DINAME 2019 - Proceedings of the XV International Symposium on Dynamic Problems of Mechanics,
M.A. Savi, T.G. Ritto and W.M. Bessa (Editors), ABCM, Buzios, RJ, Brazil, March 10th to 15th, 2019

Comparison of Two Methods of Excitation for Leak Noise Velocity Measurement in Buried Plastic Water Pipes

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Abstract: The detection and location of leaks in underground water distribution pipelines has been one of the major problems faced by water companies. In order to reduce the high rate of water loss, acoustic techniques have been developed to detect and locate leaks. Moreover, the cross-correlation method has produced good results in the estimation of the leak location. This technique uses the estimate of the time delay (cross-correlation) between the signals acquired at two different measurement positions (usually hydrants) together with the speed at which the leak noise propagates (wave-speed) along the pipe. However, there are factors that jeopardize the estimation of such parameters, for example the pipe system dynamics. In recent years, the determination of increasingly accurate values of time delay has been the subject of study by many researchers in the field of leak detection. Although the value of wave-speed is obtained by tabulated values according to the type of material and the length of the pipe, such values do not always correspond to the actual velocity in the pipe section. One way of estimating the velocity of leak noise propagation is to use an external source of excitation to generate vibratory signals in the pipeline section of interest. This article, describes ways to estimate the leak noise velocity along a section of the pipe in a real condition using two different types of sources of excitation. The first one uses an external leak located outside of the section (out-of-bracket excitation) where the sensors are located. The second type of excitation uses an actuator to generate controlled impacts on the pipe system at one of the measurement positions.

Keywords: leak detection, cross-correlation method, wave-speed estimation.

INTRODUCTION

Studies have shown that a significant amount of water provided by water distribution utilities is lost due to problems in the distribution pipes. According to the São Paulo State Basic Sanitation Company (SABESP), it is estimated that around 3.5 billion liters of water per day pass through the distribution pipelines in São Paulo (SP) and the water loss index reaches 30%. Leaks correspond to 19.5%, and fraud and robbery of water directly from the pipe system is equivalent to 10.5% (SABESP, 2018).

It should be noted, that zero loss of water does not exist anywhere. However, there are countries that work hard to reduce the wastage of potable water and have become a reference in the administration of water resources, such as Japan (MAISONNAVE, 2015). Studies on the subject indicate that vibro-acoustic techniques have demonstrated good results in the detection and localization of leaks, and are therefore widely used by water companies compared with non-acoustic techniques. The acoustic techniques employed to locate leaks often use the vibration of the pipe generated by the leak to estimate its location. Among them the cross-correlation method has been widely used (GAO et al., 2004).

In the cross-correlation method, vibration or acoustic sensors are attached to access points that delimit a section of a pipe where there is suspicion of leakage, and through an analysis of the signals measured by the sensors, it is possible to estimate its location (GAO et al., 2004). Figure 1 shows a diagram of a pipeline with the sensors installed at two access points, and the distances from the leak to sensor 01 is d_1 and from the leak to sensor 02 is d_2, while the length of the pipe between the two sensors is d.

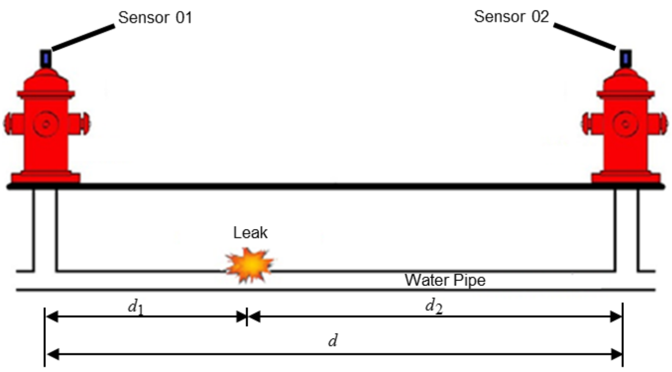

Figure 1 – Schematic of a pipeline system with a leak, together with the vibration sensors connected to the measurement points.

After acquisition of the vibration generated by the leak via the sensors installed either side of the leak, cross-correlation of the signals is performed, in which the similarity between the measured signals is estimated. When there is a maximum in the similarity, then there is a peak in the cross-correlation and this gives an estimate of the time delay T_0 between the two measured signals. The time delay will be zero when $d_1 = d_2$ and non-zero otherwise. The peak occurs at the time difference in the arrival of the leak noise between the sensors. The estimation of the leak position from sensor 01 is given by

$$d_1 = \frac{d - cT_o}{2} \tag{1}$$

where c is the velocity of leak propagation, which is usually obtained through standard tables or by using an equation (GAO et al., 2004).

To obtain a good estimate of the location of a leak, it is necessary to have a reliable time delay estimate, and a good estimate of the leak noise velocity. There are factors, however, that can influence the estimation of the time delay using the cross-correlation method, such as the dynamics of the pipe system (ALMEIDA et al., 2015). The velocity of leak noise propagation varies according to the material and geometric properties of the pipe, and it is also affected by the type of soil where the pipe is buried (BRENNAN et al., 2018; SCUSSEL et al., 2018). The use of an incorrect leak velocity value results in an error in estimating the distance from the access point to the leak, as can be seen from Eq. (1).

Almeida (2013) proposed a method to estimate the velocity of leak noise propagation, which is based on exciting the pipe using an actuator, and then determining the time taken for the wave generated to propagate through the section of the pipe. An alternative way to estimate the wave-speed propagation is to use a leak outside the pipe section of interest. The leak noise will propagate through the pipe to both sensors.

This article is based on a study carried out using two different types of external sources of excitation to estimate the wave-speed in a section of pipe in a test-rig located in São Paulo state. One excitation method uses an out-of-bracket leak to excite the pipe and the second method of excitation uses vibration generated by an actuator. Once the velocity of leak noise propagation is determined, a leak is then created in the system as shown in Fig. 1. The leak location is then estimated by using Eq. (1) with the measured speed of leak noise propagation.

EXPERIMENTAL PROCEDURE

Figure 2 shows a schematic of the experimental set up in which a section of pipe is delimited by two access points (access point 01 and access point 02). The sensors used were accelerometers, and the actuator is shown at access point 01. Also shown is the out-of-bracket leak excitation, and an in-bracket leak. The experiments were conducted on part of a test-rig of a water company used for tests on leak detection equipment and personnel training, a schematic diagram of which is shown in Fig. 3. The pipe-section of the test-rig where the experiments were performed is made of plastic, some parameters of which are shown in table 1. A pump was used to pressurize the system. The out-of-bracket excitation and the leak were generated by opening the valves shown in Fig. 3. The water from the opened valves was returned to a reservoir used to feed the pipe system.

The acquisition system used for data collection was the LMS SCADA system from Siemens. For all the measurements described in this paper, 60 second time histories were captured using a sampling frequency of 8192 Hz.

Table 1 – Properties of the pipe section.

Properties	Values
Young's modulus, *E* (N/m²)	2×10^9
Pipe radius, *a* (mm)	35.8
Pipe-wall thickness, *h* (mm)	3.4
Bulk modulus of the water, B_w (N/m²)	2.25×10^9
Shear modulus of the soil, *G* (N/m²)	1.8×10^8
Free-fluid wavespeed, c_f (m/s)	1500

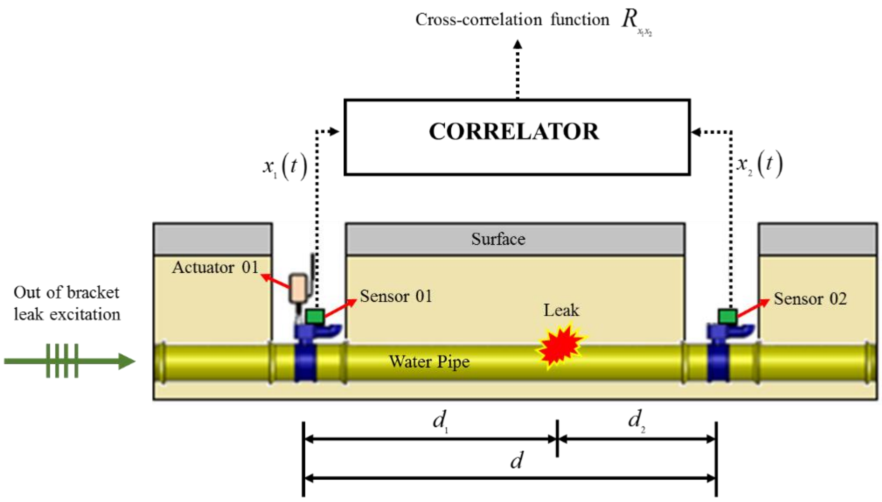

Figure 2 – Schematic of a pipeline for leak detection using acoustic/vibration signals with a leak between the two sensors. Also shown are actuators installed at the access points, together with an out-of-bracket excitation due to a "controlled" leak for leak noise velocity estimation.

Estimation of Leak Noise Velocity

The methodology proposed by Almeida (2013) was used to obtain the velocity of leak noise propagation in a section of the pipe. In the first method, the out-of bracket leak excitation was used as the source of vibration in the pipeline to obtain the wave-speed estimate. The second method used a vibration actuator to excite the pipe. Two different types of actuator were used: a commercial actuator (Integral Shaker – LMS Qsources Excitation Hardware) and a geophone-type sensor configured in reverse so that it generated an impact when the inertial mass collided with the geophone casing.

Geophones are passive analog sensors that convert vibration into a voltage signal. In its interior there is a magnet, suspended by springs and surrounded by a coil to generate an electric signal. Such a sensor is widely used for earthquake measurements. The reason for choosing this sensor as an actuator was that it could be easily found in the market, as well as its price (around a few hundred reais) which is much lower than a commercial actuator (a few thousand reais). For a geophone to operate as an actuator, an excitation signal must be applied at the output terminal which will provide a vibration caused by the displacement of the magnetic mass located therein. A schematic representation of a geophone acting as an actuator is shown in Fig. 4.

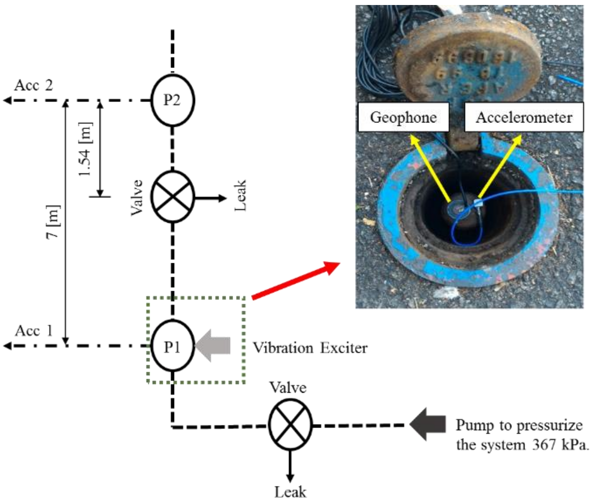

Figure 3 – Schematic of the test-rig used.

Preliminary laboratory tests were undertaken to determine whether the geophone would "rattle" when a voltage was applied. To minimize the power required to generate impacts the geophone (Sensor Nederland SM-24 UB 10 Hz 375 Ω) was excited at its resonance frequency of about 10 Hz. Although a sine wave signal could be used in practice, it was decided to use a repeating chirp signal between 0 to 2000 Hz with a duration of 1 second which caused the geophone to rattle as the excitation signal passed through the 10 Hz frequency. This was done as the chirp signal gave a cross-correlation function that was easier to interpret.

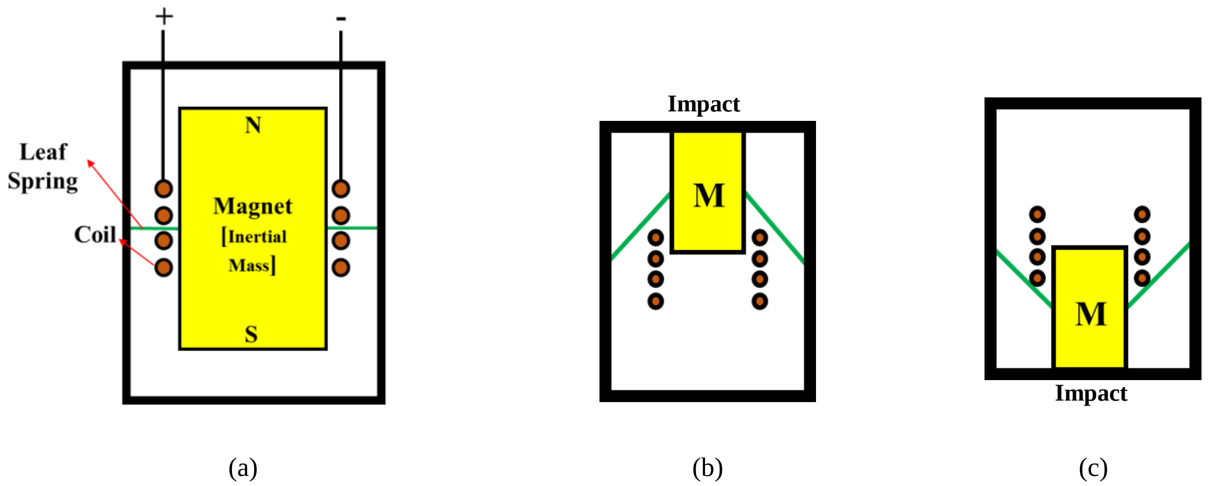

Figure 4 – Use of a geophone as an actuator; (a) Internal Structure of a geophone; (b) Impact at the top; (c) Impact on bottom.

The wave produced by an external source of excitation propagates in the pipe from access point P1 to access point P2, and was measured at both access points using accelerometers (PCB – 333B30). The cross-correlation function of the measured signals was used to calculate an estimate of the time taken τ for the wave to travel through the pipe section. Combining this with knowledge of the distance between the two access points d , the leak noise velocity estimate was calculated using $c = d/\tau$.

Estimation of the Leak Location

First, a leak was generated between the access points as shown in Fig. 3. As with the procedure for estimating the leak noise velocity, the accelerometers at points P1 and P2 captured the vibration of the pipe. The cross-correlation function of the measured signals was then used to calculate the time delay T_0 . Using the estimate of the leak noise velocity, Eq. (1) was then used to determine the leak location.

RESULTS

Estimation of Leak Noise Velocity

The time delay between two signals can be estimated both in the time and frequency domains. In the time domain, the cross-correlation function is used for the calculation of the time delay, since the peak presented in this function corresponds to the time delay between the two signals (Shin and Hammond, 2008). In the frequency domain the time delay between the signals is determined by the phase gradient of the cross spectral density.

To determine the power spectral density between the signals, a *Hanning* window was used with 50% overlap and a 4096 point FFT (Fast Fourier Transform). This results in a frequency resolution of 2 Hz and a time resolution of 0.122 ms. For each measurement shown here, a different frequency bandwidth was used, because the frequency range over which energy of the impact/leak existed, was different in each case.

Figures 5 (ai) and (bi) show the results for out-of-bracket leak excitation. The cross-correlation coefficient after applying a bandpass filter (300 to 600 Hz) to the signals in the time domain can be seen in Fig. 5 (ai). The time delay was calculated to be 12.70 *m*s corresponding to a wave speed of 551 m/s. The time delay calculated from the phase gradient of the cross spectral density was 12.49 *m*s, which corresponds to a wave speed of 560 m/s. This was calculated in the frequency range 300 to 600 Hz, which is shown in Fig.5 (bi).

Figures 5 (aii) and (bii) show the results obtained when using a commercial actuator (Siemens LMS shaker) which was excited with a chirp signal (10 to 2000 Hz in 5 seconds) repeated periodically. The cross-correlation coefficient, after applying a bandpass filter (300 to 650 Hz) to the signals in the time domain, can be seen in Fig. 5 (aii). The time delay was calculated to be 13.92 *m*s, corresponding to a wave speed of 503 m/s. The time delay calculated from the phase gradient of the cross spectral density was 14.34 *m*s, which corresponds to a wave speed of 488 m/s. This was calculated in the frequency range of 300 to 650 Hz, which is shown in Fig. 5 (bii).

Figures 5 (aiii) and (biii) show the results obtained when using the geophone as an exciter. It was driven by a chirp signal (0 to 2000 Hz in 1 second) which was repeated every second. The cross-correlation coefficient, after applying a bandpass filter (300 to 530 Hz) to the signals in the time domain, can be seen in Fig. 5 (aiii). The time delay was calculated to be 13.67 *m*s, corresponding to a wave speed of 512 m/s. The time delay calculated from the phase gradient of the cross spectral density was 14.37 *m*s, which corresponds to a wave speed of 488 m/s. This was calculated in the frequency range of 300 to 530 Hz, which is shown in Fig. 5 (biii).

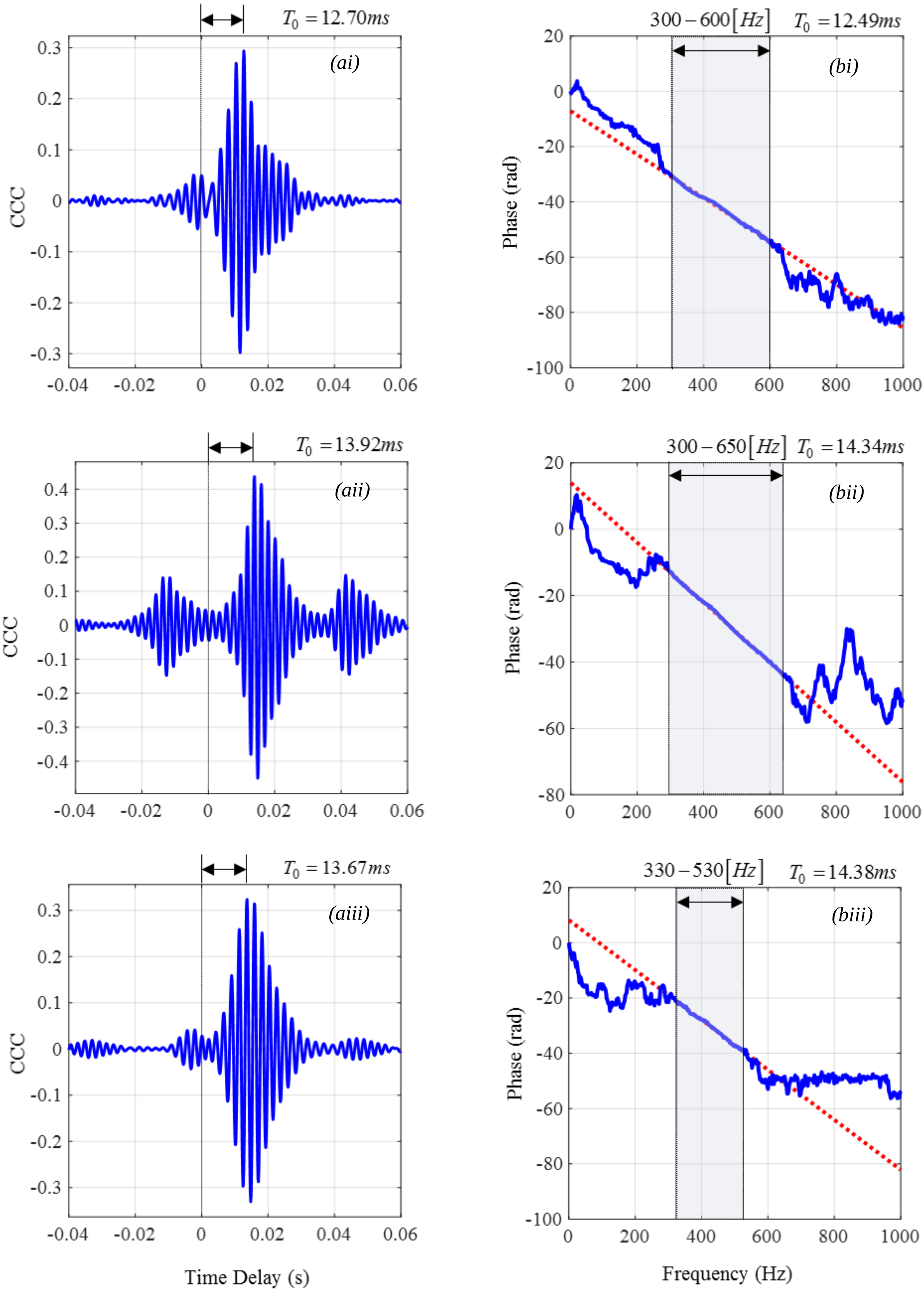

Figure 5 – Graphical results. The labels 'i', 'ii' and 'iii' correspond to the results when using an out-of-bracket leak, a commercial shaker and a geophone as the excitation source, respectively; (a) Cross-Correlation Coefficient; (b) Phase of the Power Spectral Density. ▬ Data measured; ···· Straight line estimation.

The results obtained are summarized in Table 2.

Table 2 – Results of the wave-speed estimation.

Type of Excitation	Source	Time Delay obtained from the CCC [*ms*]	Estimation of Wave-speed 01 [m/s]	Time Delay from the Phase of S_{xy} [*ms*]	Estimation of Wave-speed 02 [m/s]
Out-of-bracket Excitation	Leak	12.70	551	12.29	560
Actuator	LMS Siemens	13.79	503	14.32	488
	Geophone	13.67	512	14.37	487

Estimation of the Leak Location

After estimating the velocity of leak noise propagation, this was used in a further experiment to determine the location of the in-bracket leak shown in Fig. 3. The cross-correlation coefficient, after applying a bandpass filter (320 to 620 Hz) to the signals in the time domain, can be seen in Fig. 6 (a). The time delay was calculated to be -7.69 *m*s. The time delay calculated from the phase gradient of the cross spectral density was -8.34 *m*s. Note that in this analysis, the values obtained for the time delay are negative, which implies that the leak is located nearer to point P2 compared with point P1.

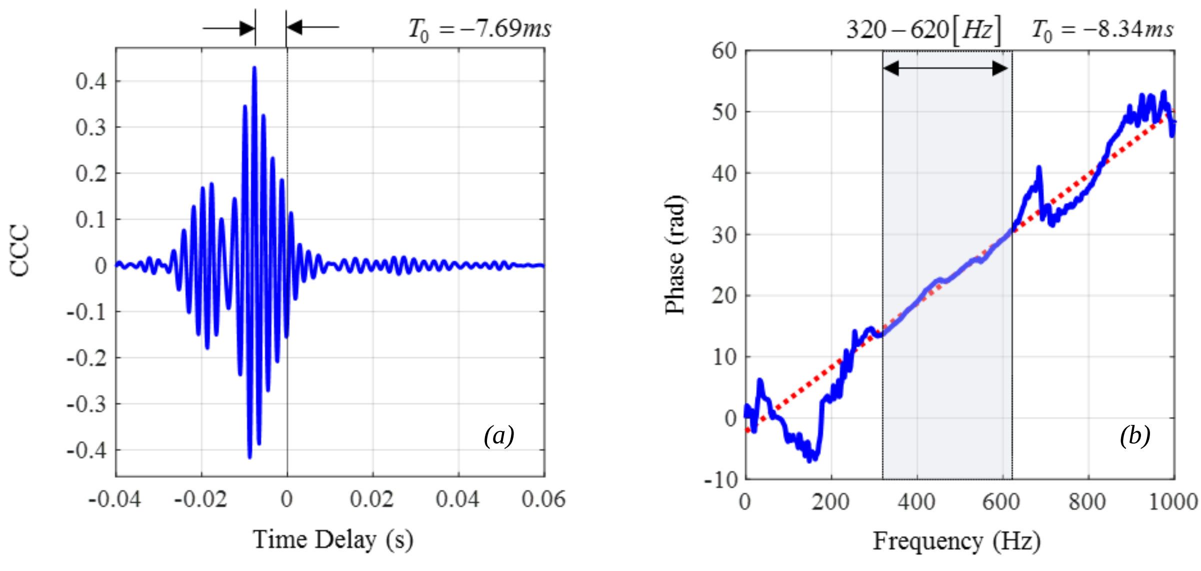

Figure 6 – Graphical results to estimate the location of the leak in the pipe section; (a) Cross-Correlation Coefficient; (b) Phase of the Power Spectral Density. — Data measured; ···· Straight line estimation.

Equation (1) is now used to determine the location of the leak. Using the various measured leak noise velocities, the distance from position P1 can be determined. As there was relative consistency between the velocity estimates from time and frequency domain data, results are shown only for the time delay and velocities measured using the cross-correlation coefficient. The results are shown in Table 3.

Table 3 – Results of the leak location.

Type of Excitation	Source	Wave-Speed [m/s]	Distance d_1 [m]
Out-of-bracket Excitation	Leak	551	5.62
Actuator	LMS Siemens	503	5.44
	Geophone	512	5.47
Theoretical Equation		495	5.40
Real Value			5.46

DISCUSSION

Leak Noise Velocity

Examining Table 2, it is evident that there is reasonable consistency between the wave speed estimated in the time and frequency domains. There are a number of differences in the data from vibration excitation of the pipe system and acoustic excitation by way of an out-of-bracket leak. The main difference is the slower wave speed (larger time delays) estimated when the pipe is excited by the shakers compared to acoustic excitation. This is believed to be due to the dynamics of the pipe system. One main difference between the two excitation methods was that reflections due to structural discontinuities were evident in the data. One of these reflections is particularly evident in the cross-correlation coefficient shown in Fig. 5 (aii), which manifests itself as additional peaks at about -0.15 s and 0.4 s. It is believed that other reflections with much smaller time delays are also present in the data. This belief is based on detailed knowledge of the pipe test rig. Smaller time delays can have an impact on the time delay estimation as discussed by Brennan et al. (2016). In such a case, the estimated time delay is greater than the actual time delay, which is consistent with the measured data. Therefore, it is thought that the wave speed in the test rig is closer to 560 m/s than to 488 m/s. It is also apparent from the plots shown in Fig. 5 that the bandwidth over which a non-dispersive wave propagates from point P1 to point P2 is different in each case. This bandwidth is estimated by examining the phase of the cross spectral density, and is taken to be when the frequency range over which the phase is linear with frequency. The bandwidth is dependent upon many things, one of which is the way in which the excitation mechanism couples into the pipe, which is affected by local dynamics, (ALMEIDA et al., 2015).

The measured results can be compared with a theoretical prediction based on an expression reported by Brennan et al. (2018). It is given by

$$c = c_f \left(\frac{1}{1 + \dfrac{1}{\dfrac{Eh}{2B_w a} + \dfrac{G}{B_w}}} \right)^{1/2} \tag{2}$$

where the parameters are defined in Tab. 1. Using the values given in this table, the velocity of leak noise propagation is estimated to be 495 m/s. It should be noted that the shear modulus of the soil G is an estimated value, which means that there is some uncertainty with the predicted value using Eq. (2).

Leak Location

It can be seen from Tab. 3 that the estimates of the leak location are within 12 cm of the actual position. It should also be noted that the location estimates are better when the wave speed is estimated from shaker rather than acoustic excitation. Close examination of Fig. 6(a) reveals that reflections of the acoustic wave occur in this measurement. Again, this is believed to be due to the detailed geometrical layout of the pipe. It is also believed that the reflections cause an error in the time delay estimate and hence the position of the leak. It is speculated that the two errors effectively compensate for each other, which means that the best estimate of the leak location is when the wave speed estimate from the actuator is used.

CONCLUSIONS

In this article, two approaches to estimate the velocity of leak noise propagation in a buried water pipe have been investigated. The first method uses an out-of-bracket leak to generate a wave which is sensed by accelerometers at two points a known distance apart. The second method uses an actuator attached to one of the measurement points to excite a wave in the pipe. Two types of actuator were used. One was a tapping device, which was a geophone operated in reverse, and a commercial actuator used for comparison. It was observed that the estimated wave speed was higher when structural actuators were used compared to when out-of-bracket leak noise excitation was used. It was thought that this difference was due to reflections occurring in the pipe system according to the type of excitation, and this is currently a topic under investigation. In both cases, however, a similar wave was excited, and this wave is responsible for leak noise propagation in plastic pipes. To verify the wave speed estimation, a leak was generated between the access points and the measured time delay from measured data was combined with the estimated leak noise velocity to determine the (known) leak position.

ACKNOWLEDGMENTS

The authors would also like to acknowledge the financial support from FAPESP, Process Nos. 2013/50412-3, 2016/01733-0.

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