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LEAK DETECTION USING VIBRATION-ACOUSTIC BASED TECHNIQUES: SIMULATION AND SIGNAL PROCESSING FOR PHYSICAL UNDERSTANDING

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Abstract. *Water scarcity together with high distance between large urban centers and water resources areas are the main factors for water treatment companies to be under pressure to reduce actual network losses. One way to reduce such water loss via leakage is by using vibration-acoustic based techniques aiding in leak detection and location. However, such techniques require relatively complex signal processing where the estimation of the time delay between two sensors, usually located either side of the suspected leak, is carried out by using the cross-correlation function (CCF), for example. One way in which this problem can be investigated is by using wave models. Moreover, simplifications can be applied to such models, allowing them to be used for physical investigation or generating simulated leak signals to study the use of signal processing tools. Hence, the aim of this work is to use a wave propagation model to generate simulated signals to be processed in order to estimate the time delay by using cross-correlation function, which is the main vibration-acoustic technique employed for leak detection in buried water pipes. Moreover, a virtual environment is developed for analysis and data interpretation for ordinary people who want to understand a bit more of leak detection problems.*

Keywords*: Leak; Wave propagation model; Cross correlation, Buried water pipe.*

1. INTRODUCTION

The availability of drinking water is becoming a global problem especially due to the increment in water consumption (demand) and water shortage due to perhaps the climate change. Hence, water shortage is a big concern worldwide. According to Shiklomanov (1993), less than 3% of the planet's water is fresh water, being part of this amount not proper for consumption. Water distribution systems are susceptible to water leakage, which can cause environmental and structural problems. According to SNIS (*Sistema Nacional de Informação sobre Saneamento*) (2018), water lost in distribution systems reached a figure of 38.3% in Brazil. Moreover, the water lost reached 55.1% in the north of the country, and 34.4% in the central west of Brazil, showing that such wastage varies from region to region, and the amount lost is not acceptable for worldwide standards. These figures are much higher than the ones found in Japan (around 2%) and Europe (around 18%), for example.

According to Lambert and Wirner (2000), there are two types of water loss: apparent losses and actual ones. Apparent losses are those caused by measurement errors, water meter problems or any other computational error. Actual losses are those caused by leaks, inefficient fluid transport, and clandestine connections (water theft). SABESP (2013) estimated that 30% of water is lost in its pipe distribution systems, located in São Paulo State. The company's current policy aims to reduce this loss to 17% by the end of the decade. Water loss reduction can result in water supply availability, which in turn means saving natural and financial resources (SNIS, 2018).

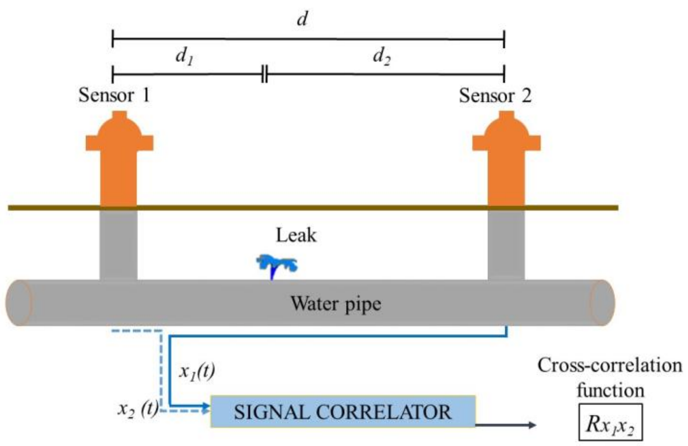
In many countries, including Brazil, modern plastic pipes such as PVC (Polyvinyl Chloride) and HDPE (High-Density Polyethylene)/HPPE (High-Performance Polyethylene)/MDPE (Medium-Density Polyethylene) are the most commonly used pipes applied to underground distribution networks of potable water and residential sewage. On average, a large percentage of water loss via the distribution system between the treatment plant and the consumer will occur in plastic pipes (SABESP, 2013). As stated earlier, water is a natural source that is becoming scarcer, so sanitation and water distribution companies are under pressure to reduce water loss, so that, locate and repair leaks rapidly is required by such companies. ‘

Due to this major problem, management procedures were and are formulated, where the main aim is water loss containment policy focused on profitability and sustainability of water distribution companies. These procedures can be divided into non-acoustic and acoustic methods. Non-acoustic methods can be time consuming and complex technique, which may require a long time to identify the leak, as shown by Hunaidi et al. (2000). Some of the non-acoustic methods are tracer gas, thermography, flow and pressure modeling, and ground penetrating radar (GPR). Acoustic methods have been shown to be more effective and are widely used by water companies. One of these techniques is the cross-correlation function performed using two vibratory signals from a single leak to estimate the time delay between these signals and locate where the leak likely to be located. The use of this technique, however, requires some experience of the user together with some interpretation of this problem. The latest can be achieved by using simple models which can be formulated to give a physical insight into the problem. One way of modeling this problem is by using wave propagation models with some simplifications. Hence, this paper will investigate a simple wave model that gives the required physical insight under a controllable environment. Moreover, simulated leak data, which can be used together with classical signal processing tools, such as the cross-correlation function, will be generate in order to show how the signal processing tools can be evaluated in leak detection problems. Hence, simulated leak time histories will be simulated at the measurement positions, processed in frequency domain via the modulus and phase of the CPSD (Cross Power Spectral Density) and the time delay estimated using the cross-correlation function.

2. INVESTIGATION OF LEAK DETECTION PROBLEMS USING THE CROSS-CORRELATION METHOD

Locating leaks in buried pipes is a difficult task to be carried out. This can be assisted using vibro-acoustic techniques, such as cross-correlation function. The cross-correlation calculates the time delay between two signals, which in the case for leak detection, these signals are the ones sensed by sensors places either side of the leak position. Since, these sensors measure the same leak noise signal, however, at different positions. It is worth mention that these measurement positions are generally hydrants or fittings to the buried pipe. Figure 1 shows a schematic of the set-up used for leak detection in buried pipes, being sensors placed at hydrants located either side of the leak. The distance between the sensors is $d = d_1 + d_2$, where d_1 e d_2 are the respective distances between the leak and the measurement points at sensor 1 and sensor 2. Moreover, the signals measured at each point are $x_1(t)$ for the sensor 1 and $x_2(t)$ for the sensor 2.

Figure 1. Schematic of how sensors can be placed at measurement positions (in this case hydrants) to perform vibro-acoustic technique so-called as cross-correlation.



The presence of a leak can be observed as a distinct peak in the cross-correlation function between $x_1(t)$ and. The peak in the cross-correlation function occurs at the time delay T_0, which is the difference in arrival time at both sensors. The leak position can be estimated as (Fuchs and Riehle, 1991)

$$d_1 = \frac{d - cT_0}{2}, \quad (1)$$

where c is speed at which the leak noise propagates along the pipe (Gao et al., 2004). In general, vibro-acoustic techniques, such as the cross-correlation are effective in detecting leaks in metal pipes, but such effectiveness is drastically affected in plastic pipes, as investigated by Gao et al. (2004). This fact can be attributed to two important factors: the first is due to the considerable uncertainty regarding the actual leak velocity in plastic pipes at the moment that the leak detection and location procedures are performed. The leak noise velocity estimation must be known a priori for vibro-acoustic methods to be effective (Brennan et. al, 2005). The second factor is the high attenuation present in plastic pipes, so that leak noise does not propagate over long distances in plastic pipes, which is not the case for metal pipes. This attenuation occurs due to different ways of energy dissipation of the vibratory/acoustic signal (Muggleton et al., 2002; Muggleton and Brennan, 2005). Hence, the major problem is how good the estimations of leak noise velocity and the delay between sensors 1 and 2 can be achieved. Usually the leak noise velocity is provided by commercial leak noise correlators or it can be calculated analytically. The time delay, however, is estimated via the cross-correlation function or by using the phase of the CPSD. The cross-correlation can be interpreted as a degree of similarity between two signals, so that, when the signals $x_1(t)$ and $x_2(t)$ are similar, the cross-correlation function has a maximum value, ie it has its peak at the delay when $\tau = T_0$. If the distances between the sensors and the leak position are the same, so that $d_1 = d_2$, then the signal delay will be zero $(T_0 = 0)$, so that the peak of the cross-correlation will be at the origin. However, if the distances between the sensors and the leak are different $(d_1 \neq d_2)$ then the signal delay will not be zero $(T_0 \neq 0)$, and the peak will be shifted from the origin along the x-axis (delay axis). In some cases, it is recommended to express the cross-correlation function in a normalized form known as the cross-correlation coefficient, which can be calculated as

$$\rho_{x_1x_2}(\tau) = \frac{R_{x_1x_2}(\tau)}{\sqrt{R_{x_1x_1}(0)R_{x_2x_2}(0)}}, \tag{2}$$

where $R_{x_1x_1}(0)$ and $R_{x_2x_2}(0)$ are the auto-correlation functions for the signals $x_1(t)$ and $x_2(t)$, respectively, when $\tau = 0$. The cross-correlation coefficient is within a range of -1 to +1, being defined by Bendat and Piersol (1993). Hence, this work aims to simulate leak situations by using the wave model given by Gao et al. (2004) where soil effects are neglected but fluid-structure interaction is kept.

3. MODELING THE LEAKAGE PROBLEM IN BURIED PIPES USING WAVE PROPAGATION MODEL

Gao et al. (2004) proposed an analytical model to describe the behavior of a fluid filled pipe using the wave propagation theory, so that, the wave number of a fluid-filled pipe is calculated. This model, however, is only valid well below the ring-frequency, which is the case for real leak problems. The wave number for a fluid filled pipe, according to Gao et al. (2004) is given by

$$k^2 = k_f^2\left(1+\frac{2Ba}{Eh+j\eta Eh}\right), \tag{3}$$

where k_f is the wave number considering a free fluid, η is the pipe wall loss factor, B is the Bulk modulus of fluid, E is Young's modulus of the pipe material, a is the pipe radius and h is the pipe wall thickness. The η is usually within 0.05 and 0.15, and it is related to the loss within the fluid-structure (water-pipe) interaction. The leak noise velocity can be theoretically calculated as

$$c = c_f\left(1+\frac{2Ba}{Eh}\right)^{-\frac{1}{2}}, \tag{4}$$

where c_f corresponds to the free fluid wave velocity, that is, there are no boundary conditions delimiting the fluid, such as the pipe. It can be observed that the pipe properties are responsible for changing the c_f speed, being this reduced when surrounded by the pipe. The attenuation, which is related to the energy loss ("dissipation") between the fluid and pipe wall can be calculated as

$$\beta = \frac{1}{c_f}\frac{\eta Ba/Eh}{\left(1+(2Ba/Eh)\right)^{\frac{1}{2}}}. \tag{5}$$

Considering that the pressure at any point along the pipe can be gives as $P = P_0(\omega)e^{-ikl}$, where $P_0(\omega)$ is the frequency dependant acoustic pressure amplitude when $l = 0$. Hence, the Frequency Response Function (FRF) between the pipe section of length l and the leak is defined by (Gao et al., 2004)

$$H(\omega, l) = e^{-i\omega l/c} e^{-\omega\beta l}. \quad (6)$$

The impulse response, however, can be calculated by using the inverse Fourier transform of the FRF as

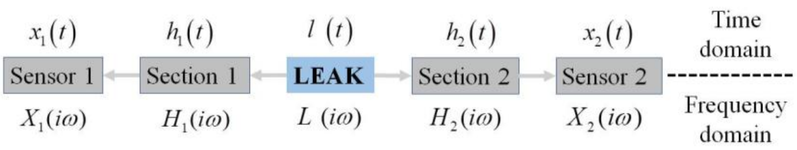
$$h(t) = F\{H(\omega, l)\}^{-1} \quad (7)$$

where $F\{\ \}^{-1}$ is the inverse Fourier transform.

4. INVESTIGATION OF THE USE OF SIGNAL PROCESSING TOOLS USING THE CLASSICAL WAVE PROPAGATION MODEL FOR A WATER-FILLED PIPE

Leak detection in buried water pipes is a complex problem that can be investigated via numerical models (ie. Finite element models) or via analytical models (ie. wave propagation models) aiding in the problem understanding. In this work, however, it is used the wave propagation model to simulate leak situations, which can be further used to investigate the main characteristics of leak noise propagation in water-filled pipes, together with classical signal processing tools used to estimate its position. Figure 2 shows a schematic how the wave propagate model can be used to reproduce simulated leak conditions in a virtual environment. This schematic shows how the problem can be carried out in frequency and time domains. The leak noise in the time domain and frequency domain is given by $l(t)$ and $L(i\omega)$, respectively. The leak noise propagates along the pipe sections, here named as Section 1 and Section 2, so that it main characteristics are changed according to the pipe properties and length. These characteristics are related to the impulse response (time domain) or FRF (frequency domain)

Figure 2. Schematic of the wave model used to simulate leak conditions under a controllable environment.

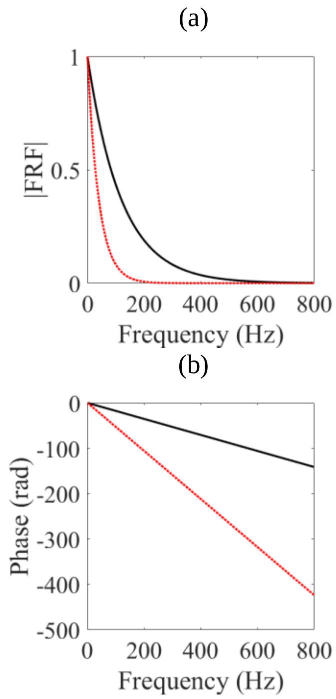


For a better insight into the problem, a simulated leak situation will be performed. This simulation consists in a plastic pipe with the properties given in Tab. 1. The distances d_1 and d_2 are set to 10 m and 30 m, respectively. Figure 3(a) and 3(b) shown the modulus and phase for the FRF calculated using Eq.(6) for the pipe Section 1 (black-solid line) and pipe Section 2 (red-dotted line).

Table 1. Value of the properties used of the plastic pipe used on the simulation.

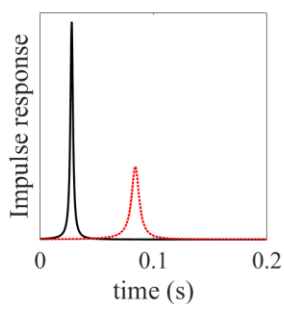
Properties [units]	**Value**
Pipe radius, a [mm]	75
Pipe wall thickness, h [mm]	9.85
Pipe wall loss factor, η	0.1
Bulk modulus of fluid, B [N/ m^2]	2.2×10^9
Young's modulus of pipe material, E [N/ m^2]	2×10^9
Free fluid wave velocity, c_f [m/s]	1500
Distance from the leak to sensor 1, d_1 [m]	10
Distance from the leak to sensor 2, d_2 [m]	30

Figure 3. The theoretical FRF calculated using Eq. (6) and the pipe properties given in Tab. 1. (a) Modulus. (b) Phase. FRF of Section 1 (black-solid line), FRF of Section 2 (red-dotted line).



It is observed that the modulus of the FRF decays exponentially, as expected being in accordance with the model used given by Eq. (6). Moreover, it can be seen that the FRF for the Section 2 decays more rapidly than for the Section 1. This is because, for this specific example, $d_1 < d_2$, the leak vibration level is higher attenuated, especially at high frequencies, for the longest pipe section, in this case Section 2. The modulus of the FRFs also shows that the pipe sections act as a mechanical low pass filter, restricting the frequency range over which leak noise signal can be found. This is the problematic characteristic mentioned previously when vibro-acoustic techniques are used in plastic pipes. Hence, the model is representative of the real problem of leak detection. Figure 3(b) shows the phase gradient of the FRF for pipe Section 1 (black-solid line) and for pipe Section 2 (red-dotted line). It can be observed that the slopes for each phase is different. This is because the wave traveling in pipe Section 2 takes longer (time) to reach the end of the section as $d_1 < d_2$. Hence, the phase slope is related to the time that each wave takes to reach the end of each section. Moreover, steeper the phase (slope) smaller is the time delay for the leak noise to reach the end of the pipe section. Hence, time delay can also be calculated by estimating the phase slope, however, this is not straight forward in practical situations. This is why cross-correlation techniques are used instead. Figure 4 shows the impulse response (IR) function of those FRFs given in Fig. 3. It is observed that the IR for pipe Section 1 is peaky and closed to the origin, while that, the IR for pipe Section 2 is more spread, smaller and further from the origin. The spread in the IR is related to the filtering characteristics of the pipe. The IR for section 2 attenuates more the leak signal (amplitude) and broader the IR shape due to its filtering characteristics. The shift is due to the time delay, which is higher for the Section 2 as this is the longest between the two sections.

Figure 4. The impulse responses calculated using Eq. (7). Impulse response of Section 1 (black-solid line), impulse response of Section 2 (red-dotted line).



The model described previously will be used to simulate two cases. Case one consists in simulating the leak as a flat spectrum, so that, the leak energy is frequency independent. However, this is not for case 2, where the leak is considered white noise with normal distribution and zero mean. The last one needs a statistical approach by estimating the CPSD if the analysis is carried out in frequency domain, for instance.

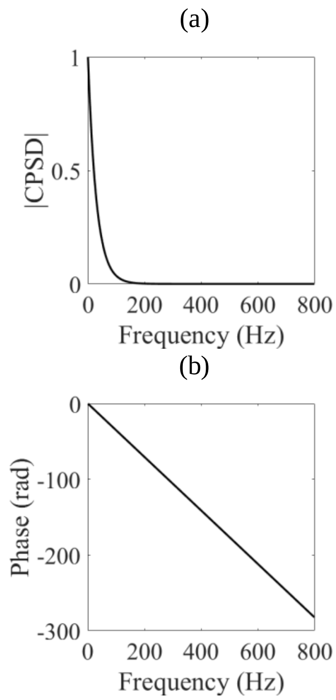
Case 1. Leak is assumed as flat spectrum characteristics

In this case, it is considered the leak with flat spectrum behaviour, so that, the spectrum is similar to the theoretical white noise signal. The CPSD can be then calculated as

$$S_{x_1x_2}(i\omega) = S_0 X_1^*(i\omega) X_2(i\omega)\,, \tag{8}$$

where $X_1(i\omega) = L(i\omega)H_1(i\omega)$, $X_2(i\omega) = L(i\omega)H_2(i\omega)$, $L(i\omega) = L_0$ is the flat spectrum behavior and $*$ denotes the complex conjugate. Figure 5(a) and (b) shows the modulus and phase for the CPSD using the case described in Table 1. It can be observed that the |CPSD| has a similar behavior as the FRFs shown in Fig. 3, reinforcing that the pipe acts as a low pass filter for pressure/displacement-like measurements. The phase, however, is between the slopes given by the phase of FRFs given by Fig. 3(b) as its slope (phase of the CPSD) is related to the different between d_1 and d_2, which gives the difference in arrival times T_0.

Figure 5. The simulated CPSD for a flat leak spectrum. (a) Modulus of the CPSD. (b) Phase of the CPSD.

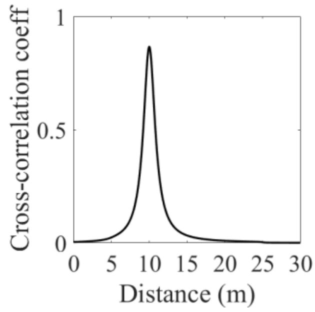


The Cross-correlation function, however, can be obtained by calculating the inverse of the Fourier transform of Eq.8 as

$$R_{x_1x_2}(\tau) = F\left\{S_{x_1x_2}(i\omega)\right\}^{-1}. \tag{9}$$

Figure 6 shows the CCF coefficient of the inverse Fourier Transform of the CPSD given by Eq. (8). The time delay axis (x-axis) has been modified using Eq. (1), so that, the peak in the CCF coefficient gives the leak position from sensor 1. It can be observed that the peak occurs at 10 meters from the distance of sensor 1, which is consistent to the model.

Figure 6. The cross-correlation coefficient given by the IFFT (inverse Fourier Transform) of Eq. (8).



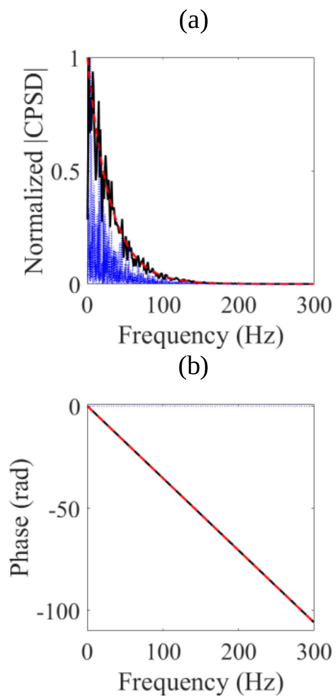
Case 2. Considering the leak signal as White noise with normal distribution and zero mean

Considering, therefore, the leakage signal as a random characteristic with normal distribution and zero mean. In this case Eq. (8) would be rewritten as follows,

$$S_{x_1x_2}(i\omega) = S_{ll}(i\omega)X_1^*(i\omega)X_2(i\omega)\,. \tag{10}$$

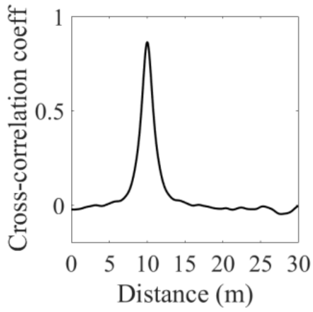
The CPSD is calculated via Welch's method for random signals, which is the case for the leak spectrum characteristics. The leak noise is simulated using a sampling frequency of 5kHz, during 10 seconds. A Hanning window with 50% overlap is also used. Two analyses were carried out: analysis 1 is conducted by setting the truncation time length at 1 second, so that, the frequency resolution is of 1 Hz. The second analysis (analysis 2) is carried out by taking the truncation length as 5 seconds, reducing the average and increasing the frequency resolution, which in this case is 0.2 Hz. Figure 7(a) and 7(b) show the normalized modulus and phase of the CPSD, respectively, for the case described previously. The blue-dotted line is related to the data without any stochastic signal processing (Welch's method), while that the black-solid line and red-dashed line stand for the analysis 1 and 2, respectively.

Figure 7. The simulation conducted by considering the leak spectrum as white noise with normal distribution and zero mean, as given by Eq. (10). (a) Normalized modulus of the CPSD. (b) Phase of the CPSD. Blue-dotted line – no average. Red-dotted line – analysis 1 (frequency resolution of 1 Hz). Black-solid line – analysis 2 (frequency resolution of 0.2 Hz).



It is observed that the Welch's method smooths the |CPSD|, enhance the shape when the average is increased, however, reducing the frequency resolution. A longer time length would sort out the problem with the smoothing for analysis 2. The phase, however, is only affected if no average is taken. Likewise for the case 1, the IFFT of Eq. (10) is performed to estimate the Cross-correlation function, which is shown in Fig. 8 via the cross-correlation coefficient (CCC).

Figure 8. The cross-correlation coefficient given by the IFFT of Eq. (10).



The difference between the above CCC and the one shown in Fig. 6 are the wobbles present in the data, which is due to the leak characteristics. However, the peak is still located at 10 meters, which is the distance from sensor 1 to the leak.

6. CONCLUSION

This paper has introduced a simple wave model, which can be used to simulate leak conditions in a controllable environment. This model can be a reasonable way to enhance the understanding of the physics behind leak noise propagation in fluid-filled water pipes. Moreover, it can contribute to a better view of classical signal processing tools and their applications to leak detection and location problem. Hence, two different ways of modelling leak noise characteristics were proposed. One model is based on a flat leak spectrum, and the second model is considering the frequency dependant spectrum with normal distribution and zero mean. The first model shown the main features of the physics behind the problem. The second one, however, signal processing techniques for smoothing the data is required. Hence, the physics and the data processing for leak detection problem in fluid-filled pipes can be investigated using these two simple models.

5. ACKNOWLEDGEMENTS

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5. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this paper.