Fault Identification in Pipeline System Using Normalized Hilbert Huang Transform and Automatic Selection of Intrinsic Mode Function

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Abstract. Pressure transient analysis has been widely used to monitor the condition of pipelines and its assessment in water distribution systems. This is a low-cost nonintrusive technique with the ability to locate uncertainties (leak, pipe fitting, blockage) at a greater distance from the measurement point. In this research, Normalised Hilbert Huang Transform (NHHT) is used as the method to analyse the pressure transient signal. However, this method has difficulty in selecting the suitable intrinsic mode function (IMF) for the advance data analysing. As an alternative, Integrated Kurtosis-based Algorithm for z-filter Technique (Ikaz), which allows automatic selection of intrinsic mode function (IMF) been used to substitute the NHHT limitation in this study. The analysis is conducted on a 67.9-meter Medium High-Density PolyEthylene (MDPE) pipe installed with single artificial leak simulator at a water pressure in the range of 1-4 bar.

1 Introduction

Water management is essential to ensure every drop of water can be distributed to the right places. The loss due to improper management is defined as non-revenue water (NRW). The problem of water leakage in pipeline distribution system is the primary cause of Non-revenue water (NRW).

Signal processing is the most famous method among the researchers due to its ability to detect and localize any disturbance (leak) and blockage in the pipeline system. Pressure Transient analysis is the most recently developed method and attracted researchers due to their cost-effectiveness. Theoretically, transient phenomena are generated due to sudden changes in the fluid propagation filled in the pipeline's system caused by rapid pressure and flow fluctuation in the systems such as rapid closing and opening valve. The wave characteristic represents the pipeline information and conditions 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.

The possibility to analyse the phenomenon in both time and frequency domain has been satisfied by implementation the time-frequency signal processing techniques such as Normalised Hilbert-Huang Transform (NHHT). NHHT analysis has been proposed in many studies due to the ability of this method to detect and capture transient phenomena that occur in the non-stationary signal. In recent years, HHT has been widely used in time-frequency analysis as signal processing method [1], [2]. This method also has difficulty in selecting the suitable IMF for advance data post-processing method known as Normalized Hilbert Transform (NHT). NHHT through Empirical Mode Decomposition (EMD) will decompose the signal into the different monocomponent and symmetric component by the sifting process. The monocomponent signal is termed as an intrinsic mode function (IMF) [3]. The main drawback of this approach is it necessitates to know the prior frequencies and level of original signal that required to be analysed [4]. Therefore, computational mathematical technique and statistical value analysis have been used by the researchers to increase the degree of automation, which eliminates the interaction of the skilled user to select the relevant IMF.

This paper proposes an Integrated Kurtosis Algorithm for Z-notch (Ikaz) filter hybridized with higher order statistical method (Kurtosis) for automatic selection of intrinsic mode function (IMF). The Ikaz method was chosen since this method is adaptive in general and powerfully detects any changes and uncertainties in the measured signal [5]. Unlike the existing statistical analysis such as variance, standard deviation, and kurtosis, Ikaz method capable of indicating both amplitude and frequency difference simultaneously by obtaining the Ikaz representation and Ikaz coefficient, $Z\sigma$. [5] and [6] has performed a detailed analysis using Ikaz on the vibrational signal acquired from rotating machinery part (Bearing) to detect tool wear during the turning process. For more details refer to Nuawi et al 2014 [5].

This paper also focuses on the implementation of Normalized Ikaz coefficient for automatic selection of intrinsic mode function using real pressure transient signal captured along the 67.9-meter medium density polyethylene pipe with single artificial leak simulator attached at a distance of 19.7 meters from the point of analysis. The result for the real pressure transient signal shows that the IMF with the highest value of Normalized Ikaz coefficient is suitable and appropriate for further analysis. Furthermore, the Normalized Ikaz also proved to be suitable as an automatic selection method in choosing better and relevant IMF. Therefore, the degree of automation for Normalised Hilbert Huang Transform (NHHT) has been improved to the detect pipe leakage in live water distribution system using pressure transient signal.

2 Integrated Kurtosis Algorithm for Z-Filter (Ikaz) Technique to Kurtosis Ratio

2.1 Integrated Based Kurtosis Algorithm for z-filter (Ikaz) technique

Ikaz method is developed based on the concept of data scattering to its centroid. The sampling frequency of the raw signal is chosen as 2.56 referring to Nyquist number [15]. Most of the researchers in signal analysis and processing are at ease with this number. To avoid the aliasing effect, the maximum frequency span is chosen using equation 1.

$$F_{\max} = \frac{fs}{2.56} \tag{1}$$

Ikaz decomposes the time domain signal into three level of the frequency range. The x-axis represents low frequency (LF) with a range of 0 – 0.25 of $f_{\max}$, followed by y-axis which represents high frequency (HF) with a range of 0.25 – 0.5 of $f_{\max}$. and the third, z-axis represents very high frequency (VF) with range 0.5 of $f_{\max}$. The 0.25 $f_{\max}$ and the 0.5 $f_{\max}$ been selected as low and high-frequency range limit respectively by referring to the 2nd order of Daubechies concept in signal decomposition process [17]. Ikaz method also contributes to the three-dimensional graphical representation of the measured signal frequency distribution. The variance (σ^2) of each frequency band; σL^2 represent a low-frequency band, σH^2 represent a high-frequency band and σV^2 represent a very-high-frequency band which calculated from equation 2, 3 and 4 to measure the scattering from data distribution.

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

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

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

The Ikaz coefficient, Zσ can be simplified in term of variance, σ as in equation 5 [16].

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

2.2 Kurtosis

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

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

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 peakness of the probability distribution associated with the instantaneous amplitudes of the time-series analysis [18]. Ikaz-kurtosis ratio is expressed in equation 7.

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

2.3 Algorithm Automatic Selection of Intrinsic Mode Function (IMF) Based on Pressure Transient Signal

Automatic Selection of Intrinsic Mode Function (IMF) Based on Pressure Transient Signal

1. Perform EMD on a pressure transient signal
2. Find local maxima of the absolute value of IMF (to take advantages of using both upper and lover envelopes) and fix the end values as maxima to ameliorate the end effect.
3. Construct a Spline Envelope (SE) through the maxima.
4. When envelope goes under the data, straight line envelope will be used for that section of the SE.
5. EMD decomposed the signal into so-called level of Intrinsic Mode Function
6. Calculate the Integrated Kurtosis Algorithm for z-filter technique to kurtosis ratio (Ikaz-Kurtosis) coefficient using Eq. 7.
7. Identified the IMF that corresponds to the largest Ikaz-kurtosis ratio coefficient.
8. Perform Hilbert Transform (HT) and Hilbert Spectrum (HS) for IMF level that contain the largest coefficient of Ikaz-Kurtosis ratio.
9. Normalize the data using SE : N-data = Data/SE. This steps can be repeated.
10. Compute IF (FM) and Absolute Value (AV) from Hilbert Transform of N-data.
11. Definition: Error Index = $(AV-1)^2$.
12. Compute Instantaneous Frequency for SE (AM).

3 Methodology

In this work, the response of the signal generated by solenoid valve is acquired using a pressure sensor. During the experiment, the solenoid valve is set to a normal closed condition, and the water hammer phenomena were induced during the opening and closing of the valve for three consecutive times. The experimental data is captured using MatLab Software.

3.1 Experimental Setup

The experimental test was performed in a circular loop pipeline system with 67.90-meter long. The network was constructed using Medium High-Density Polyethylene pipes (MDPE) with an outer diameter of 60 millimeters, the internal diameter of 55 millimeters and 2.6 millimeters mean thickness. An artificial leak simulator was installed at 19.7 meters from 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 discharged. This is to prevent sudden expansion phenomena due to the pressure waves, and to minimize the adverse pressure wave, as it will affect the data in the transducer. The calibrated speed of sound from the test rig is 524.3005 m/s.

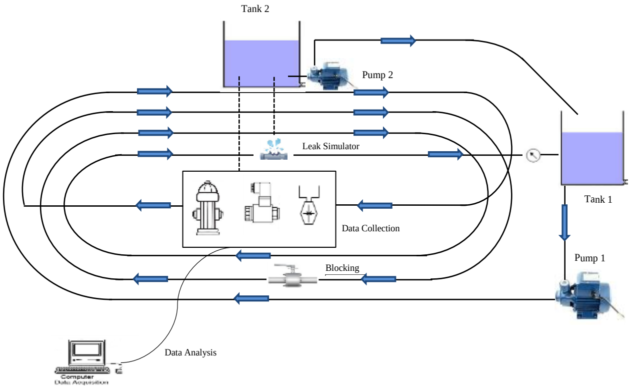

Figure 1: Schematic Diagram of Test Rig design for laboratory and experimental test

The Figure 1 schematic diagram shows the pressure sensor and solenoid valve which been installed 10 meters from the electric pump to avoid the noise during collection the data. This noise is due to the turbulent flow wave characteristic when the water flows out from pump outlet; the flow the approaches to laminar or steady state condition as it travels further from the pump. This phenomenon also generates friction to the wall pipe. Therefore 10-meter-long distance from pump to the sensor is adequate to reduce the noise. This method is commonly practiced in the pipeline leakage detection methods. The idea was adopted from the usage of pressure transient flow of water in the pipeline network. Theoretically, the pressure transient response occurs when a sudden change in the flow of water by closing or opening the valve in the pipeline network. As these phenomena happen inside the pipeline network, a wave propagation of water is expected to be created along the pipeline network, and also the characteristic of wave propagation will be used as a medium to detect leak and pipe feature along the pipeline network. The wave inside the pipeline network will propagate with different signal depends on the size of the leak, distance of leak, the type of pipe feature and distance of pipe feature.

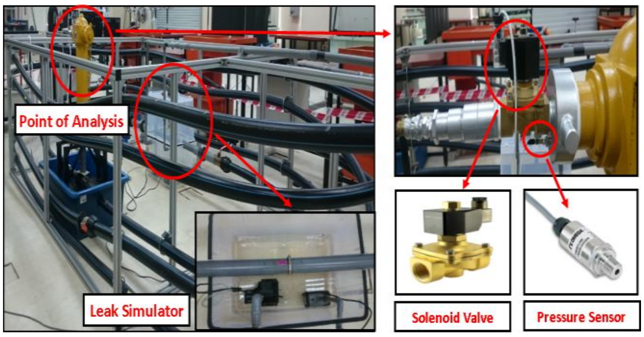

Figure 2: Experimental test rig in laboratory scale

Figure 2 shows the experimental test rig installed in Fluid Mechanic Laboratory at 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 field test. Both components play an essential role, the solenoid valve is used to generate the water hammer phenomenon and the pressure sensor is used to acquire the signal. In a few cases, the system shut down on its own due to sudden opening or closing valve and malfunction of the pump. This will generate “water hammer” occurred on the pipeline system. This phenomenon commonly happens in all pressure pipe systems, which causes substantial vibration and destruction to the pipeline system [19]. To generates this phenomenon, a solenoid valve (Figure 2) is utilized as a tool to create water hammer along the pipeline system. This situation creates the same phenomenon happens in the real system when there is a pressure disorder occur at the underground pipe.

4 Results and Discussion

The experimentation begins with acquiring the pressure transient signal from test rig using Matlab. 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 and from the burst origin through the speed of sound in water distribution system. In this work, Normalized Hilbert-Huang Transform (NHHT) which contains Empirical Mode Decomposition Method (EMD) data pre-processing method and Normalized Hilbert Transform (NHT) data post-processing method is employed as the tool to analyze the pressure transient signal.

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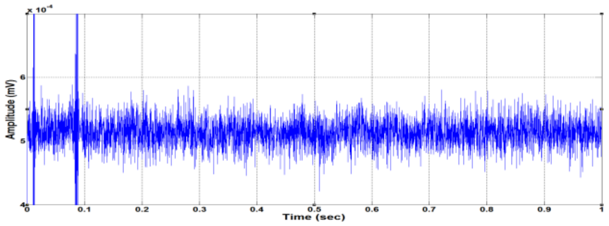

Figure 3: Raw Data for Leak and No-Leak Water Pipeline

Figure 3 illustrates the signal response from the leak and no-leak pipeline system. The first two maximum amplitudes on the figure represent the opening and closing of the solenoid valve which produces the pressure transient signal, which is transmitted along the pipeline system and reflected back due to the disturbance. The original response was recorded at two different levels of pressure: 1 bar and 2 bar. The signals captured at a different level of pressure demonstrated different results. Higher pressure creates a higher frequency of the signal and this causes for the higher amplitude of the signal. The raw signal was then analysed to extract the information contained in the signal. In this research, NHHT was used as the signal analysis tool and Normalized Ikaz was used as a tool to automatically select the right IMF. The analysis using empirical mode decomposition (EMD), decomposed the signal into level 13 of intrinsic mode function (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. Usually, the first and second levels of IMF are not considered for further analysis because these levels contain the noise frequency signal. Meanwhile, IMF level 7 and the rests contain unnecessary response of the network. All these IMF were therefore discarded. The rest, IMF level 3-6 are recombined to produce a signal without noise (Yusopet al 2017). To identify the right IMF automatically without the interaction of the skilled user, normalized Ikaz is used as an advanced statistical method for autonomous selection of the right IMF. The value of normalized Ikaz coefficient computed for each level of IMF values is presented in table 1.

Table 1: Normalized Ikaz Coefficient

IMF	Kurtosis Coefficient	Ikaz Coefficient	Normalized Ikaz Coefficient
1	2429.65	7.10e-09	2.92e-12
2	919.59	3.64e-09	3.96e-12
3	535.22	1.03e-09	1.94e-12
4	63.67	2.87e-09	4.52e-11
5	26.48	3.83e-09	1.44e-10
6	16.92	6.10e-10	3.60e-11
7	9.31	2.06e-10	2.21e-11
8	4.47	1.19e-10	2.67e-11
9	2.65	5.62e-11	2.11e-11
10	2.58	3.83e-11	1.48e-11
11	1.46	9.56e-13	6.50e-13
12	2.14	4.62e-19	2.15e-19
13	2.9	2.74e-12	9.44e-13

Table 1 illustrates the comparison among kurtosis, Ikaz and Normalized Ikaz coefficient for each level of IMF. From the observation, IMF level 1 has the highest kurtosis and Ikaz coefficient. By referring to [20], the first and second level of IMF contains the signal noise. Therefore, in this research, Ikaz and kurtosis coefficient is not suitable to be used for automatic selection of IMF. Besides that, IMF 5 contains the highest Normalized Ikaz coefficient and by referring to [20], this level is in the range of IMF 3-6 that should contain the signal without noise. To ensure IMF 5 has the highest Normalized Ikaz coefficient for consideration as the right IMF for further analysis, IMF 5 was subjected to further analysis using Normalized Hilbert Transform (NHT). The result of NHT is presented in Figure 4 and 5.

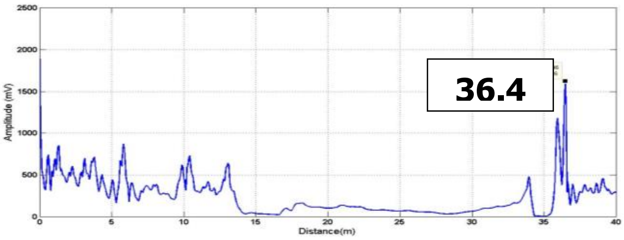

Figure 4: NHT for no-leak pipeline system

Figure 4 shows the result of Normalized Hilbert Transform (NHT) for no-leak pipeline system while Figure 5 for leak pipeline system. During this phase, non-stationary 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 [20].

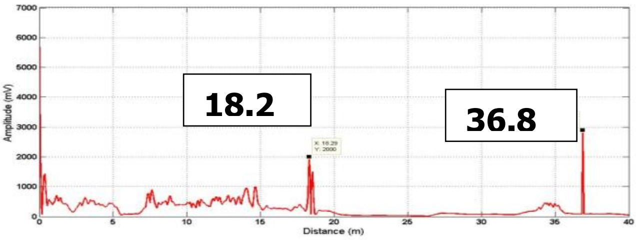

Figure 5: NHT for leak pipeline system

From the observation, it is evident that the tallest spikes and amplitude occurs at a distance 36.46 meters. By comparing to the test rig blueprint, this position is identified to be the outlet for pipes. Figure 5 shows that the tallest spikes and amplitude are at the distance of 18.29 meter and 36.88 meters. By comparing to the test rig blueprint, at distance of 18.29 meter identified to be the leak, while at the distance of 36.88 meters identified to be the outlet pipe. The experimental investigations and analysis were repeated with different pressure and the obtained findings are tabulated in Table 2.

Table 2: Comparison position of pipeline features between measured and experimental position

Water Pressure	Signal Response	Pipe Feature	Measured Position (m)	IMF contain Maximum Normalized Ikaz Coefficient	Experimental Position (m)	Error %
2 bar	**Leak Data**	**Leak**	19.7	5	18.29	7.6
		Outlet	39.8		36.88	7.3
	No Leak Data	**Outlet**	39.8	4	36.46	8.3
4 bar	**Leak Data**	**Leak**	19.7	5	19.24	2.3
		Outlet	39.8		37.08	6.8
	No Leak Data	**Outlet**	39.8	4	36.24	8.9

Table 2 illustrates the comparison of the position of pipe features between measure position and experimental position. For leak pipeline system data with 2 bar water pressure, the position of leak shows 7.6 % error and position of outlet show 7.3 % error. Meanwhile, for no-leak pipeline system data present 8.3 % error for outlet position. The final part of NHHT analysis evidently shows the position of pipe feature that is leak and pipe outlet appears at the experimental position close enough compared to each the measured position and theoretical calculation. It also demonstrates that NHHT analysis was able to detect and position the transient event occurrences in the non-stationary pressure transient signal.

5 Conclusion

This paper discusses self-decision method for IMF selection through Normalized Hilbert Huang Transform (NHHT) analysis by using a high-frequency piezoelectric pressure sensor. The results of the analysis demonstrate that the Normalized Ikaz is suitable and recommended as a self-decision method for IMF selection to implement in Hilbert-Huang Transform (NHHT) analysis. The development of automated self-decision of IMF through NHHT has been built and statistically analyzed using Normalized Ikaz. Therefore, this method is proposed and recommended to be implemented. Normalized Ikaz can be efficiently used to help in developing a real-time monitoring system for live water distribution system and can also be used to manage the issue of IMF selection. Therefore an efficient online monitoring system for leak detection can be developed. The results also verify the ability of piezoelectric pressure sensor in quickly detecting the change in response frequency of the pipeline system.

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