The importance of bandwidth selection for time delay estimation involving leak detection in buried water plastic pipes

Importancia de la selección de banda de frecuencia para estimación del retraso de tiempo en la detección de fugas en tuberias plásticas de agua enterradas

Pedro Ayala[1*], Michael Brennan[1], Fabricio Almeida[2], Fabio Kroll[1], Daniel Obata[1], Amarildo Tabone[1]

[1] *Department of Mechanical Engineering, UNESP, Ilha Solteira, SP 15385-000, Brazil*

[2]*Department of Biosystems Engineering, UNESP, Tupã, SP 17602-496, Brazil.*

Recibido (Recieved): 22/10/2018 Aceptado (Accepted): 01/12/2018

ABSTRACT

In the correlation process to detect and locate leaks in buried water pipes, the use of a filter with a determined bandwidth is important to separate noise that usually masks the leak signals. This paper, through an experimental case from a test rig in Brazil, shows that with an appropriate bandwidth is possible to obtain an accurate estimate of time delay. An inappropriate bandwidth can modify the shape of the cross-correlation function and dislocate the maximum peak. Resulting in the wrong value of time delay, hence error in the localization of the leak.

Keywords: leak detection, plastic water distribution pipes, cross-correlation method, bandwidth selection

RESUMEN

Un problema importante en las compañías de agua es detectar fugas en tuberías subterráneas, ya que el agua es una fuente limitada. Durante muchos años, se han utilizado técnicas acústicas para reducir este problema, mejorando la estimación de posicionamiento de detección de fugas. La correlación de las señales de ruido de fuga es una de estas técnicas. Además, utilizando la diferencia de tiempo de la llegada del ruido de fuga a los sensores y el conocimiento de la velocidad a la que se propaga el ruido en la tubería, se puede estimar la distancia de la fuga desde una de las posiciones del sensor. Este artículo describe la importancia de la selección del ancho de banda en la estimación del retardo de tiempo. Los casos experimentales de un banco de pruebas en Brasil se muestran para sustentar lo indicado.

Palabras clave: ancho de banda, método de correlación, detección, fugas

INTRODUCTION

In 2016, 19.8% of water was wasted due leakage in the water pipe network in São Paulo in comparison with the 16% of UK [1] Acoustic methods for leak detection and location have been applied to metallic pipes successfully and have been able to locate leaks in cast iron water pipes over large distances (upwards of 1 km). However, this technique can be problematic in plastic pipes, due to higher attenuation of the leak noise along the pipes. The vibroacoustic characteristics of a buried plastic water pipes are important in determining the bandwidth where the leak noise is confined [2].

In Brazil, the vibroacoustic characteristics of a pipe system were studied for the first time, obtaining important information that can help leak detection professionals in the measurement procedures and data processing [3]. Leak signals are usually contaminated with background noise, so selecting the bandwidth for analysis is important to give a good shape of the cross-correlation function and greater reliability in the calculation of the time delay. In some circumstances the bandwidth is restricted because of resonances in the system, and ref. [4] describes a procedure in which the shape of the cross-correlation is improved.

* Corresponding author.:
E-mail: payala@dimm.com.pe

This paper describes leak detection using the correlation method. An appropriate and an inappropriate bandwidth are used in an experimental case to show the effects on time delay estimation for leak noise signals.

LEAK DETECTION USING CORRELATION

Figure 1 shows a typical situation in which leak noise is used to detect and locate its position. The leak position from the access point 2 is given by [5],

$$d_2 = \frac{d - cT_0}{2}, \quad (1)$$

where c is the speed of propagation of the leak noise, $d = d_1 + d_2$ is the total distance between the sensors, and $T_0 = (d_1 - d_2)/c$ is the difference in arrival times of the leak noise at the sensor positions (time delay).

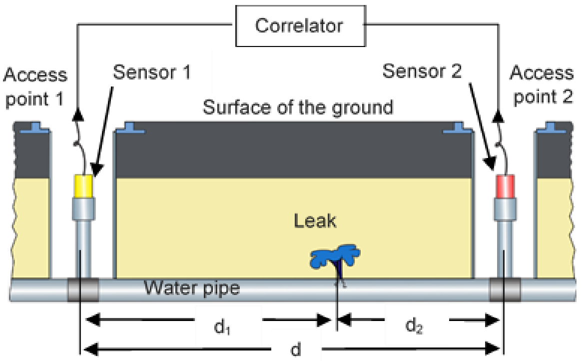


Figure 1. Typical diagram of leak detection and location in buried water pipe using acoustic signals with a leak between two sensors.

The cross-correlation function can be determined from the inverse Fourier transform of $X_1(\omega)X_2^*(\omega)$, where * denotes conjugation, ω is circular frequency, $X_1(\omega)$ and $X_2(\omega)$ are the Fourier transforms of the measured signals $x_1(t)$ and $x_2(t)$, respectively, [5]. The peak in the cross-correlation function gives the time delay estimate T_0 between the measured signals. Sometimes, it is useful to use the cross-correlation coefficient (CCC), which is the cross-correlation function in a normalized form with a scale of -1 to +1, it is given by [6], $\rho(\tau) = R_{12}(\tau)\big/\sqrt{R_{11}(0)R_{22}(0)}$, where τ is the lag of time, and $R_{11}(0)$ and $R_{22}(0)$ are the values of the auto-correlation function at positions 1 and 2, when $\tau = 0$.

BANDWIDTH SELECTION

Leak signals are usually contaminated with coherent noise and it is necessary to filter the signal to increase the signal noise ratio (SNR). The selection of the bandwidth to filter the signals of interest, is based on the coherence between the signals. The coherence function $\gamma_{x_1x_2}^2$ is given by [6].

$$\gamma_{x_1x_2}^2 = \frac{\left|S_{x_1x_2}(\omega)\right|^2}{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}, \quad (2)$$

where $S_{x_1x_2}(\omega)$ is the cross-spectral density function (CSD) between the measured signals, $S_{x_1x_1}(\omega)$ and $S_{x_2x_2}(\omega)$ are the Power Spectral Densities (PSD) of two leak signals $x_1(t)$ and $x_2(t)$ respectively and ω is circular frequency. This function has limits of $0 \le \gamma_{x_1x_2}^2 \le 1$. Ref [7] shown that if the coherence is higher than 10^{-3} the phase of the CSD can be unwrapped successfully. Thus this can be used to estimate an appropriate initial bandwidth for the analysis.

MEASUREMENT PROCEDURE

The test rig was pressurized with 4 bar and the material of the pipe is PVC with outer diameter 71.6 mm and thickness of 3.4 mm. Referring to Fig. 1, d1=1.54 m and d2=5.46 m. Piezoelectric accelerometers PCB Model: 333B30 with a sensitivity of 100 mV/g were connected to the access points and used for vibration measurements. The sensors were mounted by using wax on their bases to guarantee the contact. Figure 2 shows a schematic of the experimental setup. The signals from the sensors were transmitted through cables of approximately 20 m length to the data acquisition system. Leak signals were collected simultaneously for 2 minutes at a sampling rate of 8192 Hz. Leak noise data was processed and analysed in the frequency domain (PSD, CSD and coherence), and in the time domain by using the CCC. The bandwidth was set so that for all frequencies between the upper and lower frequency the coherence is > 10^{-3}. The time delay estimate T_0 is obtained from the peak of the CCC and with the known distances d_2 and d the speed of propagation of the leak noise can be calculated using eq. 1.

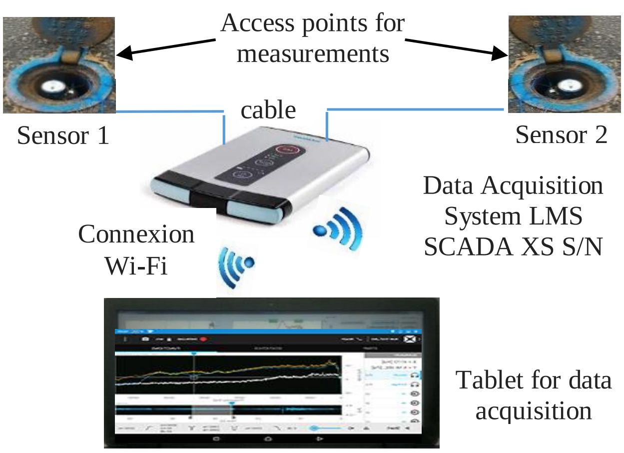


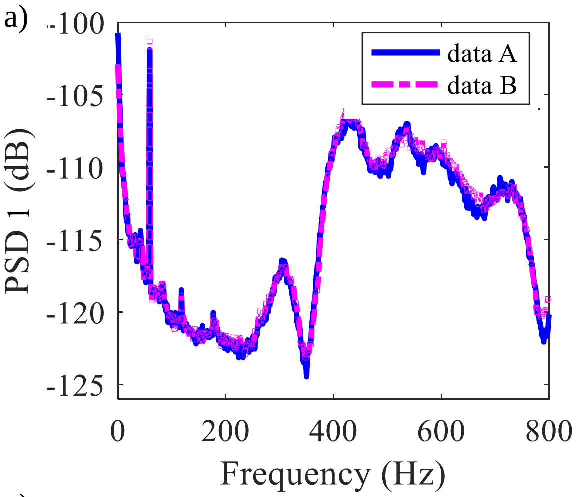
Figure 2. Schematic of the experiment to be carried out in the test rig.

RESULTS AND OBSERVATIONS

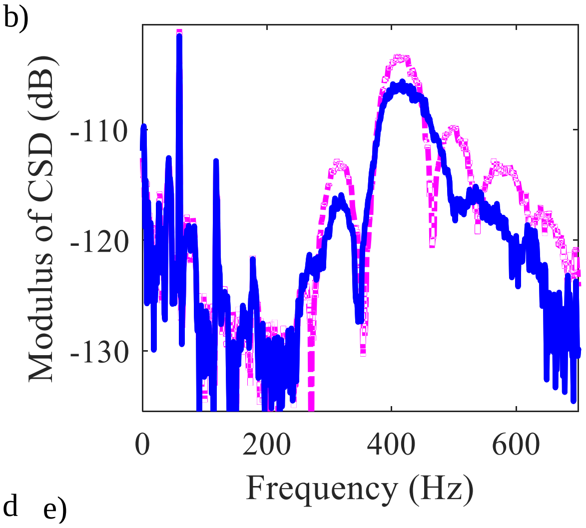
Figure 3 shows two sets of data from measurements of leak noise signals with accelerometers placed at access points 1 and 2 with a simulated leak in-bracket at a known position. Two sets of measurements were made and analysed. In figure 3a) and 3b) the PSD for two different measurements are shown, here named as data A and B, for position 1 and 2, respectively. It is observed from figure 3a) and 3b) that the level of vibration at access point 1 is higher than at access point 2. This is because of the leak is closer to point 1. Moreover, in figure 3b) it is observed that data B has an increment of the level of vibration between 250 and 700Hz in comparison with data A, possibly due to some wave reflections in the pipe or system dynamics. In figure 3c) the CSD is shown for data A and B. It can be observed that data B has more ripples than data A (which is possibly due to reflections in the system). This behaviour is also related to the behaviour in the phase of the CSD shown in figure 3d), for example at a frequency of 354 Hz. In figure 3e) the coherence is shown for data sets A and B, where ripples are also present, which also due to reflections in the system. The bandwidth is 242-648 Hz for data A and is 272-757 Hz for data B. The time delay obtained is 7.9 ms and the wave speed calculated is 497 m/s for both cases. Figure 4 shows a comparison between the same data but using a coherence of 10^{-2}, this restricts the bandwidth to 352-602 Hz for data A and 359-464 Hz for data B. This results in a time delay T_0=7.9 ms for data A and a time delay T_0=10.4 ms for data B. This difference is because for the data B, the shape of the cross-correlation function was modified, shifting the maximum peak. In the field a wrong value of time delay would result in an incorrect location of leak.

The wave speed calculated is 497 m/s for data A and 377 m/s for data B. Compared with the theoretical wave speed of 540 m/s given in ref [8] the analysis of data B gives a value far from this.

a)



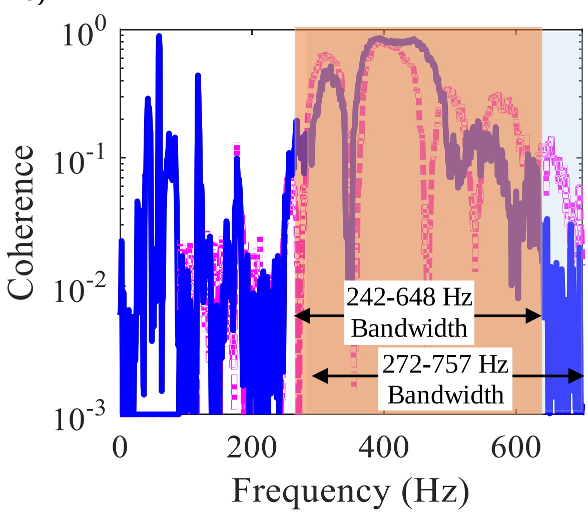
b)



c)

d

e)



f)

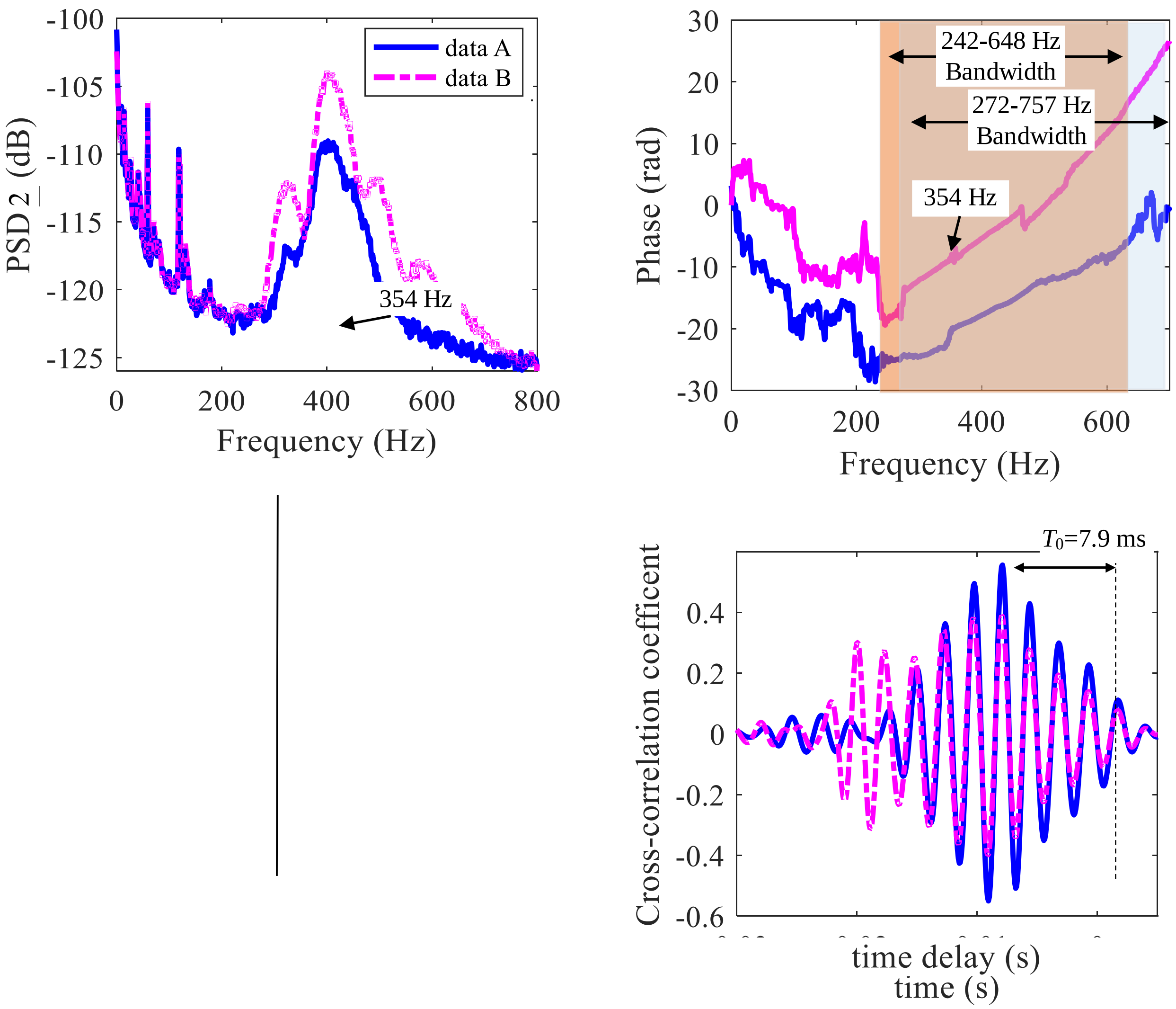
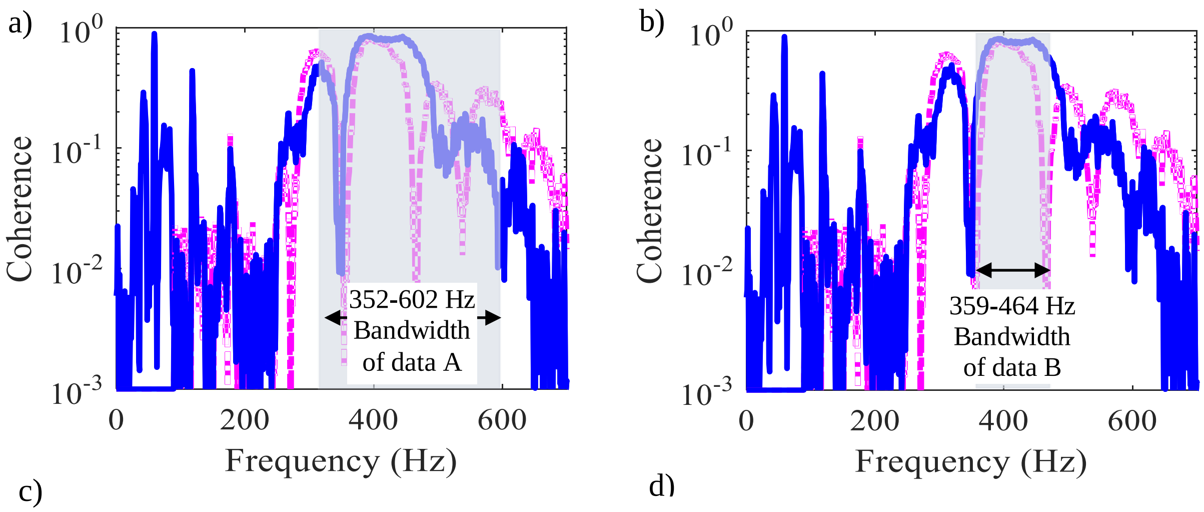


Figure 3 – Measured of leak noise signals using accelerometers placed at points P1 and P2 with a simulated in-bracket leak for a known position. Data A (in solid blue line) and data B (in dashed pink line) are from measurement at the same position but at a different time, using an appropriate selection of bandwidth, (limit of coherence 10^{-3}). (a) and (b) Power Spectral Density (PSD) for the access point 1 and 2. (c) Modulus of cross-spectral density (CSD) for signals recorder from the access point 1 and 2; (d) Coherence; (e) Phase of the cross-spectral density (CSD) and (f) Cross-correlation Coefficient (CCC) evaluated over the bandwidth selected. (Values in dB ref. V2)



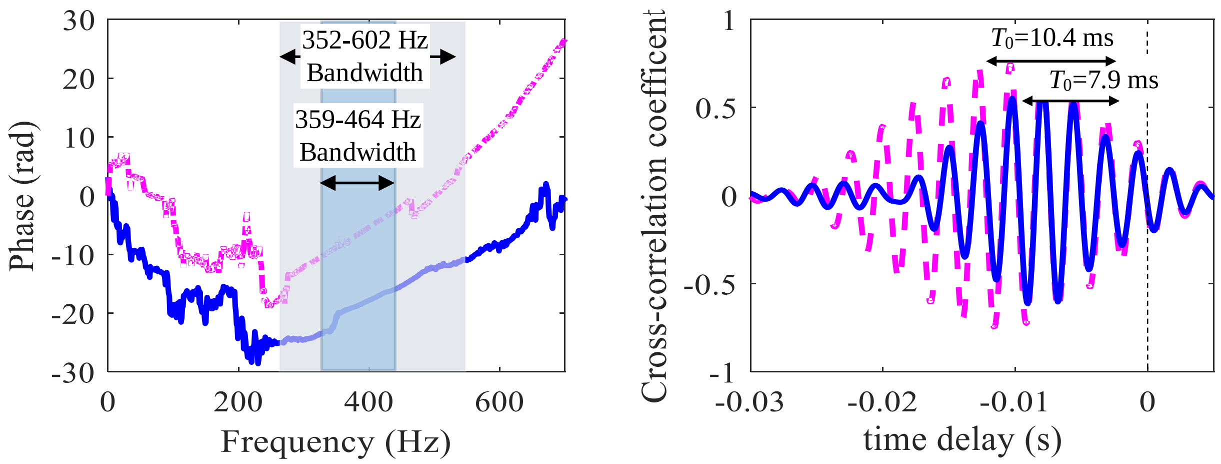


Figure 4 – Comparison between the two data sets shown in Fig. 3, data A and data B are from measurements at the same position but a different time. Data A (in solid blue line) and Data B (in dashed pink line) are from measurement at the same position but at a different time, using an inappropriate selection of bandwidth (limit of coherence 10^{-2}) (a) and (b) Coherence for data A and data B, (c) phase of CSD and (d) Cross-correlation Coefficient. (Values in dB ref. V2).

CONCLUSIONS

This paper has discussed some issues in the correlation of leak noise to determine the location of a leak. Using experimental data from a test rig located in Brazil, the importance of selecting the correct bandwidth of leak noise data has been highlighted.
Two data sets were studied from the same location, with different bandwidths being used for time delay estimation. It was shown that this resulted in two time delay estimates, which corresponded to two different wave velocities in the pipe, one of which was very different from the value expected.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from FAPESP, Process Nos. 2013/50412-3 and 2015/26342-0.

REFERENCES

[1] News SABESP 2016, International Seminar on Loss Control. Available in: http://site.sabesp.com.br/site/imprensa/noticias-detalhe.aspx?secaoId=65&id=7045 16 October 2017.

[2] Hunaidi O, Chu W T 1999 Acoustical characteristics of leak signals in plastic water distribution pipes, *Journal of Applied Acoustics* **58**, 235–254.

[3] Ayala P C., Brennan M J, Almeida F C L, Kroll F, Obata O, Tabone A 2017 Vibroacoustic characteristics of leak noise in buried water pipes in Brazil, I Jornada Peruana Internacional de Investigación en Ingenieria.

[4] Gao Y, Brennan M J, Yuyou L, Almeida F C Ll, Joseph P F 2017 Improving the shape of the cross-correlation function for leak detection in a plastic water distribution pipe using acoustic signals s, Journal of Applied Acoustics. **127**, 24-33.

[5] Gao Y, Brennan M J Joseph P F, Mugleton J M, Hunaidi H A. 2004 Model of the correlation function of leak noise in buried plastic pipes, Journal of Sound and Vibration. **227**, 133-148.

[6] Kihong S, Hammond J K 2008 fundamentals of signal processing. New York: John Wiley & Sons p 403.

[7] Muggleton J M, Brennan M J, Gao Y, 2011 Determining the location of buried plastic water pipes from measurements of ground surface vibration, Journal of Applied Geophysics. **75**(1), 54-61.

[8] Brennan M J, Karimi M, Muggleton J M, Almeida F C L, Kroll de Lima F, Ayala P C, Obata D, Paschoalini A T, Kessissoglou N. 2018 On the effects of soil properties on leak noise propagation in plastic water distribution pipes, *Journal of Sound and Vibration.* **427**, 120-133.