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Pipe leak diagnostic using high frequency piezoelectric pressure sensor and automatic selection of intrinsic mode function

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Abstract. In a recent study, the analysis of pressure transient signals could be seen as an accurate and low-cost method for leak and feature detection in water distribution systems. Transient phenomena occurs due to sudden changes in the fluid's propagation in pipelines system caused by rapid pressure and flow fluctuation due to events such as closing and opening valves rapidly or through pump failure. In this paper, the feasibility of the Hilbert-Huang transform (HHT) method/technique in analysing the pressure transient signals in presented and discussed. HHT is a way to decompose a signal into intrinsic mode functions (IMF). However, the advantage of HHT is its difficulty in selecting the suitable IMF for the next data post-processing method which is Hilbert Transform (HT). This paper reveals that utilizing the application of an integrated kurtosis-based algorithm for a z-filter technique (I-Kaz) to kurtosis ratio (I-Kaz-Kurtosis) allows/contributes to/leads to automatic selection of the IMF that should be used. This technique is demonstrated on a 57.90-meter medium high-density polyethylene (MDPE) pipe installed with a single artificial leak. The analysis results using the I-Kaz-kurtosis ratio revealed/confirmed that the method can be used as an automatic selection of the IMF although the noise level ratio of the signal is low. Therefore, the I-Kaz-kurtosis ratio method is recommended as a means to implement an automatic selection technique of the IMF for HHT analysis.

1. Introduction

Water plays an important role in the contribution of 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 is rapidly becoming the number one global resource concern. Consequently, with the increase in the number/demand 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 [1] reported that water loss for most country falls into the range of 20%-30% and for Malaysia, the figure is 43% of NRW. NRW refers to the circumstance in which the amount of water reaches 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 reaches to the consumer not metered) and metering inaccuracies. Nowadays, minimizing 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 NRW. Lately, water authorities' concern of leak in water distribution system is growing, and thus 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 generated by rapid opening and closing of valves. In the recent year, water authorities voiced out such concern in reducing the NRW. Pressure Transient analysis is a recently developed technique/method for leak detection and has attracted researchers to conduct more studies due to its cost effectiveness.

The possibility to analyse the pressure transient phenomenon in both time and frequency domain has been satisfied by the implementation of time-frequency signal processing techniques such as Hilbert-Huang Transform (HHT). HHT analysis was proposed due to the ability of this method to detect and capture the occurrence of transient phenomena through the non-stationary signal. In recent years, HHT has been more widely used as time-frequency analysis as signal processing method [3], [4]. HHT was proposed as newly developed and powerful method to analyze non-linear and non-stationary signal [5].

However, this method has the difficulty in selecting the suitable IMF for the next data post-processing method which is Hilbert Transform (HT). Through the Empirical Mode Decomposition (EMD), HHT will decompose the signals into the different monocomponents and symmetric components by the sifting process. The monocomponent signal is called intrinsic mode function (IMF) ([6]). The main drawback of this approach is the necessity to know a priori of the frequencies and level of original signal that should be analysed [7]. The HHT analysis in this case is not completely automatic because it requires the interaction of skilled user to select which IMF level is suitable for further analysis. Therefore, automatic selection for better IMF is needed to overcome this problem. The mathematical computational technique and statistical value analysis were applied by the researcher to increase the degree of automation, and then eliminates the interaction of skilled user to select the relevant IMF.

There have been relatively few recent studies and statistical approach on measurable quality for automatic selection of relevant and appropriate intrinsic mode function (IMF). [8] 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. [7] demonstrated Merit Index as an indicator that allows automatic selection of IMF level. The research/study utilizes rotary element (gear) signal to test the efficiency of merit index in the selection 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, [9] introduced computation of correlation coefficient value for each level of IMF as quantifiable quality in selecting appropriate IMF level. In the research/study, vibration signal is captured from rolling element (bearing), then the signal is 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 compared to the original signal. [10] presents an Energy-Based approach through mutual information (MI) coefficient as a method of selection relevant IMF. The research/study was done by applying the synthetic signal embedded in white noise and real world signal. Mutual Information (MI) is also utilized as a method to select appropriate IMF in biomedical signal processing conducted by [7].

This paper 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 I-Kaz was chosen since the approach of this method was adapted in general [leak detection techniques] and detects very well any changes and uncertainties of the measured signals [11]. 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, $Z\sigma$. Detailed experimental result was discussed by [11] and [12] using vibrational signal acquired from rotating machinery part (Bearing) and detected tool wear during turning process respectively. In a study conducted by Nuawi 2014 et al, the I-Kaz was compared to

variance and the results revealed that the variance parameter was unable to detect both amplitude and frequency changes in the non-stationary signal. Thus, the I-Kaz method was reliable especially for monitoring purposes where the observation on the changes of the signal amplitude and frequency were commonly required ([11]).

The effectiveness and reliability of the I-Kaz-kurtosis ratio as the automatic selection of IMF is shown/demonstrated using artificial pressure transient signal and random signal generated using Matlab, and the results revealed that IMF with maximum value of I-Kaz-kurtosis ratio coefficient is relevant and appropriate for further analysis. The research also comprises the comparison of the effectiveness of kurtosis with IKaz as the automatic selection method for better IMF. This paper focuses on the implementation of I-Kaz-kurtosis ratio coefficient as the automatic selection means/technique of intrinsic mode function using real pressure transient signal captured along the 57.9 meter medium density polyethylene pipe with single artificial leak simulator attached within 37.8 meter distance away from the point of analysis. The result for real pressure transient signal showed that the IMF contains highest value of I-Kaz-kurtosis coefficient, which is suitable and appropriate for further analysis. Furthermore, the I-Kaz-kurtosis ratio is proven suitable as automatic selection method for better and relevant IMF. Therefore, the degree of automation for Hilbert Huang Transform (HHT) was enhanced in detecting 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 (I-Kaz) 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 ([11]). Most of the researchers in signal analysis and processing are comfortable with the number. To avoid the aliasing effect, the maximum frequency span will be of equation 1.

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

I-Kaz decomposes the time domain signal into three levels 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} , and 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} were selected as low and high-frequency range limits respectively done by referring to the 2nd order of the Daubechies concept in signal decomposition process [13]. Referring to the kurtosis, I-kaz method contributes to three-dimensional graphical representations of the measured signal frequency distribution. The variance, σ^2 of each frequency band which is σL^2 represent as a low-frequency band, σH^2 represent as a high-frequency band and σV^2 represents as a very-high-frequency band which is calculated as in equation 2, 3 and 4 to measure the 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 [12].

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

2.2. Kurtosis

Kurtosis describes the 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 illustrates the expectation operation. The kurtosis demonstrates the spikiness and peakedness of probability distribution associated to the instantaneous amplitudes of the time-series analysis [14]. Therefore, the I-kaz-kurtosis ratio is 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 (I-Kaz-Kurtosis) coefficient using Eq. 7.
4. Identified the IMF that corresponds to the largest I-Kaz-kurtosis ratio coefficient.
5. Perform Hilbert Transform (HT) and Hilbert Spectrum (HS) for IMF level that contains the largest coefficient of I-Kaz-Kurtosis ratio.

3. Piezoelectric Pressure Sensor

Piezoelectric pressure sensor was designed and suited to measure dynamic pressure. It is typically not suited for static pressure measurements. Sensor with special capabilities are needed to measure dynamic pressure including turbulence, blast, ballistic, and engine combustion. High frequency piezoelectric pressure sensor has the capabilities to measure fast response of pressure change, ruggedness, high stiffness, extended range, and has the ability to measure quasi static pressures. This type of pressure sensor has the capabilities to capture signal with continuous operating system even for underwater, 'dirty' experiment and also field test application for a long range cable. Basically, this transducer is ideal for all dynamic pressure applications for a temperature range from -196 to +135 °C. With the advantages of detecting small pressure changes at high pressure levels, this sensor is one of the most practically used ones in real applications. This type of pressure transducer is practically used in the application that includes hydraulic and pneumatic systems, blast and ballistic, very repeatable, wide dynamic range, fast rise time, and also fluid borne raise.



Figure 1. Piezoelectric pressure sensor.

Figure 1 illustrates the piezoelectric pressure sensor that was utilized in this experiment. Basically, the sensor has the ability in detecting fast frequency response in the pipeline system. The signal and frequency response from the pipeline system represent the pipeline condition. The reflection signal acquired in the pipeline system basically represents the response from the pipe features such as pipefitting, blockage, leak and strangest precipitates in the pipelines system. The excitation frequency, vibration from test rig, water pump frequency and other noise provides some effect to the signal acquired by the piezoelectric sensor. In this research Hilbert Huang Transform (HHT) acts as the Signal analysis method, and then was utilized in extracting the noisy signal in order to get the real reflection signal that represents the pipeline information.

4. Methodology

The experimental test was regulated in a circular loop pipeline system with 57.9-meter long. The network was constructed using Medium High-Density Polyethylene pipes (MDPE) with an outer diameter 60 millimeters, 55 millimetres of internal diameter and 2.6 millimeters mean thickness. An artificial leak was installed at a point of 37.8 meters away from the point of analysis in the pipeline system. The outlet of the pipe is kept connected to a free surface tank where the water from the pipe ends is discharged. This is to prevent sudden expansion phenomenon of the pressure waves, and minimizing negative pressure wave, as it will affect the collected data from the transducer. The speed of sound calibrated from the test rig is 524.3 m/s.

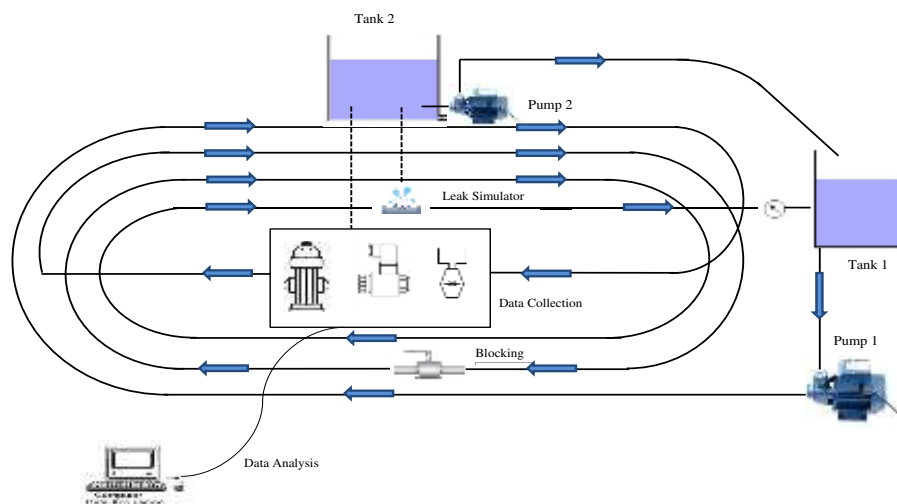


Figure 2. Schematic diagram of test rig design for laboratory and experimental test.

The schematic diagram (Figure 2) shows the piezoelectric pressure sensor and solenoid valves installed 10 meters away from the electric pump to avoid too much noise during the collection of the data. This is due to wave characteristic as turbulent flow when the water exits from pump outlet, the flow is approaching in laminar or steady state condition due to the distance traveled. This phenomenon is generated by friction from wall pipe due to water flow and damping. This research mainly utilized pressure transient respond as the method of detection and location in the pipeline system. The idea is proposed from the usage of pressure transient flow of water in the pipeline network. Theoretically, pressure transient responds occur when there is a sudden change in the flow of water by closing or opening of the valves in the pipeline network. As the phenomena happened inside the pipeline network, wave propagation of water will be created along the pipeline network, and also the characteristic of wave propagation will be used as a medium to detect leak and pipe features along the

pipeline network. The wave inside the pipeline network will propagate with different signal depending on the size of the leak, distance of leak, type of pipe features and distance of pipe feature.



Figure 3. Experimental test rig in laboratory scale.

Figure 3 shows the experimental test rig installed at the Fluid Mechanic Laboratory in University Malaysia Pahang Malaysia. The fire hydrant cap was designed and fabricated to fix the solenoid valve and pressure sensor as well as to make the system robust for a field test. Both components play an important role in each task as solenoid valve is used to generate the water hammer phenomenon and piezoelectric pressure sensor is used to acquire the reflection signal. In a few cases, the system will shut down by itself due to sudden opening or closing of valve and malfunction of the pump. This will generate the occurrence of “water hammer” in the pipeline system. This phenomenon took in all of the pressure pipe systems, frequently causes vibration and destruction on pipeline system [15]. To generate this phenomenon, solenoid valve (Figure 3) was utilized as a tool to create water hammer along the pipeline system.

5. Results and Discussion

The data of the experiment acquired from the transducers using Matlab represent the pipeline system behavior and characteristics. The signal acquired retrieves the characteristics of the whole pipeline system itself. The pressure transient waves propagated along the pipeline system in both directions, away from the burst origin through the speed of sound in water distribution system. In this paper, Hilbert-Huang Transform (HHT) which contains Empirical Mode Decomposition (EMD) as data pre-processing method and Hilbert Transform (HT) as data post-processing method were employed as the tools to analyze the pressure transient signal.

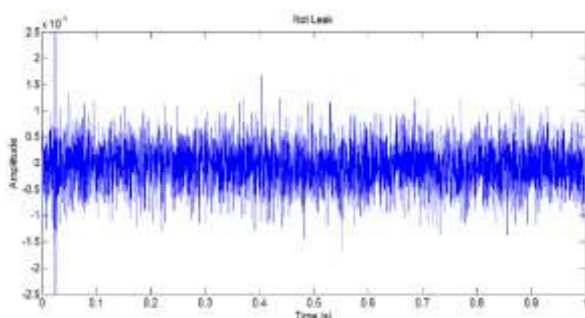


Figure 4. Signal Response for No Leak Data.

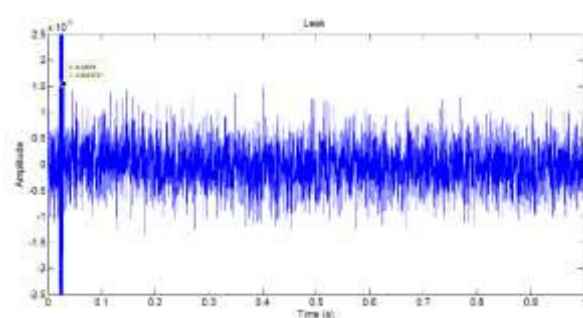


Figure 5. Signal Response for Leak Data.

Figure 4 represents the response signal for no leak data while Figure 5 represents the signal response for the leak data. The first maximum amplitude on the signal response presented in both figure 4 and 5 represents the opening and closing of the solenoid valve that produces pressure transient which is transmitted and reflected around the pipe system. The original response was recorded at three different levels of pressure: 1 bar and 2 bar. The signals captured using a different level of pressure demonstrated different results. Higher pressure creates higher frequency of the signal and this causes the higher amplitude of the signal.

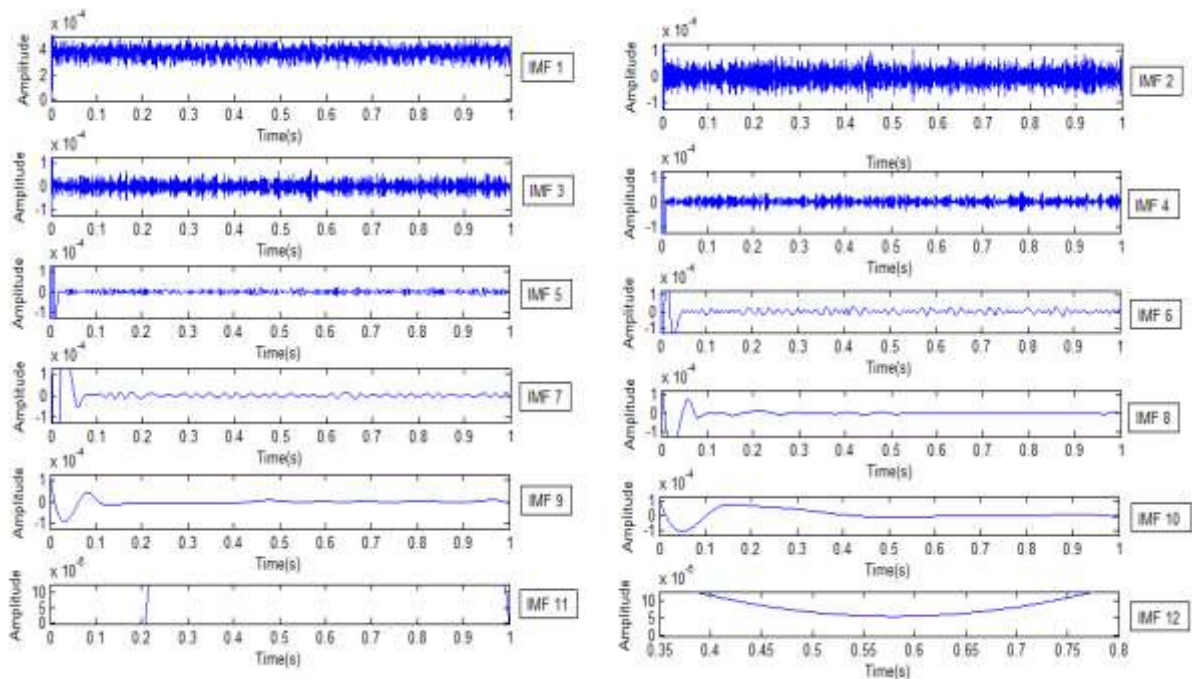


Figure 6. IMF level 1-12 for no leak data.

EMD decomposes the signal response acquired from the test rig into level 13 of intrinsic mode function (IMF). Figure 6 shows amplitude versus time for the first level 12 of IMF. The first level of IMF is a group of higher frequency signal which is noise signal. The last level was a reserve for the lower frequency signal. Commonly, the first and second levels of IMF are not considered for further analysis because these levels contained frequency signal noise. Meanwhile, IMF level 7 and the rests contain basic response 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 [16]. Therefore, to identify which level of IMF that is suitable for the final step of Hilbert-Huang Transform (HHT) which is Hilbert Transform (HT), Integrated Kurtosis Algorithm for Z-filter technique to kurtosis ratio (I-Kaz-Kurtosis) was employed. Since EMD decomposes the signal response into level 13 of IMF, the I-Kaz-Kurtosis ratio was utilized to compute the coefficient for each level. Therefore each level of IMF contains different value of I-Kaz-Kurtosis ratio coefficient.

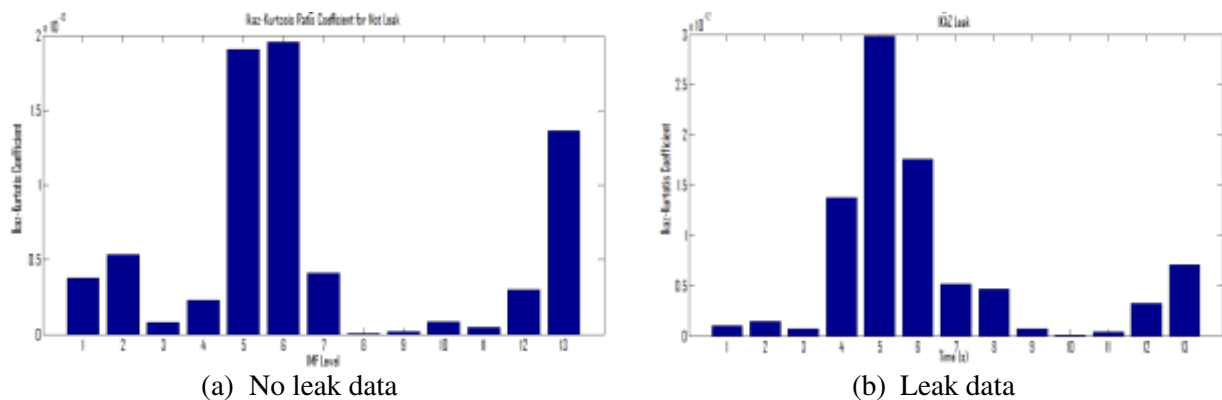


Figure 7. I-Kaz-Kurtosis ratio coefficient

Figure 7 (a) and 7 (b) represent the I-Kaz-Kurtosis ratio coefficient histogram. The X-axis shows the IMF level meanwhile, Y-axis shows the value of I-Kaz-Kurtosis ratio coefficient. From the observation, the maximum and highest value of I-Kaz-Kurtosis coefficient were suitable IMF level to be considered for 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 I-Kaz-Kurtosis ratio consists of the IMF selection criterion which is clear and narrow spikes. The lower the value of I-Kaz-Kurtosis ratio, the more obscure of the IMF selection criterion. The final results of Hilbert-Huang Transform (HHT) are presented in Figure 8 and 9.

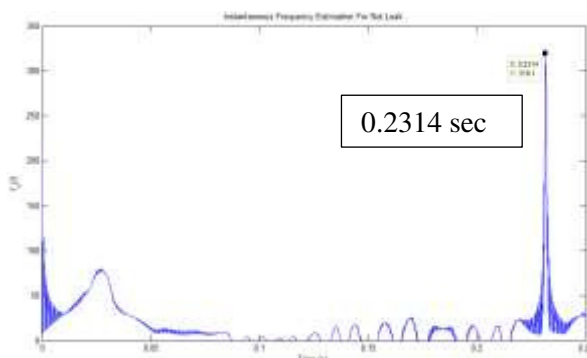


Figure 8. Instantaneous frequency estimation for no leak data

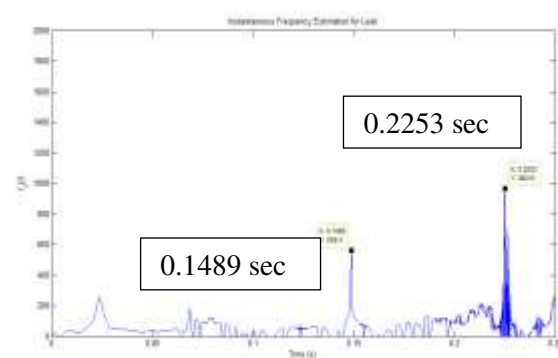


Figure 9. Instantaneous frequency estimation for leak data

Figure 8 and 9 illustrates the final results of Hilbert-Huang Transform (HHT) which is Hilbert Transform (HT) for IMF level that contains the highest value of I-Kaz-Kurtosis ratio coefficient (I-Kaz-Kurtosis). The graph presented in figure 8 and 9 is the instantaneous frequency estimation for no leak and leak data. During this phase, nonstationary signal, in which frequency value changes at any moments, is more useful to characterize a signal in terms of its instantaneous frequency. Instantaneous frequency describes the frequency that locally fits the signal [17]. From the observation, clear and obvious transient can be seen from the final part of HHT analysis. The clear spikes and transient are more clearly seen after Hilbert Transform (HT) take charge in this phase. Figure 8 shows clear spikes at the position of 0.234 seconds compared to the theoretical calculation of the spikes generated by the outlet of the pipeline system. Meanwhile, in Figure 9, obvious/salient spikes were present at the position of 0.1489 seconds and 0.2253 seconds compared to theoretical calculation of the spikes

generated by leak and pipe outlet. Therefore, it proves the I-Kaz-kurtosis ratio work properly as self-decision method for IMF.

Table 1. Comparison of position spikes between measured position and experimental position.

Water Pressure	Signal Response	Pipe Feature	Measured Position (m)	Measured Position (sec)	IMF contain Maximum I-Kaz-Kurtosis ratio Coefficient	Experimental Position (m)	Experimental Position (sec)	Error %
1 bar	Leak Data	Leak	37.8	0.144	6	39.03	0.149	3.0
		Outlet	57.9	0.221		59.06	0.225	2.0
	No Leak Data	Outlet	57.9	0.221	5	61.34	0.234	5.9
2 bar	Leak Data	Leak	37.8	0.144	4	38.03	0.138	3.2
		Outlet	57.9	0.221		58.06	0.204	2.2
	No Leak Data	Outlet	57.9	0.221	5	61.01	0.231	6.1

Table 1 illustrates the comparison of position spikes between theoretical calculation and experimental position. For leak data, the position of leak shows 3% error and position of outlet shows 2% error. Meanwhile, no leak data present 5.9% error for outlet position. The final part of HHT analysis clearly shows the position of pipe feature that is leak and pipe outlet appears at the same position compared to each the original position and theoretical calculation. It also proves that HHT analysis was able to detect and positioning the transient event occurred in the non-stationary pressure transient signal.

6. Conclusions

This paper discusses self-decision method for IMF selection through Hilbert Huang Transform (HHT) analysis by using high frequency piezoelectric pressure sensor. The result proves that the I-Kaz-kurtosis ratio is suitable and advisable as a 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 analyzed using I-Kaz-kurtosis ratio. Therefore, this method was proposed and advised to be implemented. By efficiently utilizing I-Kaz-kurtosis ratio, and the real-time monitoring system for live water distribution system, it can be used to manage the issue of IMF selection; therefore online monitoring system of leak detection can be developed. The results also prove the ability of piezoelectric pressure sensor in detecting fast response frequency change in the pipeline system.

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