Development of Intelligent Leak Detection System Based on Artificial Pressure Transient Signal Using Integrated Kurtosis-Based Algorithm for Z-Filter Technique (I-Kaz)

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ABSTRACT

In recent studies, the analysis of pressure transient signal can be seen as an accurate and low-cost method for the leak and feature detection in water distribution system. This paper applied Hilbert-Huang Transform (HHT) as a method to analyse the pressure transient signal. HHT is a way to decompose a signal into intrinsic mode function (IMF). However, this method has the difficulty in selecting the suitable IMF for the next data post-processing method which is Hilbert Transform (HT). To develop intelligent leak detection system through Hilbert-Huang Transform (HHT) analysis, the selection for IMF must be automated and self-decision making process through the system. The current paper presented the implementation of Integrated Kurtosis-based Algorithm for z-filter Technique (I-Kaz) to kurtosis ratio (I-Kaz-Kurtosis) for the purpose of self-decision method in selecting IMF with the correct IMF selecting criterion. This work demonstrated artificial sine signal constructed using Matlab software in order to identify the effectiveness and accuracy of this method. Meanwhile, a random signal was also generated to test the efficiency of I-Kaz-kurtosis ratio. The analysis results using I-Kaz-kurtosis ratio revealed that the method was suggested to be used as self-decision method to select the right IMF. The performance of I-Kaz-kurtosis ratio was also tested using random signal and this method revealed positive results. Meanwhile, the efficiency of I-Kaz-kurtosis ratio

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was compared to kurtosis coefficient, and this method revealed better result from kurtosis coefficient. Therefore, I-Kaz-kurtosis ratio is recommended and advised to be implemented as self-decision method for selecting the IMF through HHT analysis and intelligent leak detection system can be developed.

Keywords: *Leak detection, Pressure Transient, I-Kaz, Hilbert-Huang Transform (HHT)*

Introduction

Water is one of essential parts that contributes to economic growth of a country. In recent decade, water has been one of the major interesting research subjects due to water pollution and Non-Revenue Water (NRW) conflict caused by the growing of human population. Referring to Water Economy Network (WEN) 2016, water scarcity is rapidly enhancing as the number one global resource concern. Within twenty years, the on-going shortage of clean accessible fresh water will be from 300 million cubic meters to 2.8 billion cubic meters [1].

One of the current significant discussions among world researcher is water leakage from water distribution network. The main causes of the leak are due to aging pipelines, corrosion, erosion, excessive pressure resulting from operational error and water hammer (caused by rapid opening and closing valve). Lai [2] conducted one of the first global surveys that reported water loss from several different countries and cities which discovered that these varied from low of 9% in Germany to a high of 43% in Malaysia. Most countries fell into the range of 20% to 30% of Non-Revenue Water (NRW). Regarding to report submitted by International Water Association (IWA) and AWWA Water Loss Control Committee’s 2003 [3], it is estimated that 5 billion kWh of power generated each year in the United States is wasted water that is either lost via leaks or not paid by customer. It appears that between treatments plants and consumer, 25-50% water is lost due to leakages. For that reason, minimizing water loss during transportation process through pipeline system is very essential. Therefore, in recent decades, leak detection method is one of the current significant discussions among the world researcher.

The pressure transient analysis ongoing method is used as a new technique as this method does not only detect a leak, but it also captures other pipe feature reflection. Transient phenomena is generated 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 rapidly closing and opening valve or pump failure. These phenomena will produce pressure waves propagation along the pipeline system with the speed of sound in the fluid. The propagation waves that travel with constant speed along the system will provide and capture pipe characteristic due to reflected wave from various boundaries such as a junction, pipe feature, outlet, reservoir and presence of the leak. Due to effectiveness and cost reduction, a variety of leak detection methods has been developed based on pressure transients such as reflected wave or timing methods, transient damping method, frequency response method, Genetic Algorithm techniques and inverse transient analysis.

From the last two decades, most of the researchers focused on properties of pressure transient for leak detection. Bruno and M.Ferrante [4] used properties of transient pressure waves for leak detection in outfall pipes through the effect of a leak on wave propagation which was then established over the numerical result. The result was compared throughout laboratory experiment. Location of leakage was achieved by timing the reflected pressure waves and speed of sound. The occurrence of transient damping was determined by the presence of a leak and the timing of the damping indicated its location. Brunone and M.Ferrante [5] also investigated the same methods through unsteady pressure waves initiated by closure of an upstream valve known as pressure transient techniques. In their research, they applied the analysis of time history of pressure during a transient event presence on the location of the leak as to be determined by measuring the time for wave to propagate from the leak point to measurement section. Sheffield Group also implemented the same method for leak investigation and location [1]. Covas [6] and Stephens [7] applied reverse engineering techniques with a model that was optimised to fit experimental transient data. This method was reliable to used be in identifying leaks and pipe feature. Liou [8] implemented cross-correlation analysis as a method to analyse transient pressure signal. This technique work used the first reflection of the pressure wave from the disturbance in the flow profile caused by a leak in the system. Taghvaie [9] proposed Orthogonal Wavelets Transform charge as data decomposition method or filtering method and cepstrum analysis as post-processing method.

Since there are various methods that can be used to analyse pressure transient signal, this paper focused on the method instantaneous frequency analysis based on pressure transient signal captured within the live water distribution network. The instantaneous frequency of the signal was analysed using Hilbert-Huang Transform (HHT). HHT analysis was chosen since the ability of this method to detect and capture transient event occurred in the non-stationary signal. In recent years, HHT has been widely used as time-frequency analysis as signal processing method [10] [11]. HHT was proposed as a newly developed and a powerful method to analyse non-linear and non-stationary signal [12]. The restraint to apply this method was a selection of IMF. The previous researcher applied this method by selecting the intrinsic mode function (IMF) visually. Since HHT analysis decomposes the signal into intrinsic mode function (IMF) with different amplitude and frequency band through Empirical Mode Decomposition (EMD), there is no significant method to select IMF automatically by the system. The previous researcher selected IMF level visually and the selection criterion for IMF was narrow or clear spikes and transient. M.F Ghazali [1] proposed kurtosis analysis to select IMF level automatically by the system. From the study, kurtosis analysis was not suitable to be implemented as self-decision method due to lower noise level ratio of the signal. In biomedical signal processing, Kurtosis coefficient was also used as verification stages in electrocardiogram signal to ensure that the generic prediction IMF consisted of extrema based [13]. For rotating machinery fault monitoring, G.F Bin [12] proposed energy moment of IMF as eigenvector to express the failure factor of each IMF. Besides that, for identifying gear faults condition, Ricci [14] introduced a merit index as self-decision method of IMF to be further analysed.

This paper presented the implementation of Integrated Kurtosis Algorithm for z-filter Technique-kurtosis ratio (i-Kaz-kurtosis) as self-decision method for IMF selection depending on IMF selection criterion. From this study, the artificial signal was generated using Matlab software and further analysis was conducted using instantaneous frequency analysis through Hilbert-Huang Transform. Meanwhile, the random signal was also analysed using I-Kaz-kurtosis ratio in order to test the efficiency and effectiveness of this method as self-decision method for IMF selection. Besides that, I-Kaz-kurtosis ratio was also compared with kurtosis coefficient in order to prove whether this method worked properly as compared to kurtosis coefficient. From this research, it proved that I-Kaz-kurtosis ratio was able to select IMF automatically depending on IMF selecting criterion with narrow or clear spikes and transient although the noise level ratio was lower. Therefore, the intelligent monitoring system can be developed using Hilbert-Huang Transform (HHT) since the implementation of I-Kaz-kurtosis ratio as self-decision method was proven suitable to select IMF.

Methodology

The experiment was conducted using artificial sine wave constructed with 4096 sample of data in a second using 4096 block size number. The sine wave was developed using Formula 1.

$$y = 0.2 \sin (2 \pi 100) t + 1.0 \sin (2 \pi 340) t \tag{1}$$

The test signal (Figure 1) was developed with a combination of two different frequency and amplitude range. Both signals consisted of 100 Hz and 340 Hz frequency range and it was intentionally defined to be different amplitudes of 0.2 and 1.0, respectively.

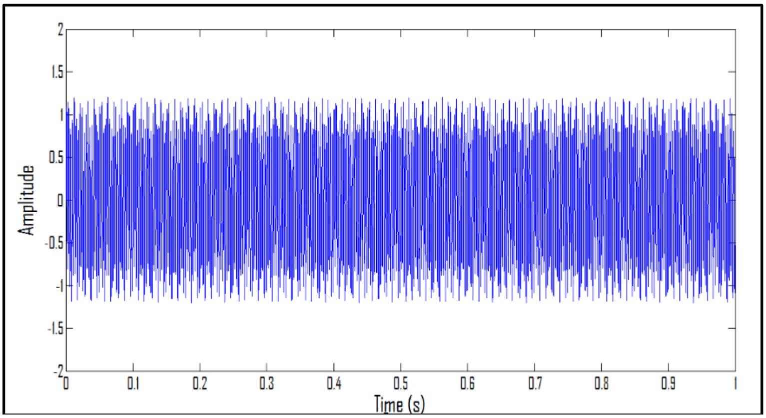


Figure 1: Artificial Pressure Transient Signal

Three non-stationary test signals named as A1, A2 and A3 was developed with three different spikes and transient characteristic. The test signal A1 (Figure 1) had the characteristic of the transient at 0.4331 seconds with an amplitude of 1.75, followed by test signal A2 (Figure 3) which had a transient event in 0.4836 seconds with an amplitude of 1.35 respectively. The last test signal named as A3 (Figure 4) developed 3 spikes with different amplitude and position. The amplitude heights were 1.45, 1.5 and 1.4, followed by the positions of spike at 0.1421, 0.4126 and 0.7742 respectively. The spikes or transients were developed in signal A1, A2 and A3 which represented as reflection point caused by the leak, pipe feature, and blockage in the pipe.

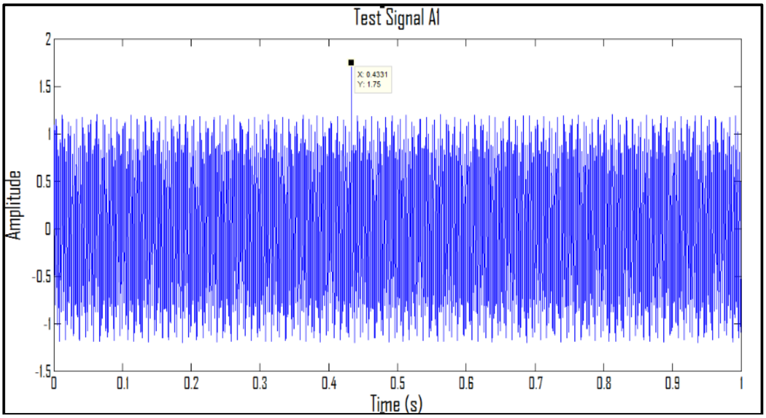


Figure 2: Test Signal A1

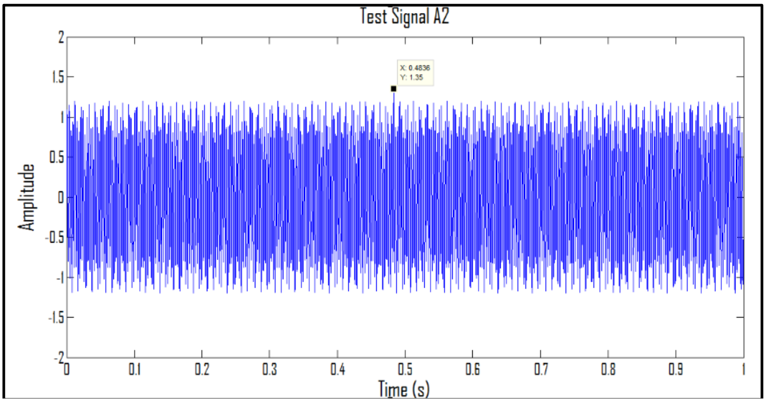


Figure 3: Test Signal A2

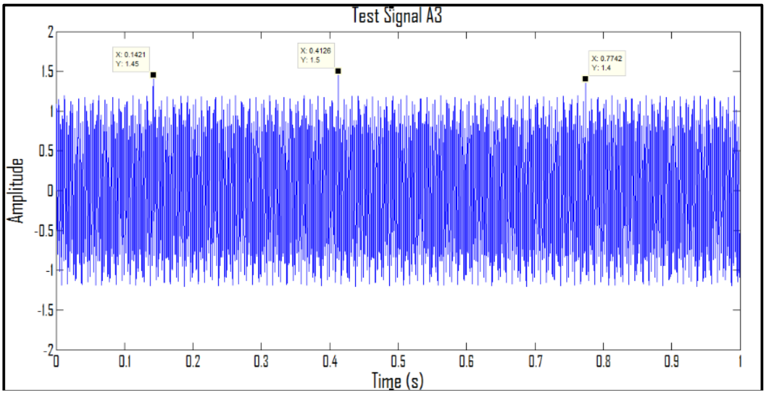


Figure 4: Test Signal A3

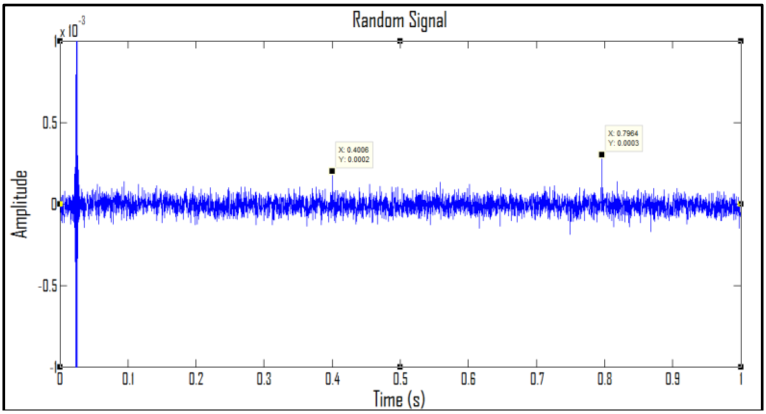


Figure 5: Test Signal A4

In order to test the effectiveness and accuracy of I-Kaz-kurtosis ratio as self-decision method in selecting IMF, the test signal A2 was developed with lower transient compared to transient test signal A1; therefore the noise level ratio of test signal A2 was lower than test signal A1. On the other hand, test signal A3 was developed with the mixing of 3 different transient heights and positions.

Besides that, test data A4 was developed using a random signal by mixing it with various frequency noise and amplitude. Random signal was represented as mirroring of pressure transient signal during real field test and was generated using Matlab software. By observing test data A4, a couple of transient phenomena was simulated at positions of 0.4006 and 0.7964 seconds. The entire test signals went through instantaneous frequency analysis to detect a transient event in the signal.

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

Integrated based Kurtosis algorithm for z-filter technique

Integrated Kurtosis-based Algorithm for z-filter technique (I-Kaz) is the method developed based on the concept of data scattering about its centroid. Sampling frequency of the raw signal was chosen as 2.56 by referring to Nyquist number [15]. Most researchers in signal analysis and processing were comfortable with the number. To avoid the aliasing effect, the maximum frequency span will be of formula 2.

$$F_{\max} = \frac{fs}{2.56} \tag{2}$$

I-kaz decomposes the time domain signal into three levels of the frequency range, which are x-axis that represents low frequency (LF) with a range of 0 – 0.25 of f_{max}, followed by y-axis that represents high frequency (HF) with a range of 0.25 – 0.5 of f_{max}. Finally, z-axis represents very high frequency (VF) with range 0.5 of f_{max}. The 0.25 f_{max} and the 0.5 f_{max} were selected as low and high frequency range limits respectively done with referring to the 2nd order of the Daubechies concept in signal decomposition process [16]. Referring to the kurtosis, I-kaz method contributes three-dimensional graphical representations of the measured signal frequency distribution. The variance, σ^2 of each frequency band are σL^2 that represents a low-frequency band, σH^2 represents a high-frequency band and σV^2 represents as very-high-frequency band which are calculated as in formula 3, 4 and 5 in order to measure scattering of data distribution.

$$\sigma L^2 = \frac{\sum_{i=1}^{N}(x_i - \mu_L)^2}{n} \tag{3}$$

$$\sigma H^2 = \frac{\sum_{i=1}^{N}(x_i - \mu_H)^2}{n} \tag{4}$$

$$\sigma V^2 = \frac{\sum_{i=1}^{N}(x_i - \mu_V)^2}{n} \tag{5}$$

The I-Kaz coefficient, Ƶσ can be simplified in terms of variance, σ as in formula 6 [17].

$$Ƶ\sigma = \sqrt{(\sigma L^2)^2 + (\sigma H^2)^2 + (\sigma V^2)^2} \tag{6}$$

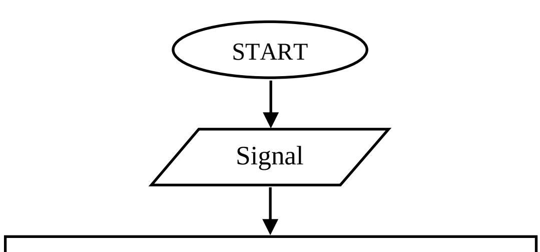
Kurtosis

Kurtosis is described 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;

$$\text{Kurtosis}(x) = \frac{E\{(x-\mu)^4\}cc}{\sigma^4} \tag{7}$$

where μ and σ represent the mean and standard deviation of time series signal respectively. The E{.} illustrates the expectation operation. The kurtosis demonstrates the spikiness and peakness of probability distribution associated to the instantaneous amplitudes of the time-series analysis [18]. Therefore, the I-kaz-kurtosis ratio is expressed as formula 8.

$$ZK\sigma = \frac{(\sqrt{(\sigma L^2)^2 + (\sigma H^2)^2 + (\sigma V^2)^2})(\sigma^4)}{(\mathrm{E}\{(x-\mu)^4\})} \tag{8}$$



Flow Chart 1

Result and Discussion

The test signals A1, A2, A3 and A4 (Figures 2, 3, 4 and 5) underwent instantaneous frequency analysis based on artificial pressure transient signal generated by using Matlab software. The instantaneous frequency signal was continued to be analysed using Hilbert-Huang Transform (HHT). HHT analysis decomposed the signal into a different level of the frequency band and amplitude called as intrinsic mode function (IMF) through Empirical Mode Decomposition Method (EMD). The first level was a group of higher frequency signal and the last portion indicated the level of lower frequency signal. IMF level 1-2 contained the highest frequency which mostly consisted of noise. Meanwhile, IMF level 7 and the residue contained basic response of the network. All of these IMFs were therefore discarded. The rest which were

IMF level 3-6 were recombined to produce a signal without noise [19]. For all test signals, EMD decomposed the signal into 13 levels of frequency band and amplitude. The coefficient of I-Kaz-kurtosis ratio was calculated for each level of IMF. The coefficient of I-Kaz-kurtosis ratio was plotted in histogram chart.

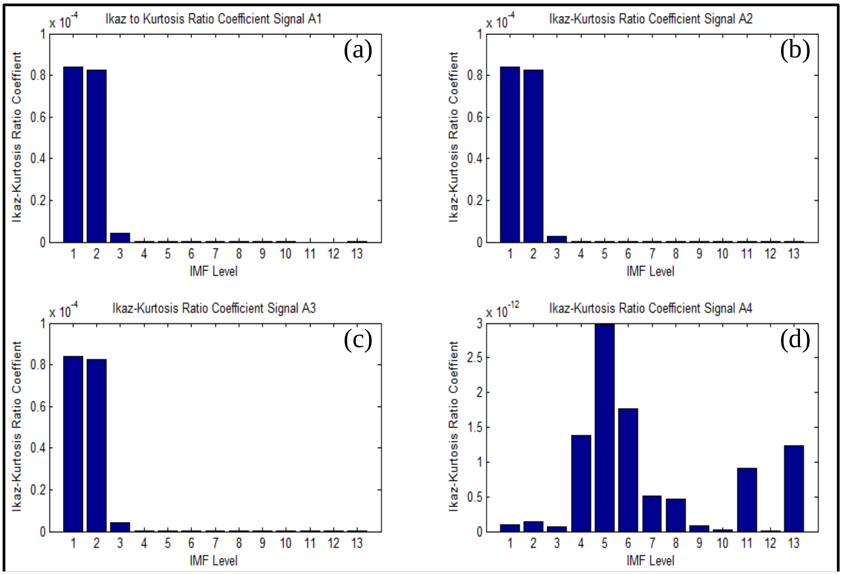


Figure 6: I-kaz-Kurtosis ratio coefficient versus IMF Level (a) Test Signal A1, (b) Test Signal A2, (c) Test Signal A3, and (d) Test Signal A4

Figure 6 (a), (b), (c) and (d) represent the I-Kaz-kurtosis ratio coefficient histogram versus IMF decomposition level. The first four of IMF with maximum I-Kaz-kurtosis ratio coefficient was plotted in figures 7, 8, 9 and 10. From the observation, IMF with higher I-Kaz-kurtosis ratio coefficient was the IMF level that contained narrow and clear spikes or transient event. The lower I-Kaz-kurtosis ratio coefficient for IMF, the more obscure of spikes and transient event of a signal. Therefore, for the test signals of A1, A2 and A3, the maximum of I-Kaz-kurtosis ratio coefficient was reserved by IMF level 1, but the test signal A4 was represented as a random signal and the maximum value of I-Kaz-kurtosis ratio coefficient was reserved by IMF level 5. Each IMF with the maximum of I-Kaz-kurtosis ratio coefficient was plotted as amplitude versus time graph (figure 7(a), 8(a), 9(a) and 10(b)) to show the IMF that contained selection criterion.

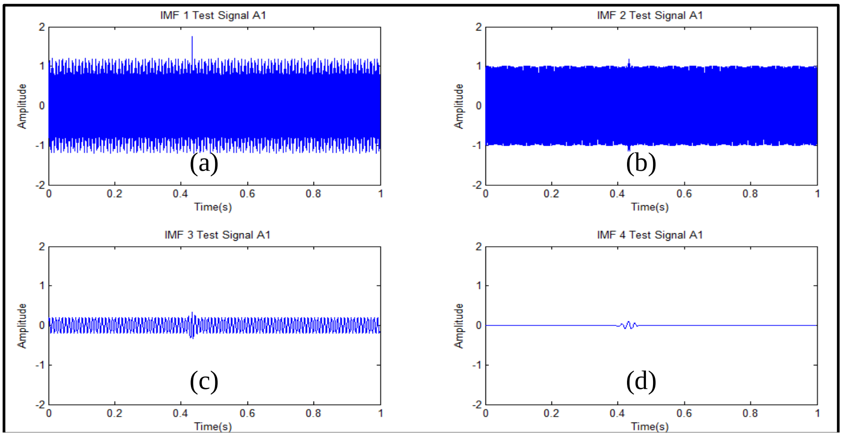


Figure 7: IMF for Test Signal A1 (a) Level 1, (b) Level 2, (c) Level 3 and (d) Level 4

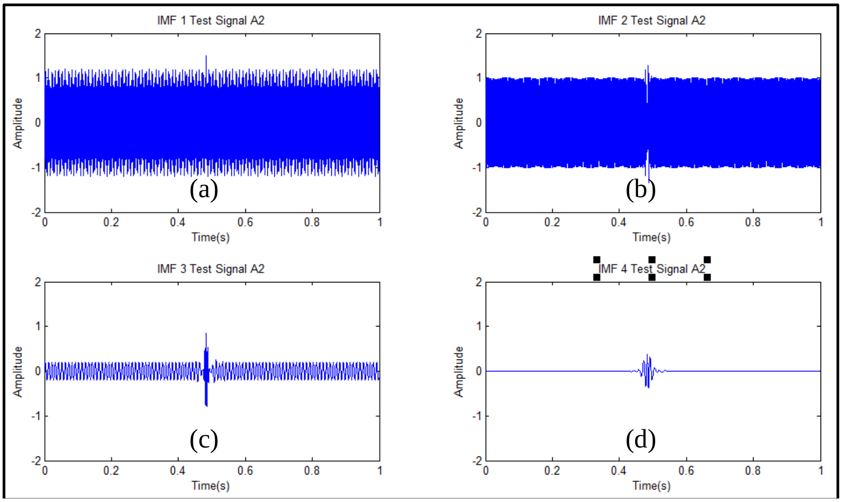


Figure 8: IMF for Test Signal A2 (a) Level 1, (b) Level 2, (c) Level 3 and (d) Level 4

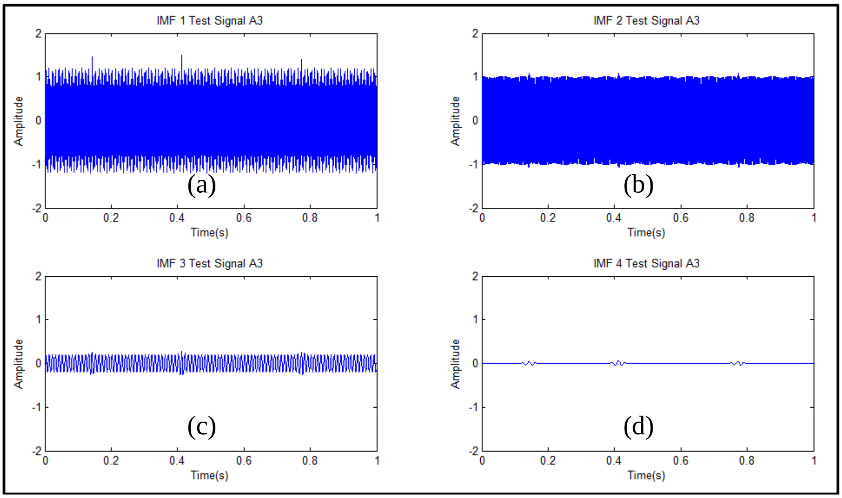


Figure 9: IMF for Test Signal A3 (a) Level 1, (b) Level 2, (c) Level 3 and (d) Level 4

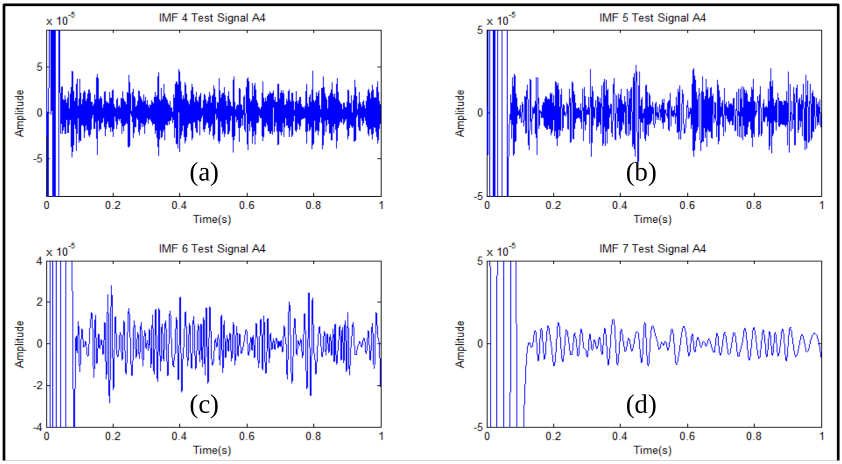


Figure 10: IMF for Test Signal A4 (a) Level 4, (b) Level 5, (c) Level 6 and (d) Level 7

Figures 7(a), 8(a) and 9(a) represent IMF level 1 for test signal A1, A2, and A3. The level was chosen as the maximum value of I-Kaz-kurtosis ratio coefficient of test signal A1, A2 and A3 reserved on IMF level 1. Figure 10(b) represents IMF level 5 for test signal A4 as the maximum I-Kaz-kurtosis ratio coefficient reserved on IMF level 5. From the observation, it was proven that the maximum value of I-Kaz-kurtosis ratio coefficient for IMF level had a selecting criterion for IMF. As shown in figures 7(a), 8(a), 9(a) and 10(b), the amplitude height and position of artificial transient events were clearly seen. The characteristics of transient events had the same position from each original test signal such as test signal A1 was simulated with transient event at position 0.4331 second, and the IMF level 1 of that signal also had transient event at the same position. This phenomenon can also be seen for test signal A4 that represents a random signal. So far, it proved that I-Kaz-kurtosis ratio worked properly as self-decision method for IMF selection. The selected IMF proceeded to the estimation of instantaneous frequency through Hilbert Transform (HT) analysis. The results were plotted in the estimation of instantaneous frequency versus time graph.

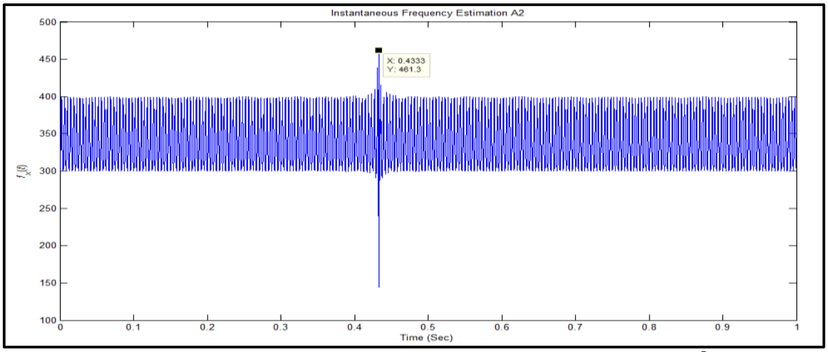


Figure 11: Instantaneous Frequency Estimation Test Signal A1

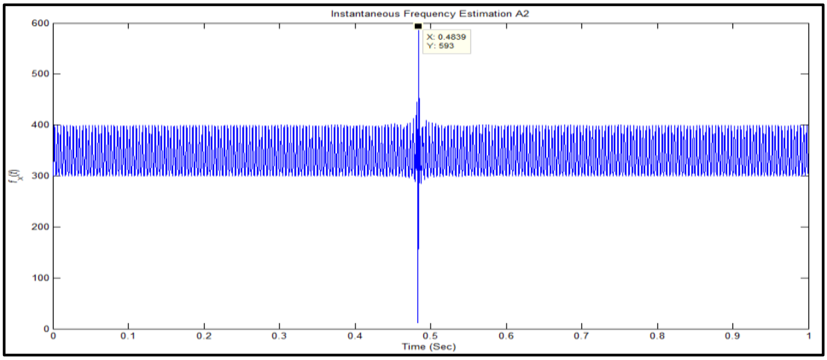


Figure 12: Instantaneous Frequency Estimation Test Signal A2

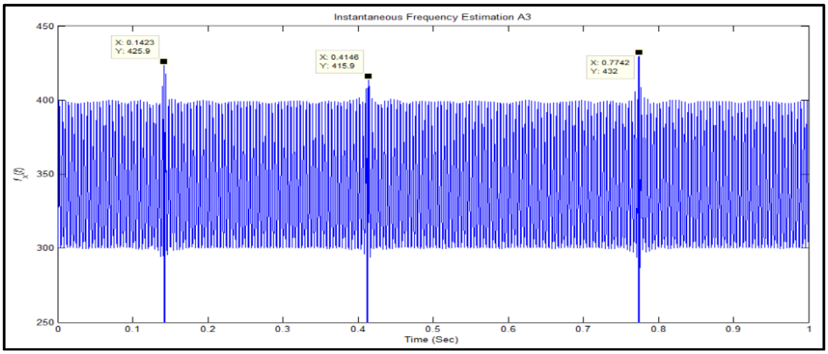


Figure 13: Instantaneous Frequency Estimation Test Signal A3

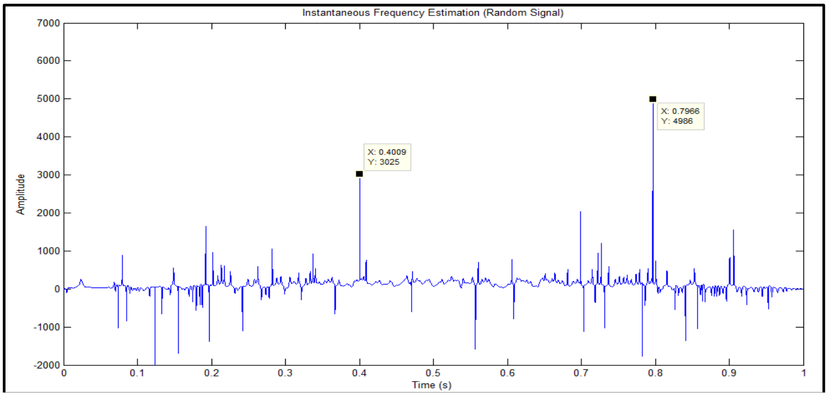


Figure 14: Instantaneous Frequency Estimation Test Signal A4

Figures 11, 12, 13 and 14 illustrate the final results of Hilbert-Huang Transform (HHT) from test signals A1, A2, A3, and A4. During non-stationary signal phase, frequency value changes at any moment and it is more useful to characterise a signal in terms of instantaneous frequency. Instantaneous frequency is described as the frequency that locally fits the signal [1]. From observation, clear and obvious transient was seen from the final part of HHT analysis. Compared to the test signal, spikes and transients were clearly seen in this phase. Therefore, it proved that I-Kaz-kurtosis ratio worked properly as self-decision method for IMF. From the final part of HHT analysis, it clearly showed that the position of artificial transient was generated by test signal that appeared at the same position compared to each original test signal. It also proved that HHT analysis was able to detect and position the transient event which occurred in the non-stationary pressure transient signal. The previous researcher implemented kurtosis coefficient as self-decision method for IMF, but the method was unable to select IMF that contained the selection criterion. In order to prove that I-Kaz-kurtosis ratio worked properly as compared to kurtosis coefficient, kurtosis analysis was implemented to test signal A1 and A4. The result is illustrated below.

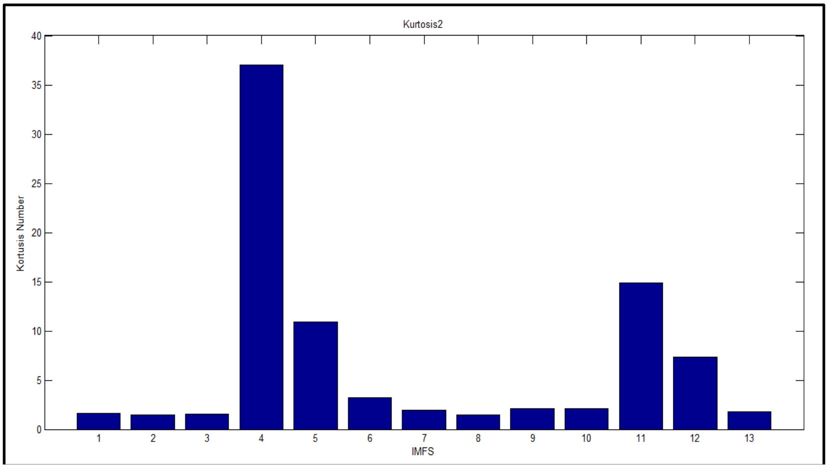


Figure 15: Kurtosis Coefficient Test Signal A1

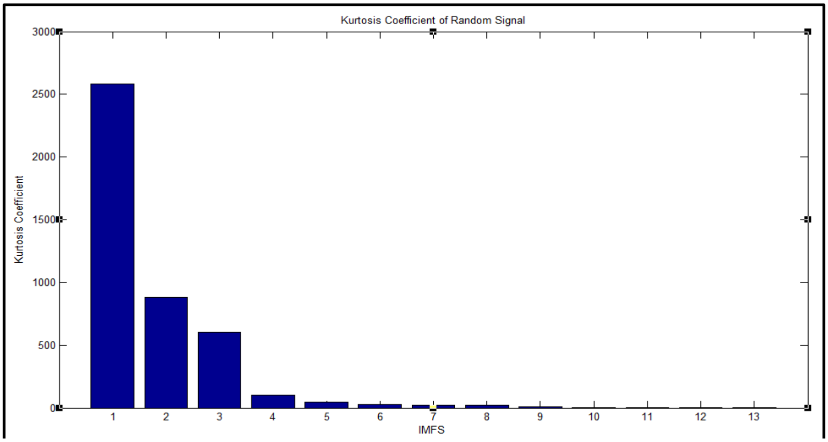


Figure 16: Kurtosis Coefficient Test Signal A4

Figures 15 and 16 represent kurtosis coefficient versus IMF level for test signals A1 and A4 respectively. From observation, the maximum of kurtosis coefficient was a reserve for IMF level 4 for test signal A1 followed by IMF level 1 for test signal A4. The amplitude versus time graph for the maximum coefficient of IMF for test signal A1 and A4 is presented below.

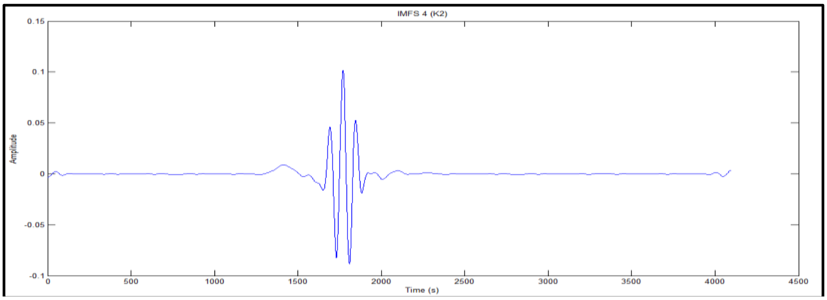


Figure 17: IMF level 4 Test Signal A1

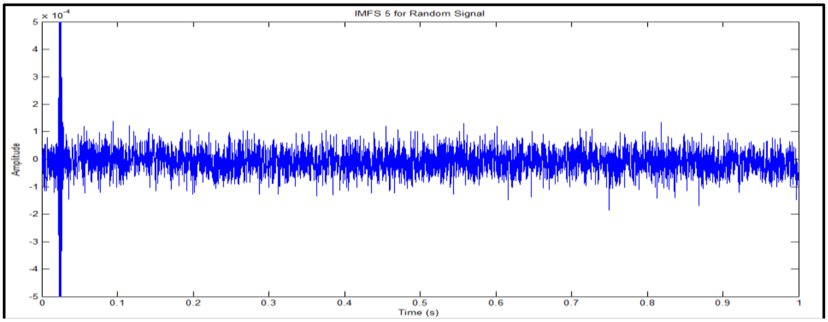


Figure 18: IMF level Test Signal A4

Figures 17 and 18 represent the maximum of kurtosis coefficient for IMF test signals A1 and A4. From figure 17, transient was clearly shown but very broad in position and peak. Then, there was no fixed position of peak and spikes. A narrow band of spikes and transient was one of IMF selection criterion, so far, for these cases, IMF level 4 for test signal A1 did not fulfill the IMF selection criterion. Therefore, IMF level 4 for test signal A1 was not suitable to be selected because the transient characteristics were very broad. From Figure 18, no clear transient and spikes appeared although artificial transients were generated at positions of 0.4006 and 0.7964 seconds. This relied on [19] statement that IMF level 1 and 2 had the highest frequency which mostly consisted of noise. Therefore, for the test signal A4, IMF level 1 was not suitable to be selected for further analysis which was Hilbert Transform (HT).

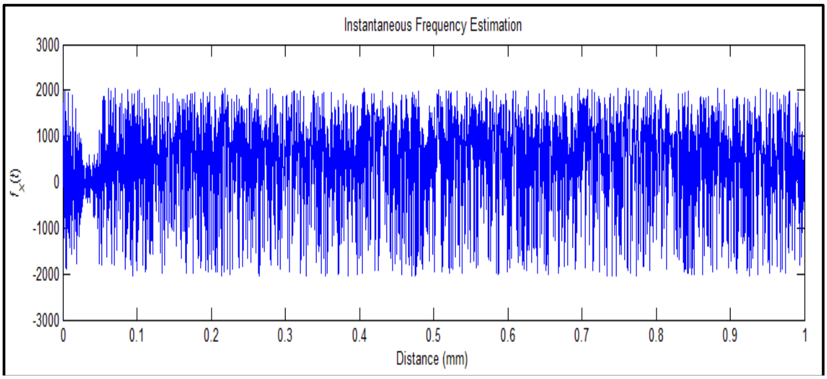


Figure 19: Instantaneous Frequency Estimation IMF level 4 Test signal A1

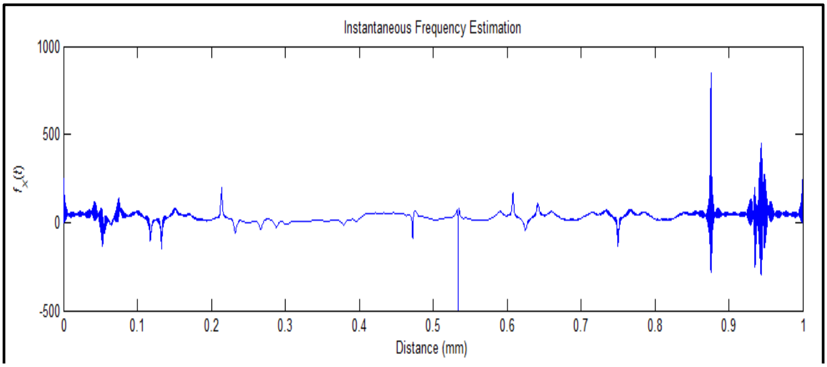


Figure 20: Instantaneous Frequency Estimation IMF level 1 Test signal A4

Figures 19 and 20 represent Hilbert Transform (HT) analysis for IMF level 1 and level 4 of test signals A1 and A4. From the observation, it was strongly proven that IMF level 1 and 4 for test signals A1 and A4 were not suitable to be selected for further analysis which was HT. Therefore, Kurtosis coefficiently was not advisable as self-decision method for IMF selection.

Conclusion

This paper discussed on self-decision method for IMF selection through Hibert Huang Transform (HHT) analysis. The result proved that the I-Kaz-kurtosis ratio was suitable and advisable as a self-decision method for IMF selection to be implemented in Hilbert-Huang Transform (HHT) analysis. Meanwhile, from the current research, it was proven that I-Kaz-kurtosis ratio worked properly compared to kurtosis. The development of automated self-decision of IMF through HHT was 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 intelligent system can be used to manage the issue of IMF selection; therefore, online monitoring system of leak detection can be developed.

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