage of pipe along the piping system. Water loss from the water distribution systems remains one of the leading problem concerns facing not only developing, but also developed countries all over the world. One of the major factors to the water loss as water transmission and distribution networks continue to deteriorate with time is pipes aging [2].

In Malaysia, Perlis recorded highest NRW that is lost in process of distributing to customer that is around 60.7%. As mention in [3], Kedah, Kelantan and Pahang followed Perlis in high NRW recorded over the year around 50%. By year 2020, Malaysia hope to reduce the water losses from NRW problem to 25%. In addition, pipe leakage, water thief and metres inaccuracies become the major causes of high NRW [3]. Pipe leakage seem to be the highest contributor in water losses in water distribution system.



Pipe leakage can cause by several failure type such as pipe cracking either longitudinal or circumferential, bell splitting or shearing, and corrosion pitting or blowout hole. This entire problem can happened due to corrosion, soil erosion, excavation work, and welding or joint failure. A lot of method already be implement by water industries and researcher in order to overcome this problem. Water industries also provide investment in order to build technology to overcome or reduce water loss problem [4].

Pressure transient wave method most studied by researchers worldwide in order to overcome and locate the leakage position especially for underground pipeline network that cannot be inspect visually due to low cost and good accuracy. Theoretically, transient phenomena occur due to sudden or rapid open and closing valve. The transient wave inside the pipeline with influence by speed of sound naturally carry information about pipeline features such as leak, junction, blockage, and outlet. However, the problem focus on how the transient signal transmitted inside the pipeline need to be analyse. Researchers gather their idea on signal analysis method to extract all features inside the signal captured by using pressure sensor. Nowadays, many method for pressure transient analysis already been practice in real life problem such as wavelet [5], cepstrum analysis [6], inverse transient analysis [7], instantaneous frequency analysis [8], and cross-correlation [9]. Furthermore, with a high noise ratio capture inside the signal, the data can be decompose into several component of IMFs by using EMD [10]. This method proved suitable for a non-linear and non-stationary. There is problem in order to select the best component of IMF that suitable for further analysis. This research proposed Ikaz to kurtosis as method in automatically selecting component of IMF for IFA analysis. Basically, Ikaz is a statistical method develop by [11] that capable to show either amplitude or frequency difference by concurrently gain Ikaz coefficient. This solve the problem for EMD user that need to find skilful user to select the best IMF for further action.

In this research, TKEO implement as an IFA to extract the information inside the noisy signal to locate the position of artificial leak and outlet. Signal that is select by Ikaz to kurtosis ratio from several IMFs will undergo TKEO analysis so that the data can be gain in time-frequency domain. As a nonlinear operator, TKEO function to track energy and clarify the data into instantaneous amplitude and instantaneous frequency of a mono-component data [12-14]. TKEO is proved to be reliable used for a non-linear and non-stationary data as [12] used this method to analyse various speech analysis applications.

## 2. Empirical Mode Decomposition (EMD)

EMD method in one of the well-known method among researcher especially that deal with signal that contaminated with noise. EMD is powerful tool to that can classify original signal into several component of IMFs from high frequency data to low frequency data and one of the self-adaptive method. [15]. The mainframe equation of this method can be write as

$$x(t) = \sum_{i=1}^N c_i(t) + r_N(t) \quad (1)$$

Where  $c_i(t)$  indicates the  $i$ th IMF and  $r_N(t)$  indicates the residual of the original signal  $x(t)$ . IMF that generate by EMD divide into several component depending on the signal noise to ratio level. This IMF must satisfy two main condition while  $r_N(t)$  usually a constant. Those conditions are:

- Number of extrema and number of zero crossing either equal or different at most by one.
- At any point, the local average of upper and lower envelope is equal to zero [16].

### 3. Integrated Kurtosis Algorithm for Z-Filter (Ikaz) Technique to Kurtosis Ratio

#### 3.1. Integrated Kurtosis Algorithm for Z-Filter (Ikaz)

Founder of Ikaz using 2.56 Nyquist number in developing this statistical method because many researcher in signal processing worldwide contented with this value [11]. The value of maximum frequency follow equation (2) in order to avoid the aliasing phenomenon.

Original signal in time domain will be decompose into three range of frequency as stated below:

- Low frequency (LF) range of  $0-0.25 f_{\max}$ : for x-axis
- At high frequency (HF) range  $0.25 f_{\max} - 0.5 f_{\max}$ : for y-axis
- Very high frequency (VF) range  $0.5 f_{\max}$ : for z-axis

Second order of Daubechies theory is applied in order to determine  $0.25 f_{\max}$  as low frequency limit while  $0.5 f_{\max}$  as high frequency limit based on signal decomposition process [17]. Ikaz also yield 3-D illustration of frequency signal distribution based on kurtosis. Variance,  $\sigma^2$  of each signal frequency band calculated that are  $\sigma_L^2$ ,  $\sigma_H^2$  and  $\sigma_V^2$  in order to measure scattering of data distribution and provided in equation (2), (3) and (4) respectively.

$$\sigma_L^2 = \frac{\sum_{i=1}^N (x_L^i - \mu_L)^2}{n} \quad (2)$$

$$\sigma_H^2 = \frac{\sum_{i=1}^N (x_H^i - \mu_H)^2}{n} \quad (3)$$

$$\sigma_V^2 = \frac{\sum_{i=1}^N (x_V^i - \mu_V)^2}{n} \quad (4)$$

Finally, the coefficient of Ikaz is finalised as below:

$$Z\sigma = \sqrt{(\sigma_L^2)^2 + (\sigma_H^2)^2 + (\sigma_V^2)^2} \quad (5)$$

#### 3.2. Kurtosis

Kurtosis one of the statistical method that functions to measure peakiness a signal that contains spikes. It is suitable to be used in pressure transient signal that known as non-stationary signal and formulated as in equation (6).

$$Kurtosis(x) = \frac{E\{(x-\mu)^4\}}{\sigma^4} \quad (6)$$

Where  $\mu$  is mean while  $\sigma$  represent its standard deviation of time series signal. As a result the, the final equation of Ikaz to kurtosis ratio become as equation (7).

$$ZK\sigma = \frac{\left(\sqrt{(\sigma_L^2)^2 + (\sigma_H^2)^2 + (\sigma_V^2)^2}\right)(\sigma^4)}{E\{(x-\mu)^4\}} \quad (7)$$

#### 4. Methodology

The experimental setup in this research focused on to replicate the transient signals phenomenon that occurs due to the change of pressure inside the pipe and generates water hammer inside the pipe. For lab scale experiment, water hammer phenomena create by using solenoid valve that as opening and closing valve to robust with the situation in real life.

##### 4.1. Pipeline system (test rig)

This experiment was conducted by using 67.9m of MDPE pipe with 60mm diameter and 2.6mm thickness. Along the pipeline network, an artificial leak is constructed at the 19.75m distance from the point of analysis as shown in Figure 1. The point of analysis in this experimental test is fire hydrant attached with an improved cap that includes a solenoid valve and pressure sensor as highlight in Figure 2. The outlet of the pipeline system placed to a surface of water inside a tank in order to make sure the water circulating inside the system. This setup was to ensure that the pump that provides water into the system could operate smoothly without any problem.

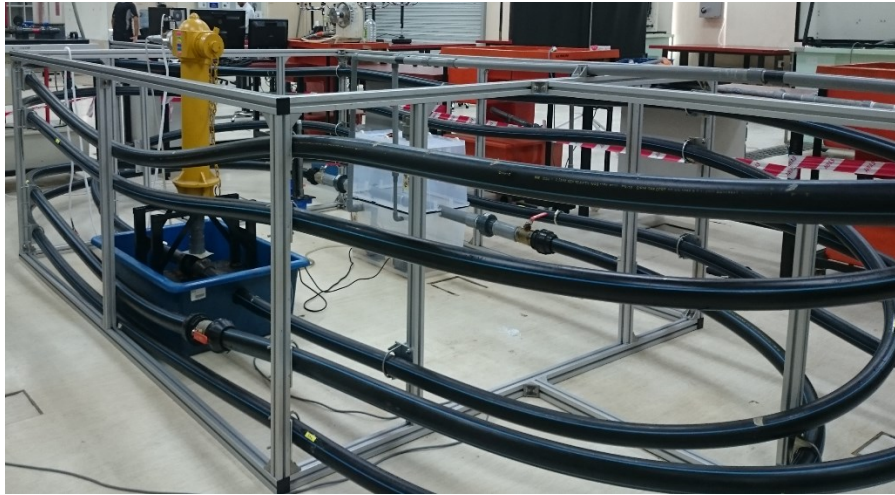


Figure 1. Artificial leak.



Figure 2. Point of analysis.

Solenoid valve that attached to the point of analysis installed 10m away from the pump position. This is due to the high level of noise generated by the pump thru the water flow inside the pipe. Water that pumps out by the pump generates a turbulent flow due to the high velocity and high pressure. This can cause friction inside the pipe between the water flow and inner wall of the pipe. As a solution, the point of analysis where the pressure sensor placed installed a little bit far from the inlet source. As mention before, when the solenoid valve surges a water hammer throughout the pipeline, the transient signal will be generated and propagate along the pipeline network with consideration of speed of sound inside the pipe. The wave transmitted inside the pipe will slowly disappear after it passes through the pipe features. Theoretically, when the transient wave propagates, it will follow the flow of water inside the pipe. When there is disturbance inside the pipe such as blockage, pipe features or leakage, the wave that travel will be distributed into three categories. The first one absorbed wave that absorbed the energy of the wave when it meets features along the pipeline. The second one is a transmitted wave that will follow the flow of water with lesser energy. The third wave has reflected the signal. This signal is the most crucial part of this research. This is because; the reflected wave will reflect the signal into the point of analysis. At this moment, the pressure sensor will collect information from the reflected wave. This wave will carry information along the pipelines networks until the original wave propagates vanish. The pressure sensor will gather all signal either inside the pipe or also from the surrounding. This will cause the data captured contaminated with high level of noise. This will overcome by applying signal analysis method that introduced in this paper.



**Figure 3.** Pipeline system.



**Figure 4.** Solenoid valve.



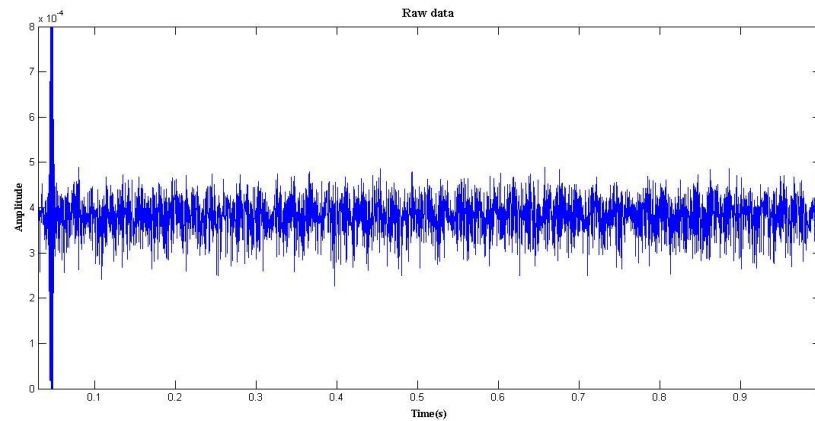
**Figure 5.** Pressure sensor.

Figure 3 shows the pipeline of the system that is fabricated for laboratory scale testing. However, this lab scale of test rig theoretically robust with real water distribution application. The new designed of fire hydrant cap make it easier for water authorities to handle the apparatus and used in a real water distribution network. The main component at the fire hydrant cap is the solenoid valve and pressure sensor as shown in figure 4 and figure 5 respectively. Solenoid valve function as water hammer generator while the pressure sensor will capture all the information along the pipeline network.

## 5. Results and Discussion

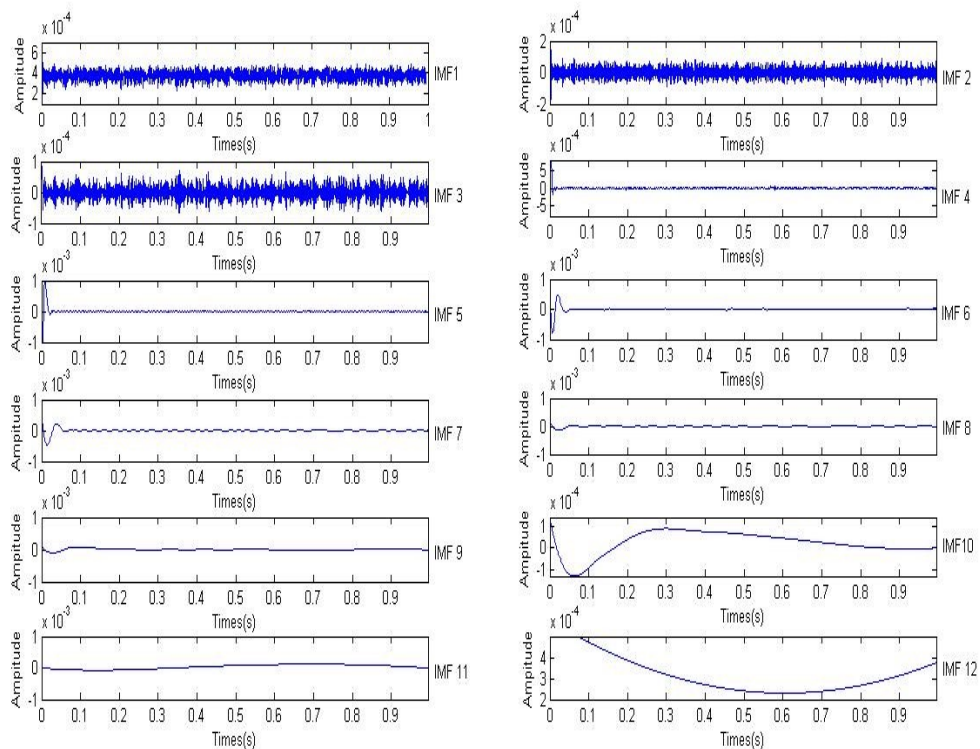
In this research, the process of gathering data done using the pressure sensor and Matlab software. The pressure transient signal inside the pipeline recorded inside Matlab software in order to be analyzed using transient signal analysis. Theoretically, original response or raw data that been captured does not show any information on pipeline features or faulty as shown in figure 6.





**Figure 6.** Raw signal for leak and no leak data.

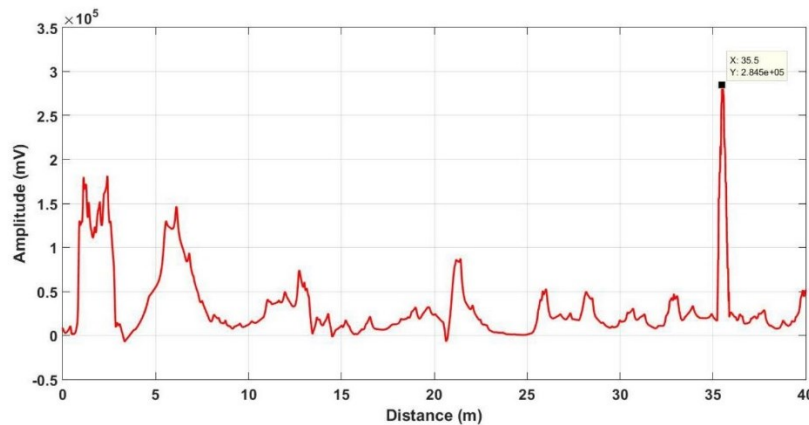
However, the signal that carries all information of the pipeline network hidden inside the original signal. The original signal that already contaminated with all type of either from surrounding or inside the pipe itself. This leads researchers to find a better way to remove all the unwanted noise that stored inside the signal. In this paper, EMD used as the method to decompose the signal into several of IMFs based on their amplitude level.



**Figure 7.** IMFs component decompose using EMD.

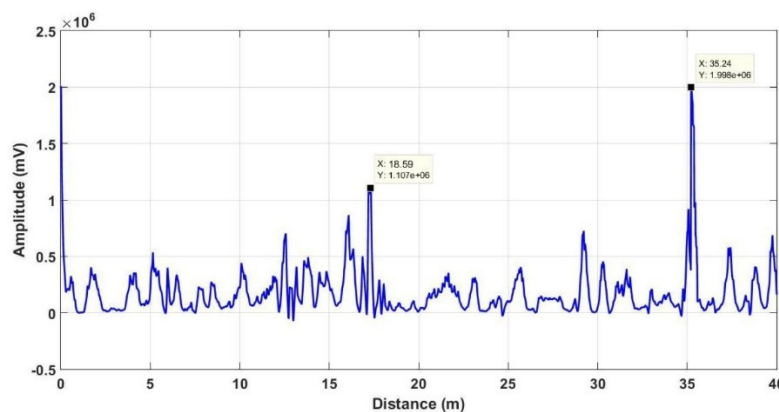
Figure 7 show all the 12 levels of the decomposed component from the original response. EMD is a powerful tool to extract the data that contaminate with noise. As clearly seen in Figure 7, the data divided

into 12 levels in order to differentiate between the noise signal and the real signal. IMF level 1 until 3 usually contains noise that captured by pressure sensor from the surrounding environment and pipe friction. However, to decide which IMF the best for further analysis, high knowledge of users needed. This paper approaches used of Ikaz to kurtosis method in deciding the best IMF for the process. Ikaz-kurtosis method will automatically select the highest Ikaz-kurtosis coefficient between 12 levels of IMF. This component of IMF used for further instantaneous frequency analysis. Instantaneous frequency domain will extract all the information contain inside the data by showing spikes based on frequency.



**Figure 8.** Instantaneous frequency approximation of 2bar without leak.

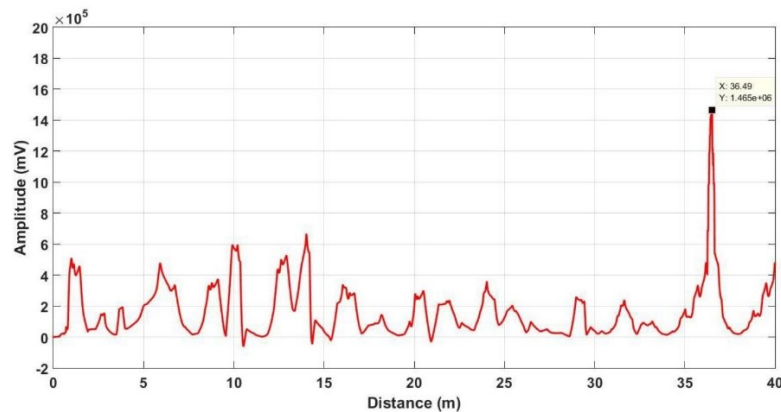
Spike that appears inside the signal after TKEO analysis means that there is information of a pipeline system either leak or other pipe features. Figure 8 shows the instantaneous frequency approximation of 2bar without leak data using TKEO analysis. As clearly, show in the figure, there is a spike that appears at 35.50m. By comparing to the actual pipeline system, the measured distance was the location of the outlet. In Figure 9, it showed that result of instantaneous frequency approximation for 2bar with artificial leak data. Two spikes clearly appeared after TKEO analysis, which means that two features extracted. The first peak appeared at 18.59m while the other appeared around 35.24m. After comparing with real pipeline network, it shows that the spikes distanced is approximate to the artificial leak and outlet position respectively.



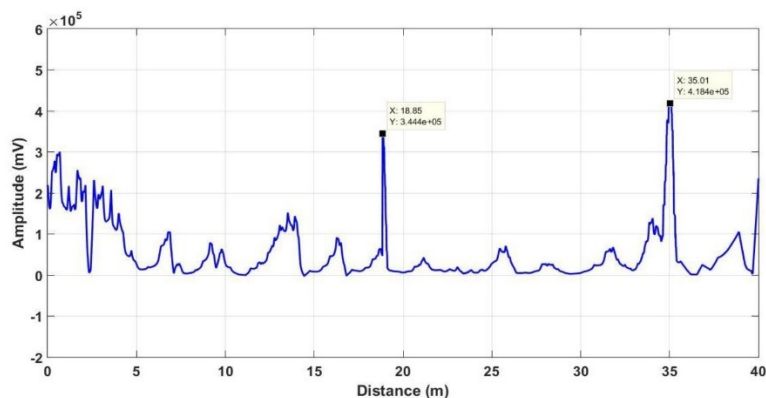
**Figure 9.** Instantaneous frequency approximation of 2bar with leak.



Figure 10 illustrates the result of TKEO as approximation instantaneous frequency analysis for 4bar pressure without a leak. The spike occurs at 36.49m and it is the position of outlet in the pipeline. While in figure 11, it is the representation of the instantaneous frequency estimation of 4bar data with a leak. The presence of two reflections corresponds to leak and outlet position in the real pipeline network. The reflection occurs at 18.85m and 35.01m inside the data after TKEO analysis.



**Figure 10.** Instantaneous frequency approximation of 4bar without leak.



**Figure 11.** Instantaneous frequency approximation of 4bar with leak.

Lastly, the tabulated data recorded in Table 1 and the percentage of error calculated between the measured distance and experimental distance. As clearly illustrate in the table, the pipeline feature of 2bar without leak data show 3.0% value of percentage error. Meanwhile, for 2bar data with leak show that the percentage of error for a leak and outlet are 5.9% and 3.7% respectively.

Besides that, the 4bar model without leak show percentage of error 0.3% for outlet position. In the model with leak data, leak signature detected in the system with an error of 4.6% while the outlet is 4.3%. Therefore, from the result obtained, it has shown that Teiger Kaiser Energy Operator (TKEO) method can extract all the data for leak and outlet of non-stationary a signal. From this research, it proved that TKEO is the best method of instantaneous frequency analysis to detect the spike inside the data. This method also can detect the presence of transient event inside a pipeline network.

**Table 1.** Percentage of error between measured and experimental distance.

Pressure	Signal Response	Pipe Feature	Measured Distance (m)	Experimental Distance (m)	Error (%)
2bar	No leak	Outlet	36.60	35.50	3.0
	Leak	Leak	19.75	18.59	5.9
		Outlet	36.60	35.24	3.7
4bar	No leak	Outlet	36.60	36.49	0.3
	Leak	Leak	19.75	18.85	4.6
		Outlet	36.60	35.01	4.3

## 6. Conclusion

As a conclusion, this paper discussed the Empirical Mode Decomposition (EMD) as the pre-processing method. The implementation of Integrated Kurtosis Algorithm for Z-Filter (Ikaz) to Kurtosis ratio show a successful outcome in automatic selecting of intrinsic mode function (IMF). It recommended using this method in order to avoid wrong decision making while selecting the IMF. Moreover, Teiger-Kaiser Energy Operator (TKEO) as post-processing method efficiently work in order to analyze the spike inside a non-stationary data. Therefore, this method can be used in real live water distribution in order to detect and locate the position of the leak along the pipeline network. With a low percentage of error, it will help water authorities to reduce the scale of searching for leak position along the pipeline system.

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