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Leak detection in gas pipeline by acoustic and signal processing - A review

Leak detection in gas pipeline by acoustic and signal processing – A review

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Abstract. The pipeline system is the most important part in media transport in order to deliver fluid to another station. The weak maintenance and poor safety will contribute to financial losses in term of fluid waste and environmental impacts. There are many classifications of techniques to make it easier to show their specific method and application. This paper's discussion about gas leak detection in pipeline system using acoustic method will be presented in this paper. The wave propagation in the pipeline is a key parameter in acoustic method when the leak occurs and the pressure balance of the pipe will generated by the friction between wall in the pipe. The signal processing is used to decompose the raw signal and show in time-frequency. Findings based on the acoustic method can be used for comparative study in the future. Acoustic signal and HHT is the best method to detect leak in gas pipelines. More experiments and simulation need to be carried out to get the fast result of leaking and estimation of their location.

1. Introduction

The pipelines operated for a number of years and tend to corrode. The slow process will lead to the big explosion if the gas is the main fluid filled in the pipeline system. The leak detection in gas pipeline is more difficult compared to water because of the poor signal noise to ratio (SNR). The large noise comes from gas flow itself. In addition, the geometrical features also one of the noise and make the leak detection in gas pipeline more complicated [1].

The leak detection techniques introduced in order to minimize the losses of medium transported by the pipeline. Three major categories can be divided to classify the technique. The first technique is automated detection, which can detect by monitoring system of pipeline network without human operator after the installation while, semi-automated detection need a certain input to perform some task in order to detect the leakage. The third category is manual detection, which is using the system and the device. It always needs to operate by human [2].

Classification of technique in order to detect leak in the pipeline also can be described as optical and non-optical methods as by Batzias [3]. Optical method more specific and sensitive compared to non-optical method, but their faces problem with the background noise. So, they need low reflection background material such as green grass, coarse snow, frost and sandy soil. But, direct and indirect leak detection also gives some idea in the classification of techniques. Direct technique normally uses visual inspection or device for detects the gas that escapes from pipeline network [4, 5].

Normally they classify the method based on their technical nature[6]. Technical nature divided in two categories which are hardware based method and software based method. Non-technical method also can be categorized in technical nature [2]. These categories sometimes mentioned as internal and external method in leak detection system [7]. In this paper, the study of gas leak detection using acoustic, sound propagation, signal analysis and some simulation synthetic signal will be discussed in detail.

2. Sound wave propagation and acoustic method

Basically, the leak can described as gas or liquid flow through the wall with the imperfection such as hole, crack or ruptures. The pressure difference in pipeline always flows from higher pressure to lower pressure. The imbalance pressure detected and analysed to detect the leak. The wave propagation or speed of sound, a will be dependent on the material and pipe diameter based on Thorley [8]. The formula of speed of wave propagation in the thin walled pipes as follows:

$$a = \sqrt{\frac{1}{\rho \left[\frac{1}{K} + \frac{D}{Ee}\phi\right]}} \qquad (1)$$

Where a = wave propagation speed in m/s, ρ = fluid density (kg/m^3), E = Young's modulus of elasticity of pipe wall material (N/m^2), K = bulk modulus of the liquid (N/m^2), and ø = a restraining factor dependent on the Poisson's ratio of the wall material and how well the pipe is supported. Equation (1) is only true for single phase fluids in rigid pipes, whereas for the flexible pipe or the fluid is multiphase, the speed of the wave will be decreased [9].

When a sound wave comes into contact with a surface, some part of the energy is reflected from it, some are transmitted through it and some is absorbed. If absorption and transmission are low, and thus most of the sound energy incident on the surface is reflected, it is supposed to be acoustically hard and can be regarded as mirror reflect the illumination [10].
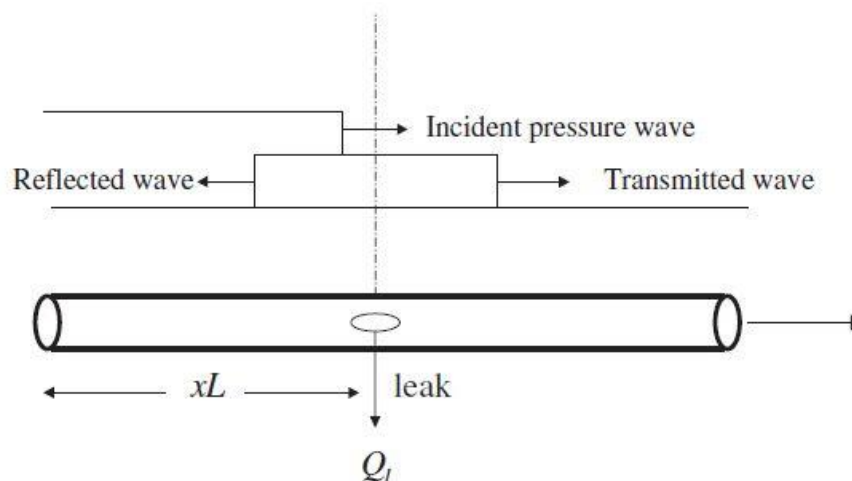

Figure 1. Conceptual wave reflection at a leak [11].

Dozens of subjects have been performed in a leaking gas pipeline using acoustic methods. The basic rule behind this acoustic method is when leak or ruptures occur, the friction between the rampart in the pipeline happen because of the pressure balance was broken. The acoustic signal will propagate to upstream and downstream [12]. The stress wave that transmitted through the pipeline can be recorded by acoustic sensor or accelerometer [13].Sound wave exhibits four different phenomena

which are reflection, interference, refraction and diffraction. Three effects that occur to the incident wave mentioned by [14, 15] are reflection, transmission and absorption as shown in figure 1 [11].

Acoustic sensor normally installed outside the pipeline network. The leak generates noise and pick up by these acoustic sensors and the most important thing is to minimize the background noise [6, 16]. The location and size can be determined by using acoustic methods. This method can be used on new as well as on existing pipe network. The fast and high sensitivity give advantages in this method compared to others. In addition, this method also offer accurate leak location and low false alarm rate [12]. But, high background and noise condition will affect the actual leak and also produce false alarm when the leak is too small [2, 6, 17, 18].

Early studies in acoustic wave was done by Watanabe [19] by measured the pipeline and its shows that sharp positive and negative pulse at a certain time using mathematical model of the pipeline acoustic. From there, they can detect the location of leak. Hunaidi and Chu [20] investigated about the characteristic of frequency content as function of leak type, flow rate, pressure of the pipeline system and also season in sound and vibration signals. The details will help in order to choose appropriate instrumentation, design of procedures, and accurate locating leaks using cross-correlation method. The technique using pulse reflectometry involving injection of sound pulse into pipeline system and the resultant of reflection will be recorded was done by Sharp and Campbell [21]. The value of the reflection coefficient for a small leak depends on leak area except for the crack. Experimental and theoretical analysis of acoustic properties of a finite elastic pipe filled with water or air was investigated by Feng [22].

A patented acoustic technique known as Acoustic to detect features such as blockage and leakage by injecting pressure pulse in the pipeline was developed [18]. The development and test of gas leakage present by Sousa [23] based on acoustic method. They used microphone to catch the leak noise by operating and non-operating of gas flow in 60 m long pipeline. Besides, the high-temperature microphones developed in nuclear power plant and successfully operating to detect the leaks with sensitivity 0.23 m3/h and also their location [24].

An acoustic measurement method was proposed to non-invasively detect L-bends and T-branches. This pipeline is buried under floors or in the walls of buildings [25]. Acoustic sensor used to detect the leaking in the pipeline and handle by operators or intelligent pigs hold the device along the pipeline to inspect the leak. Placing sensor to far will increase the risk of undetected leak while placing too close will increased the cost.

The range and dynamic pressure transducer discussed by [26]. Rocha [27] used pressure sensor to record the appearance of acoustic pressure waves. Time-frequency technique [28, 29] or low frequency impulse [26] method used in detection the leaking involves the measurement of two acoustic signals on each of a pipe segment. A recent study of experimental focus on distinguishing between signals make by leak and background noise using time-frequency analysis and added by location formula to increase accuracy [12] while Brodetsky and Savic present a new continuous acoustic leak detection system by using k nearest neighbour classifier to distinguish leaks in underground high pressure gas pipelines [30].

3. Signal processing

Dealing with dynamic signal is challenging because not-deterministic type of signal normally occurs in real application. So, signal processing was used in order to reveal the hidden information. This problem can be solved and understand by statistical behaviour or any pattern recognition. Commonly, they are applied for time domain signals. But, in the leak detection issue, the signal needs to be transformed to solve the hidden result behind the raw data. Hence, the transformation methods were used such as Fast Fourier transforms (FFT), Wavelet transforms (WT), and Hilbert Huang transforms (HHT).

Years ago, a study using cepstrum analysis was developed by using closure and open solenoid valve. The time domain obtained by identifying the delaying time between initial wave with and their reflections [31, 32]. A wavelet-based filtering was introduced for detection in gas pipeline. This main

idea is based on the echoes reflected from turbulences induced by a leak [1]. The leakage detection algorithm was combined with the filtering method which is to transform, filtering to remove noise the and also cross-correlation technique to locate the leak by using time difference between two signals [33, 34]. An algorithm for gas pipeline leak detection based on Hilbert-Huang Transform studied and they use acoustic wave measured at two sensors at different positions. The other study was done using HHT and obtain Hilbert marginal spectrum. The result comparing between the normal condition and leak condition [35]. The leakage can be detected by feature of acoustic signal extraction [36]. Mostafapour and Davoudi [13] using Donnell's non-linear theory for cylindrical shell to derive motion equation and then solve by Galerkin method.

Some simulation of synthetic data used to show the process of signal processing with different method. The signal with different frequency and amplitude is defined by the equation (2) and as shown in figure 2.

$$x(t)=5\sin(2\pi f1 t) \qquad\qquad 0 < t \le 1.0s$$
$$x(t)=10\sin(2\pi f2 t) \qquad\qquad 1 < t \le 2.0s$$

(2)

where f1 is equal to 20Hz and f2 is 80Hz respectively.

Both signals are combined with impulse at two places which are at 0.4 s and 1.6 s. The impulse represents the irregularity in the signal which means reflection of the leaks, or features in the pipeline system.
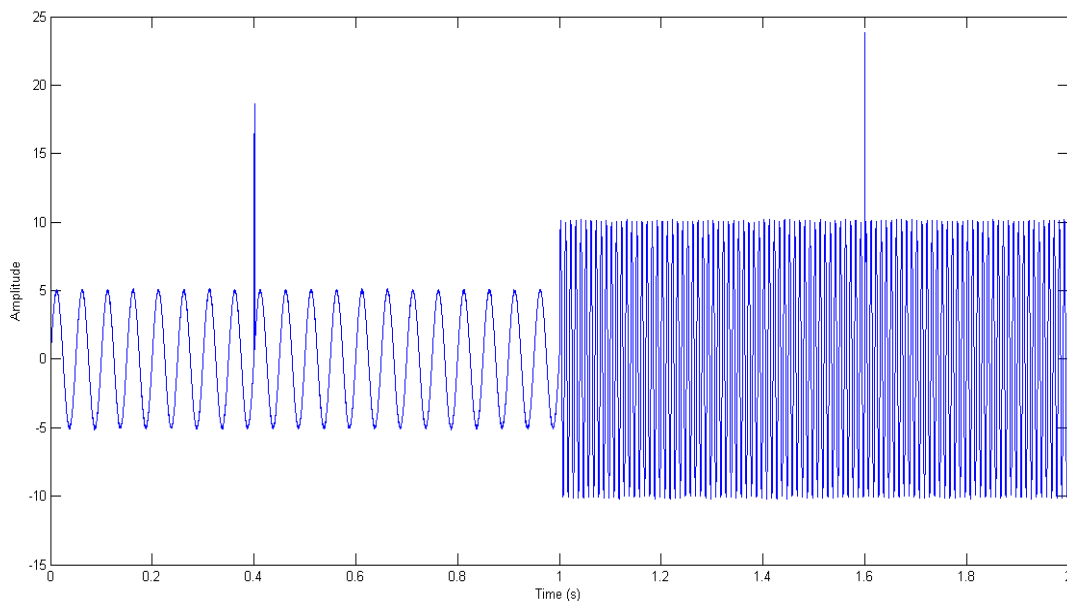

Figure 2. Time domain of the synthetic signal with 20Hz and 100Hz.

The simplest method of analysing is FFT, but there are too many drawbacks. From figure 3, both frequencies clearly seen in frequency domain. They can show the frequency, but not the time happens. The time is important since detection of leak location is based on time and speed of sound.
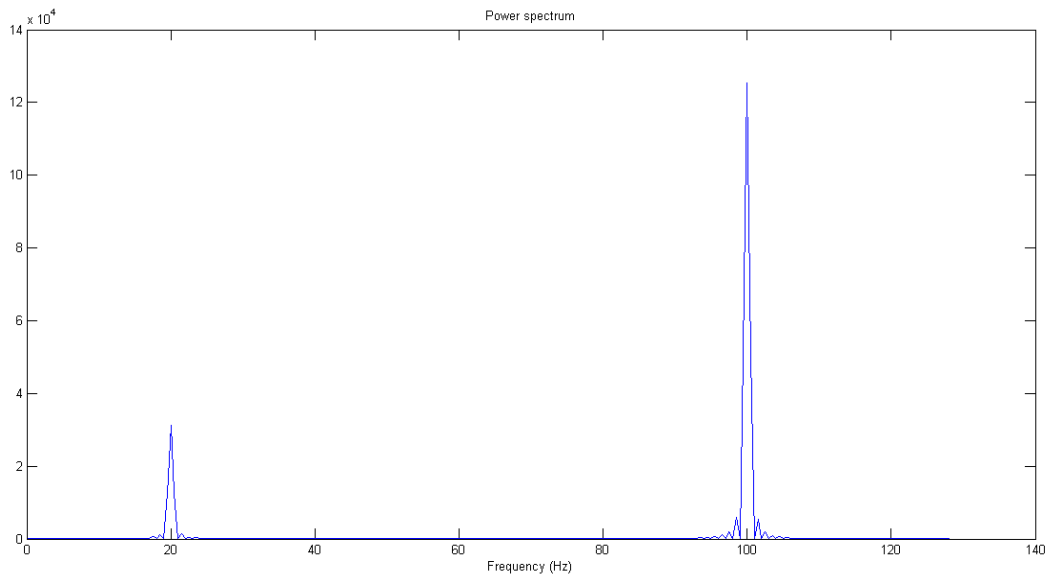
Figure 3. Frequency domain of the synthetic signal with 20Hz and 100Hz.

Compared to HHT, the result is more accurate and reliable. Figure 4 illustrates the both frequencies which are at 20Hz and 100Hz. The irregularity clearly shows at 0.4 s and 1.6 s. This plot provides a high resolution time-frequency representation and gives details of the time and frequency. It is good to provide an excellent result for the leakage in the pipeline and the location can be calculated based on the speed of sound and time delay from this plot.
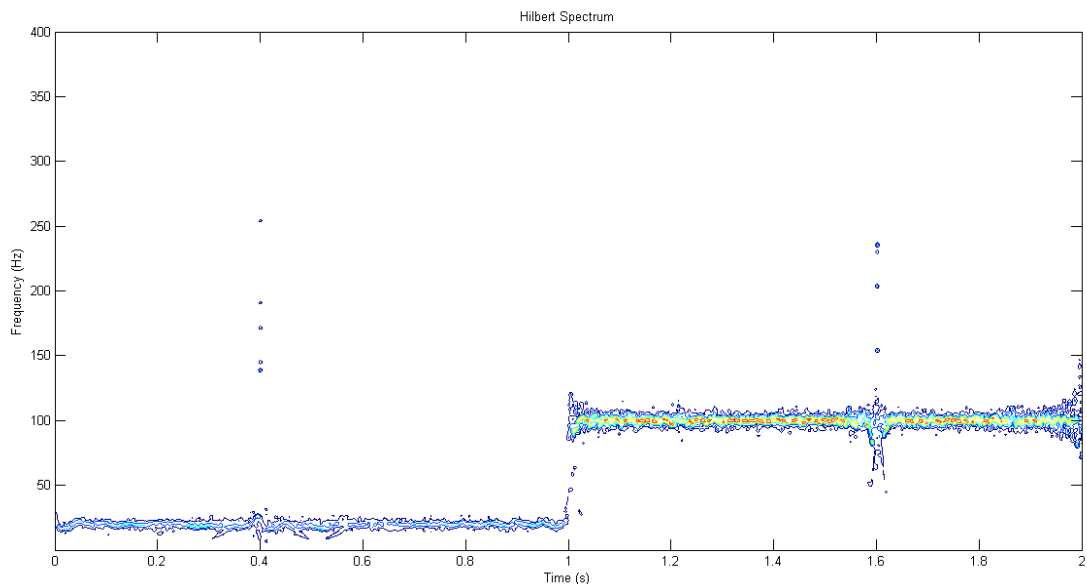

Figure 4. Hilbert spectrum synthetic signal.

The synthetic signal also compared between their advantages and disadvantages. Figure 5 shows the scalogram with Mexican hat. The wavelet analysis is also one of the powerful methods to show the frequency at the certain time. Based on the plotting in scalogram, the irregularity cannot be seen clearly. Only the spike at 1.6 s can be seen but not really good to show the result.
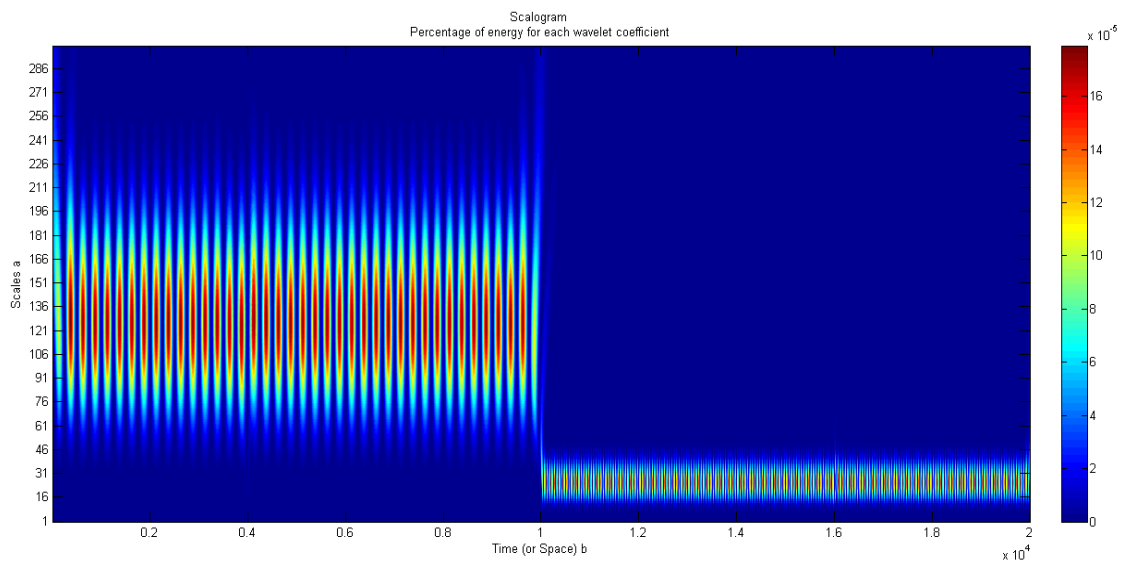
Figure 5. Scalogram of synthetic signal in Mexican hat as mother wavelet.

The spectrogram corresponding to the STFT for the synthetic signal was shown in Figure 6 below. The spike can be detected at 0.4 s and 1.6 s but unfortunately, the frequency show all over the time. There is no indicator when the frequency was happening at that time. Obviously, it fails to show the spike.
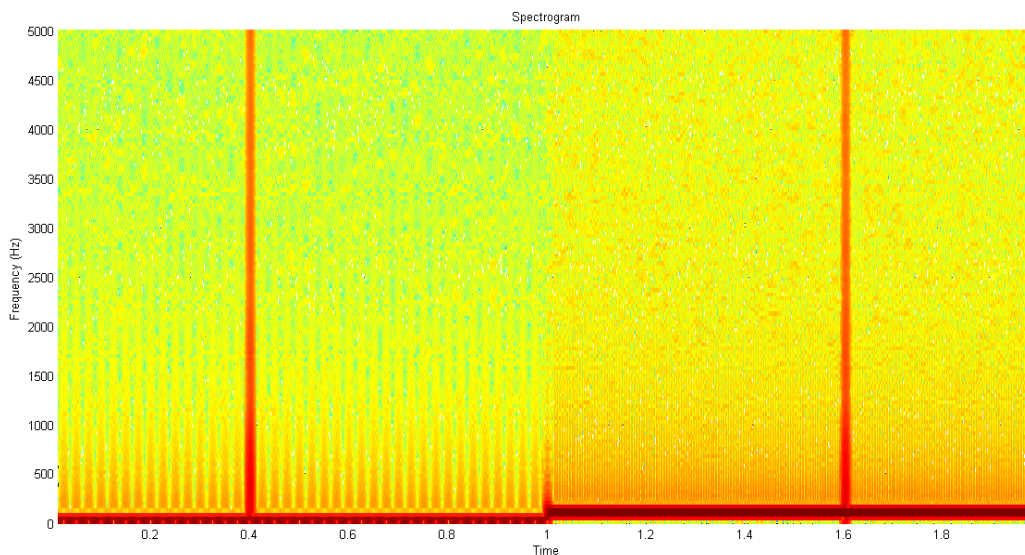

Figure 6. Spectrogram of synthetic signal with N/4.

4. Result and discussion

The finding of the present study suggests that acoustic signal and HHT analysis is the best way to detect leak in gas pipelines. Table 1 shows the common method with their advantages and disadvantages while table 2 shows the advantages and disadvantages between FFT, STFT, wavelet and HHT.

Table 1. Comparison of different method for leak detection.

Method	Speed of detection	Leak localization	Leak size estimation	Cost
Visual inspection	Slow	Yes	Yes	Cheap
Soap bubble	Slow	Yes	Yes	Cheap
Cable sensor	Fast	Yes	No	Expensive
Acoustic	Fast	Yes	Yes	Expensive

Table 2. Comparison of different method for signal processing.

Method	FFT	STFT	Wavelet	HHT
Advantages	Easy to implement		Features extraction	
		Can use for non-stationary signal	Non-stationary data analysis	Can use for all types of signal
			Multiresolution	High time-frequency resolution
			Basis function obtained by sifting and scaling a particular function	Both local and adaptive method in frequency analysis
			Analytic form for the result	Suitable for non-linear and non-stationary data analysis
			Allow filters to be constructed for stationary and non-stationary signals	Sharper spectrum
				Adaptive – data driven basis
Disadvatages	Not appropriate for nonlinear and non-stationary signals	Non-adaptive	Leakage generated by the limited length of the basic wavelet function	Lack of theoretical analysis
		Time-frequency resolution limited by the Heisenberg principle		No mathematical formulation
	Feature extraction impossible		Non-adaptive nature	No physical meaning of some IMFs
			Unable to resolve intrawave frequency modulation	

5. Conclusions

This review paper acts as a quick reference to readers, who are interested in leak detection by acoustic and signal processing. In this paper, the basic of wave propagation in gas pipeline introduced and some method were discussed to reveal the hidden information of the signal with simulation of synthetic signal. In the end, the acoustic method is the comparative method for gas leak detection study. The propagation of waves in the pipeline system will generate the friction and give important output to detect the leak. The finding provides evidence that acoustic signal as the wave propagation and HHT is the best combination to detect the leak in gas pipelines. More experiments and simulation need to be done to get the fast result of leakage and estimation of their location accurately and control the decrease false alarm.

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