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The use of transmission line modelling to test the effectiveness of I-kaz as autonomous selection of intrinsic mode function

Hanafi M Yusop^{1,*}, M F Ghazali¹, M F M Yusof¹, M A PiRemli¹, B Karollah², Rusman²

¹Advanced Structural Integrity and Vibration Research (ASIVR, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pekan, Pahang, Malaysia

²STIES, Jl. Prada Utama, Peurada, Syiah Kuala, Kota Banda Aceh, Aceh 24415, Indonesia

*Corresponding author: m.hanafiyusop@yahoo.com.my

Abstract. Pressure transient signal occurred due to sudden changes in fluid propagation filled in pipelines system, which is caused by rapid pressure and flow fluctuation in a system, such as closing and opening valve rapidly. The application of Hilbert-Huang Transform (HHT) as the method to analyse the pressure transient signal utilised in this research. However, this method has the difficulty in selecting the suitable IMF for the further post-processing, which is Hilbert Transform (HT). This paper proposed the implementation of Integrated Kurtosis-based Algorithm for z-filter Technique (I-kaz) to kurtosis ratio (I-kaz-Kurtosis) for that allows automatic selection of intrinsic mode function (IMF) that's should be used. This work demonstrated the synthetic pressure transient signal generates using transmission line modelling (TLM) in order to test the effectiveness of I-kaz as the autonomous selection of intrinsic mode function (IMF). 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 I-kaz-kurtosis ratio revealed that the method can be utilised as an automatic selection of intrinsic mode function (IMF) although the noise level ratio of the signal is lower. I-kaz-kurtosis ratio is recommended and advised to be implemented as automatic selection of intrinsic mode function (IMF) through HHT analysis.

1. Introduction

Water play an important role in the contribution to the economic growth of a country. In the recent decade, water is one of the major issues addressed in research worldwide due to the increase in water pollution and non-revenue water (NRW). Water Economy Network (WEN), reported that water scarcity rapidly enhancing the number one global resource concern. Consequently, with the increase in the number of accessible clean and fresh water, the water network will increase thus the possibility of the increment of water issues is higher. The first global survey conducted by Lai [1] reported that's water loss for most country falling into the range of 20%-30% and for Malaysia, the number is 43% of NRW. Non-revenue water (NRW) is when the amount of water reach to the consumer is lesser than the amount of water that has been produced. The losses are due to real losses such as pipeline network leakage or the apparent loss such as through theft or bypass of water network (the water reach to the consumer not metered) and metering inaccuracies. Nowadays, minimising of NRW during transportation process through pipeline network is very essential. The problem of water leaks in pipeline distribution system is the main cause of Non-revenue water (NRW). Lately, water authorities concern of leak in water distribution system, then provide some necessary incentives for investment in leak detection technology and leak reduction strategies [2]. The main cause of leaks is due to the aging



of pipelines, corrosion, erosion, excessive pressure of water resulting from operational error and water hammer generate by rapid opening and closing valve.

There are two types of leak detection technique which are an external and internal method. External method is a way to inspect pipe condition externally such as by visually inspecting the pipe condition and the internal method inspects the pipe condition, internally such as by mathematical computation and signal processing [3]. Signal processing is a famous method among the researchers due to its ability to detect and localise any disturbance (leak) and blockage in the pipeline system. Pressure Transient analysis is a recently developed method and attracted researchers due to cost effectiveness. Theoretically, transient phenomena are generated due to sudden changes of fluids propagation filled in the pipeline's system caused by rapid pressure and flow fluctuation in the systems such as rapid closing and opening valve. These phenomena generate pressure wave propagation which travels with the speed of sound along the pipeline's system then the wave characteristic represents the pipe information and condition from various boundaries such as pipe feature, junction outlet and the presence of the leak. Signal analysis is a way to extract the characteristics, identity, and information of pressure transient signal captured along the pipeline distribution system. A variety of pressure transient analysis method has been practiced among the researchers in order to extract information and characteristic of pressure transient signal such as cepstrum analysis [3], cross-correlation [4], orthogonal wavelets transform (OWT) [3], instantaneous frequency analysis [5], and inverse transient analysis [6].

The possibility to analyse the phenomenon in both time and frequency domain has been satisfied by implementation of time-frequency signal processing techniques such as Hilbert-Huang Transform (HHT). HHT analysis was proposed since the ability of this method to detect and capture transient phenomena occur in the non-stationary signal. In recent years, HHT has been more widely used as time-frequency analysis as signal processing method [7, 8]. HHT was proposed as newly developed and powerful method to analyse non-linear and non-stationary signal [9].

However, this method has the difficulty in selecting the suitable IMF for the next data post-processing method which is Hilbert Transform (HT). Since HHT through Empirical Mode Decomposition (EMD) will decompose the signal into the different monocomponent and symmetric component by the sifting process. The monocomponent signal called as intrinsic mode function (IMF) [10]. The main drawback of this approach is the necessity to know a priori the frequencies and level of original signal that's should be analysed [11]. The HHT analysis, in this case, is not completely automatic since need the interaction of the skilled user to select which IMF level was suitable for further analysed. Therefore, automatic selection for better IMF needed to overcome this problem. The mathematical computational technique and statistical value analysis were applied by the researcher to increase the degree of automation then eliminate the interaction of the skilled user to select the relevant IMF.

There have been relatively few recent studies and statistical approach on measurable quality for automatic selecting relevant and appropriate intrinsic mode function (IMF). Maji et al. [12] proposed variance and standard deviation as statistical value to differentiate each level of the decomposition of intrinsic mode function (IMF). The research was done using electrocardiogram (ECG) signal in order to detect Artificial Fibrillation (AF) rhythm and normal rhythm. Ricci and Pennacchi [11] demonstrated Merit Index as an indicator that allows automatic selection of IMF level. The research utilises rotary element (gear) signal to test the efficiency of merit index in selecting of relevant and appropriate IMF. The method works as a measure of periodicity degree and absolute skewness of each IMF level. In monitoring rotating machines, Kedadouche et al. [13] introduced computation of correlation coefficient value for each level of IMF as quantifiable quality in selecting appropriate IMF level. In the research vibration signal was captured from rolling element (bearing), then the signal extracted using a hybrid method of Minimum Entropy Deconvolution (MED), Empirical Mode Decomposition (EMD) and Teager Energy Operator (TEO). The selected IMF is the IMF which presents the higher value of correlation coefficient compare to the original signal. De Souza et al. [14] present an Energy-Based approach through mutual information (MI) coefficient as a method of selection relevant IMF. The research was done by applying the synthetic signal with embedded in white noise and real-world signal. Mutual Information (MI) also utilised as a method to select

appropriate IMF in biomedical signal processing done by Ricci and Pennacchi [11].

This research proposed Integrated Kurtosis Algorithm for Z-notch filter hybrid with higher order statistical method (Kurtosis) as the automatic selection of intrinsic mode function (IMF). The Ikaz has chosen as since the approach of this method was adaptive in general and detects very well any changes and uncertainties of the measured signal [15]. Unlike the existing statistical analysis such as variance, standard deviation, and kurtosis, I-Kaz method was capable of indicating both amplitude and frequency difference by simultaneously obtaining the I-Kaz representation and I-Kaz coefficient, $Z\sigma$. Details experimental result was discussed by Nuawi et al. [15] and Rizal et al. [16] using vibrational signal acquire from rotating machinery part (Bearing) and detect tool wear during turning process respectively. The research conducted by Nuawi et al. [15], the I-kaz was compared to variance and the results are, variance parameter was unable to detect both amplitude and frequency changes in the non-stationary signal. Thus, the Ikaz method was reliable especially for monitoring purpose where the observation on the changes of the signal amplitude and frequency were commonly required.

The effectiveness and reliability of the Ikaz-kurtosis ratio as the automatic selection of IMF was done using artificial pressure transient signal and random signal generated using Matlab and the results revealed IMF contain maximum value of Ikaz-kurtosis ratio coefficient was relevant and appropriate to be further analysed. The research also was done by comparing the effectiveness of kurtosis compared to I-kaz as the automatic selection method for better IMF. The aim of this paper focused on the implementation of Ikaz-kurtosis ratio coefficient as the automatic selection of intrinsic mode function using synthetic pressure transient response generate using transmission line modelling (TLM). TLM is a technique, computationally very efficient, for studying a wide range of wave and diffusion phenomena. The white Gaussian noise was added into each of the signal response acting as the background noise in order to make the signal response was similar to the real one. The result for synthetic signal response with added background noise generates using TLM presented the IMF contain highest value of Ikaz-kurtosis coefficient was suitable and appropriate to be further analysed. Furthermore, the Ikaz-kurtosis ratio was proven suitable as an automatic selection method for better and relevant IMF and highly proposed to test the effectiveness using real pressure transient response. Therefore, the degree of automation for Hilbert-Huang Transform (HHT) was improvised to detect pipe leakage in live water distribution system using pressure transient signal.

2. Integrated based Kurtosis algorithm for z-filter technique to Kurtosis ratio

2.1. Integrated based Kurtosis algorithm for z-filter technique

Integrated Kurtosis-based algorithm for z-filter technique (Ikaz) is the method developed based on the concept of data scattering about its centroid. The sampling frequency of the raw signal was chosen as 2.56 referring to Nyquist number [15]. Most of the researcher in signal analysis and processing are comfortable with the number. To avoid the aliasing effect, the maximum frequency span will be of equation 1.

$$F_{\max} = \frac{fs}{2.56} \quad (1)$$

Ikaz decomposes the time domain signal into three level of the frequency range, which are x-axis represent as low frequency (LF) with a range of 0 – 0.25 of f_{\max} , followed by y-axis represent as high frequency (HF) with a range of 0.25 – 0.5 of f_{\max} . Finally, z-axis represents as very high frequency (VF) with range 0.5 of f_{\max} . The 0.25 f_{\max} and the 0.5 f_{\max} was selected as low and high-frequency range limit respectively done with referring to the 2nd order of the Daubechies concept in signal decomposition process [17]. Referring to the kurtosis, I-kaz method contributes of three-dimensional graphical representation of the measured signal frequency distribution. The variance, σ^2 of each frequency band which is σ_L^2 represent as a low-frequency band, σ_H^2 represent as a high-frequency band and σ_V^2 represent as a very-high-frequency band which calculated as in equation 2,3 and 4 to measure scattering of data distribution.

$$\sigma L^2 = \frac{\sum_{i=1}^N (x_i - \mu_L)^2}{n} \quad (2)$$

$$\sigma H^2 = \frac{\sum_{i=1}^N (x_i - \mu_H)^2}{n} \quad (3)$$

$$\sigma V^2 = \frac{\sum_{i=1}^N (x_i - \mu_V)^2}{n} \quad (4)$$

The I-Kaz coefficient, $Z\sigma$ can be simplified in term of variance, σ as in equation 5 [16].

$$Z\sigma = \sqrt{(\sigma L^2)^2 + (\sigma H^2)^2 + (\sigma V^2)^2} \quad (5)$$

2.2. Kurtosis

Kurtosis describes as a measure of spikiness and hence a good indicator of peak analysis for spikes detection in a non-stationary signal component such as pressure transient. Kurtosis is expressed as;

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

where μ and σ represent the mean and standard deviation of time series signal respectively. The E illustrate the expectation operation. The kurtosis demonstrates the spikiness and peakedness of probability distribution associated to the instantaneous amplitudes of the time-series analysis [18]. Therefore, the I-kaz-kurtosis ratio expressed as equation 7.

$$ZK\sigma = \frac{(\sqrt{(\sigma L^2)^2 + (\sigma H^2)^2 + (\sigma V^2)^2})(\sigma^4)}{(E \{ (x - \mu)^4 \})} \quad (7)$$

2.3. Algorithm

Automatic selection of intrinsic mode function (IMF) based on pressure transient signal

1. Perform EMD on a synthetic pressure transient response generate from TLM
2. EMD decomposed the signal into so-called level of Intrinsic Mode Function
3. Calculate the Integrated Kurtosis Algorithm for a z-filter technique to kurtosis ratio (Ikaz-Kurtosis) coefficient using Eq. 7.
4. Identified the IMF that corresponds to the largest Ikaz-kurtosis ratio coefficient.
5. Perform Hilbert Transform (HT) and Hilbert Spectrum (HS) for IMF level that contains the largest coefficient of Ikaz-Kurtosis ratio.

3. Methodology

3.1. Simulated pressure transient signal

In this research, two simulated pipeline models were constructed with different pipe length, water pressure and a number of leaks fitted on the pipeline model. The first model (Figure 1(a)) simulated was a pipe with the leak and without a leak. The model consists of Medium High-Density Polyethylene (MDPE) pipe, which is divided into 3 section by the valve and junction (Figure 1(a)). The total distance of pipe for the first model is 70 meter with water pressure by 1 bar. The second model (Figure 1(b)) consist of MDPE pipe, which is divided into 4 section by valve and 2 junctions. For the second model, the number of the leak is 2 with total distance and water pressure acting on the

pipe is 73 meter and 2 bars respectively. For simulated signal without a leak, the resistance of the junction is set to be 3000 meanwhile for the simulated signal with the leak, the resistance at the junction set to be 30,000,000. Both models has pipe diameter with 60 mm respectively.

The design of the model was made as simple as possible in order to validate the identification approach. Opening and closing the valve (Figure 1) cause water hammer pulse which then propagates through the system. The system was applied time-varying valve as detailed describe by Beck et al. [19]. The software allows the user to set the geometry, length, and diameter of the pipes. By inserting the higher value of resistivity at the junction in order to simulate the leak feature, then some of the pressure wave generated by the valve will be reflected. By knowing the distance of the reflection point from the end of the pipe and the speed of sound that pressure waves travel through the medium, the location of the leak and pipe outlet can be determined.

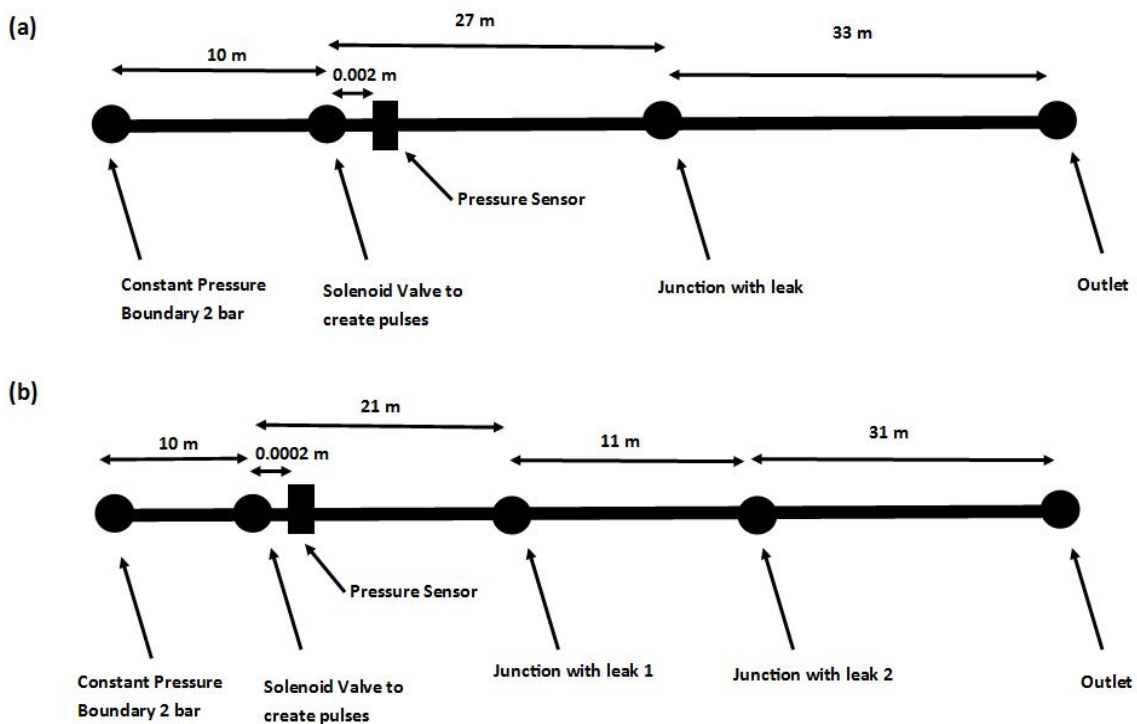


Figure 1. Pipe network model. (a) First model (b) Second model

In this research, water was utilized as simulated fluid as the medium flow in both pipeline model. It was assumed that water has Standard Temperature and Pressure (STP). The speed of sound is equal to 493 m/s since the material and pipe diameter apply on the model is MDPE and 60 mm respectively. The distance between the valve and the pressure sensor was set to 0.001 meters (Figure 1). This simulates the capture of a time history of signal response of pressure using a pressure sensor located very close to the valve. The software also allows the user to choose any number of flow and pressure data as the output from the system.

3.2. Added white Gaussian noise

The white Gaussian noise then added to each of signal response generates from TLM software in order to make the signal very close to the real pressure transient signal. The value of Signal to Noise Ratio (SNR) is a key parameter when deciding to generate white noise signal response. If the added noise is too weak to bring the changes of extrema of the original signal. Conversely, 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 [20]. According to Zhang et al. [21], it appropriates for EMD/EEMD method to set SNR between the original signal and added noise is approximately 37 dB. Therefore, the value of SNR is set to be 37 dB. 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 indicated the signal response with added noise. The signal response from TLM with added noise then going to analyse using Hilbert-Huang Transform (HHT) and Integrated Kurtosis Algorithm for Z-notch filter technique (IKAZ) as the automatic selection of intrinsic mode function (IMF). The results of the analysis will show the characteristic of the pipeline that has indicated the pipe feature (leak, blockage and pipefitting).

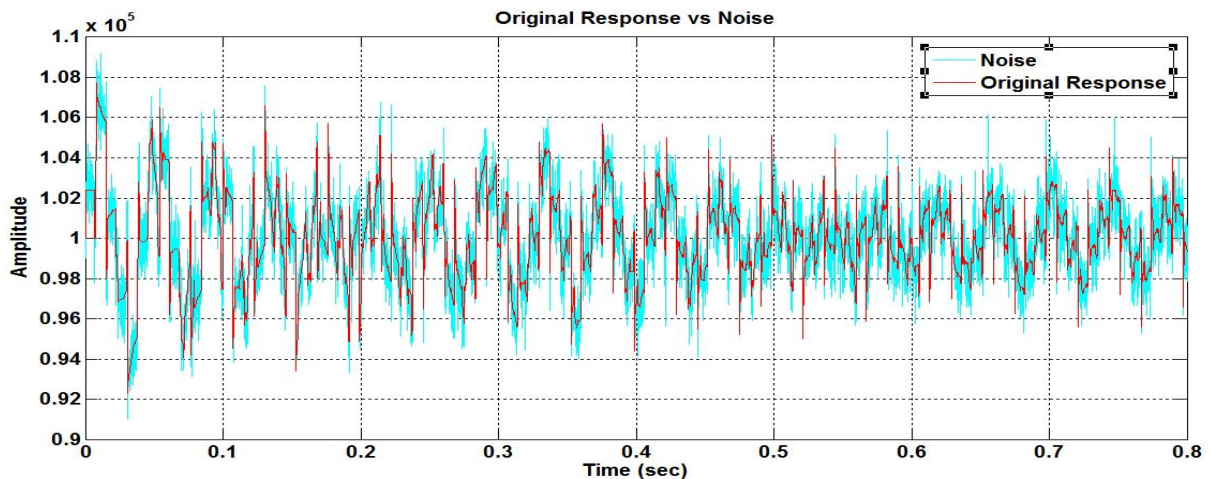


Figure 2. Signal response with added white Gaussian noise.

4. Results and discussion

Figure 3 illustrate the signal response with added noise for the first pipe network model. Figure 3 (a) and (b) show the no leak and with leak response respectively. Meanwhile Figure 4 present the signal response from second pipe network model with added noise. Presented in Figure 4 (a) and (b) are the signal response of no leak and leak respectively. By using Hilbert-Huang Transformed that's contained of Empirical Mode Decomposition (EMD) and Hilbert Transform (HT), the instantaneous frequency and phase angle of the original signal was obtained.

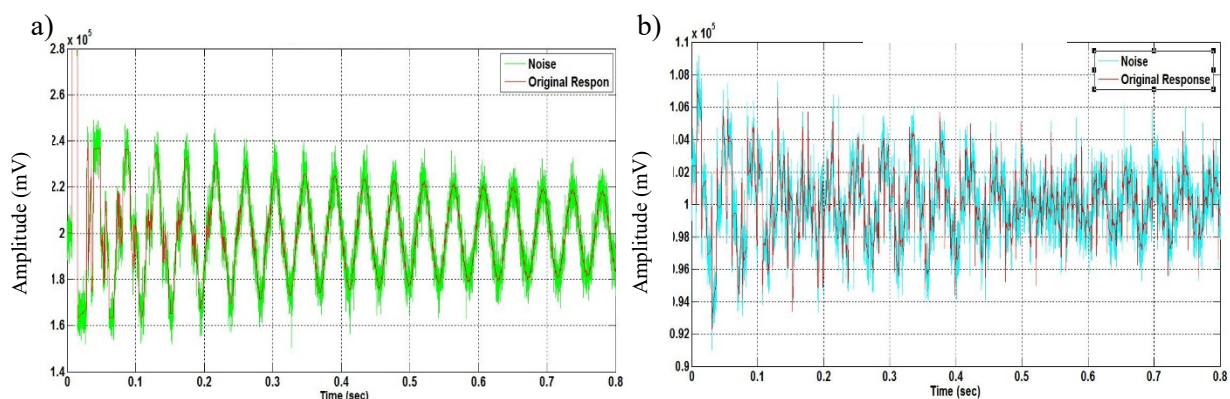


Figure 3. Signal response with added noise for first pipeline model.
a) No leak response b) With leak response

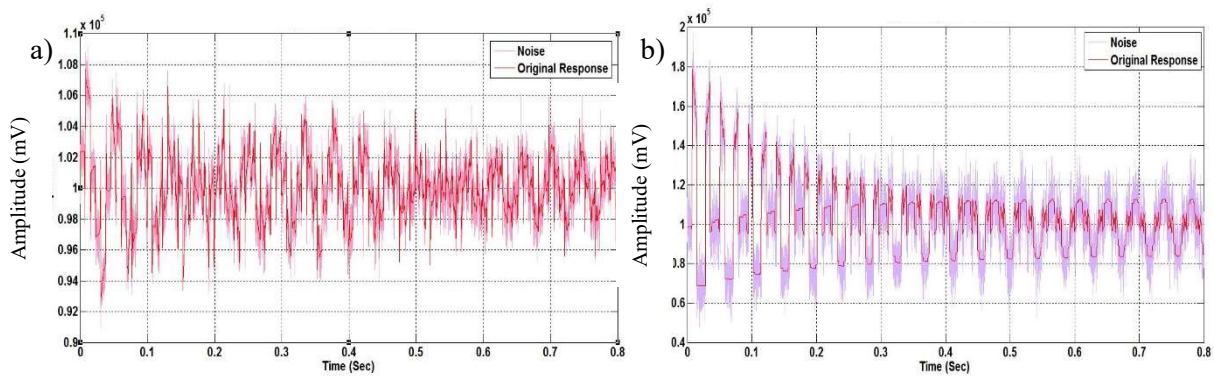


Figure 4. Signal response with added noise for second pipeline model.
a) No leak response b) With leak response

The step of analysis began with the signal response was decompose into Intrinsic Mode Function (EMD). EMD decompose the signal response into 13 levels of intrinsic mode function (IMF). Figure 5 shows the amplitude versus time for the first 12 levels of IMF. The first level of IMF is a group of higher frequency signals which is the noise signal. The last level was a reserve for the lower frequency signals. The first and second level of IMF was avoided for further analysis because of these levels contain noise frequency signals. Meanwhile, IMF level 7 and the residue contain basic respond of the network. All these IMF were, therefore, discarded. The rest which is IMF level 3-6 have been recombined to produce a signal without noise [22]. Therefore, in order to identify which level of IMF is suitable for going through the final step of Hilbert-Huang Transform (HHT) which is Hilbert Transform (HT), Integrated Kurtosis Algorithm for Z-filter technique to kurtosis ratio (Ikaz-Kurtosis) was implemented. Since EMD decomposed the signal response into 13 levels of IMF, the Ikaz-Kurtosis ratio was utilised to computed the coefficient of each level.

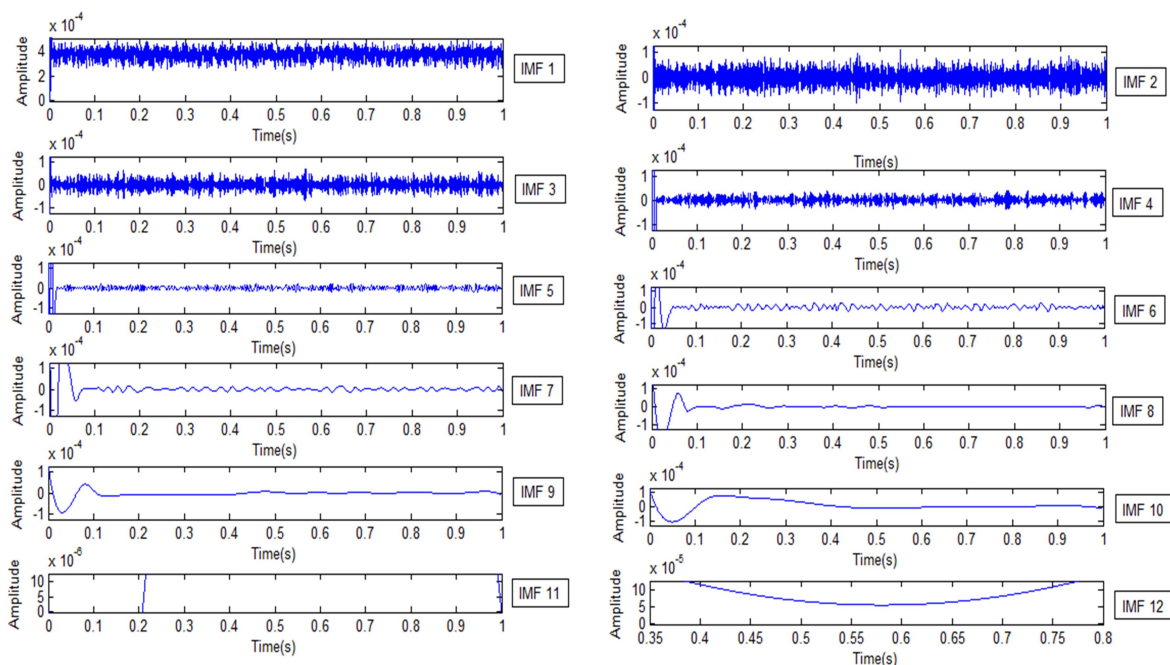


Figure 5. Intrinsic Mode Function (IMF) from level 1-12.

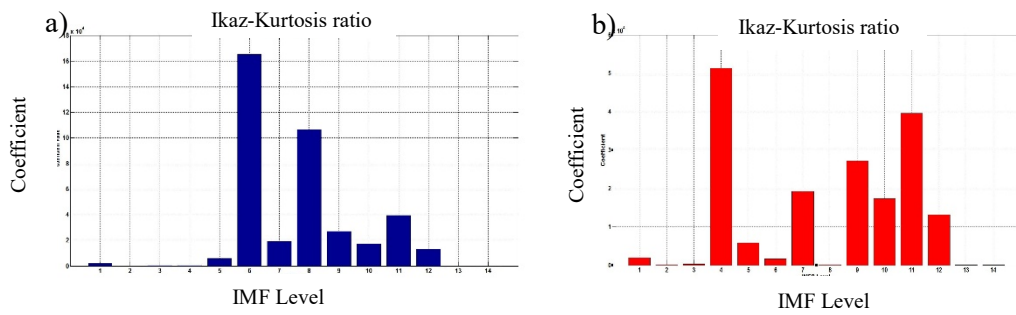


Figure 6. Ikaz-Kurtosis ratio coefficient for first pipeline model. a) No leak signal b) With leak signal

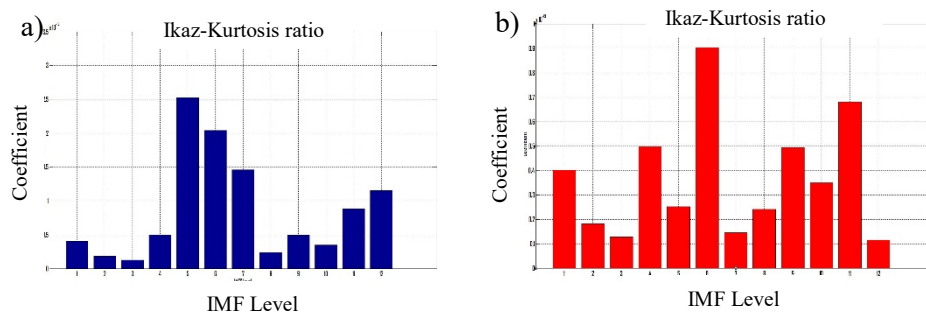


Figure 7. Ikaz-Kurtosis ratio coefficient for second pipeline model. a) No leak signal b) With leak signal

Figure 6 (a,b) and 7 (a,b) represent the Ikaz-Kurtosis ratio coefficient histogram for the first and second pipe network module for the Without leak and with leak response respectively. The X-axis show the IMF level. Meanwhile, Y-axis show the value of Ikaz-Kurtosis ratio coefficient. From the observation, the maximum and highest value of Ikaz-Kurtosis coefficient were the most suitable IMF level for going through the post-processing and the final step of Hilbert-Huang Transform (HHT) analysis which is Hilbert Transform (HT). This is because the IMF level which contains the highest value of Ikaz-Kurtosis ratio consist of the IMF selection criterion which is clear and narrow spikes. The lower the value of Ikaz-Kurtosis ratio, the obscure of clear and narrow spikes which are the main selecting criterion of IMF. In addition, the IMF level that contains the highest value of Ikaz-Kurtosis ratio coefficient was reserved on level range of 3-6. As explained above, level 3-6 have been recombined to produce a signal without noise [22]. Therefore, the level is relevant and appropriate to further analysed. As illustrated in Figure 6 (a) the IMF level 6 contained the highest Ikaz-Kurtosis ratio meanwhile 6 (b) reserved on IMF level 4. The Figure 7 (a) , show IMF level 5 was contain the highest coefficient followed by IMF level 6 for Figure 7 (b).

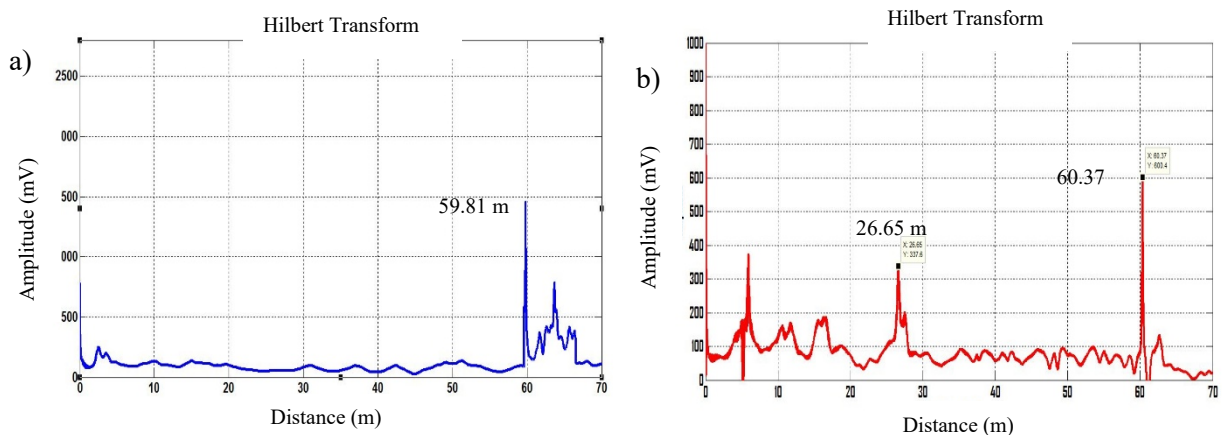


Figure 8. Instantaneous characteristic of HT analysis for first pipe network model. a) Signal without leak b) Signal with leak

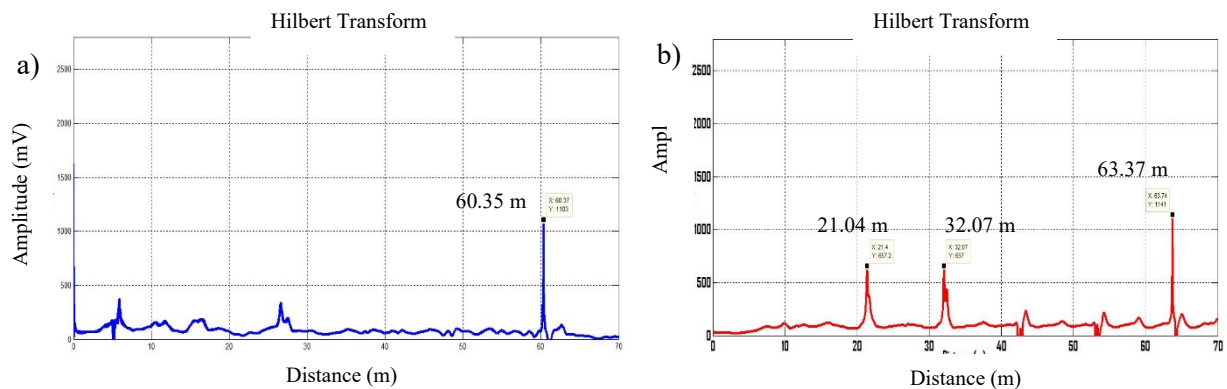


Figure 9. Instantaneous characteristic of HT analysis for first pipe network model.

a) Signal without leak b) Signal with leak

Figure 8 and 9 show the instantaneous characteristic of the signal for first and second pipe network model. Meanwhile a and b represent for a signal without leak and with the leak. The instantaneous frequency clearly highlights the presence of a reflection. The peak of the analysed 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. The distance of the reflection point is calculated by multiplying the time delay corresponding to the peak by the speed of sound in the pipe network ($a=493$ m/s) and halving this value to account for the return journey. As shown in Figure 8 (a) and (b), the presence of reflection corresponding to outlet signature is clearly seen by 59.81 m and 60.37 m respectively. Meanwhile, the reflection corresponds of leak signature seen in Figure 8 (b) was measured by 26.65 m. Figure 9 (a) and (b) illustrated the reflection with the signature of the outlet was measured by 60.35 m and 63.37 m. The reflection with the signature of leak 1 and leak 2 was measured by 21.04 m and 32.07 m respectively as presented in Figure 9 (b). There are some errors when compared the experimental positioned and simulated positioned. The comparison between simulated and experimental position is tabulated in Table 1.

Table 1. Comparison between simulated and experimental position.

Water pressure	Signal response	Pipe feature	Simulated position (m)	IMF contain maximum I_{kaz} -Kurtosis ratio coefficient	Experimental position (m)	Error %
First Pipeline Model	Leak Data	Leak	27	5	26.65	0.3
		Outlet	60		59.81	1.2
	No Leak Data	Outlet	60	4	60.37	0.6
2 nd Pipeline Model	Leak Data	Leak 1	21	5	21.04	0.2
		Leak 2	32		32.07	0.2
		Outlet	63		63.74	0.5
	No Leak Data	Outlet	63	6	60.35	4.4

As presented in Table 1, for first pipe network model contain leak signature with water pressure of 1 bar, the position of leak shows 0.3% error and position of outlet signature show 1.2% error. Meanwhile for no leak data presented 0.6% error for outlet signature position. Besides that, second pipe network model contains two leak signature with water pressure of 2 bars, the position of signature leak 1 and 2 shows 0.2% for both error and position of outlet signature show 0.5% error. Meanwhile for no leak signal response presented 4.4% error for outlet signature position. From the final part of HHT analysis, it is clearly shown that the position of pipe feature that's is leak and pipe outlet appear

at the same position compared to each original position and simulated positioned. It also proves HHT analysis able to detect and positioning the transient event occurred in the non-stationary pressure transient signal.

5. Conclusions

This paper discussed the self-decision method for IMF selection through Hilbert Huang Transform (HHT) analysis. The result proves the I-kaz-kurtosis ratio is suitable and advisable self-decision method for IMF selection to implement in Hilbert-Huang Transform (HHT) analysis. The development of automated self-decision of IMF through HHT has been built and statistically analysed using I-kaz-kurtosis ratio. Therefore, this method was proposed and advised to be implemented. By efficiently utilizing I-kaz-kurtosis ratio, the issue of IMF selection was overcome. Therefore degree of automation for Hilbert Huang Transform (HHT) was improvised to detect pipe leakage in live water distribution system using pressure transient signal.

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