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INVESTIGATION OF THE RESPONSE OF PLASTIC WATER PIPES TO LEAKS USING DIFFERENT TRANSDUCERS

Matheus M. Rocha[1], Bruno C. Campos[1], Rodrigo A. N. de Oliveira[1], Fabricio C. L. de Almeida[1]

[1] *UNESP-FEB, Department of Mechanical Engineering, Bauru, São Paulo 17033-360, Brazil*
matheus.martinez@unesp.br, bruno.cavenagui@unesp.br, nunes.oliveira@unesp.br, fabricio.lobato@unesp.br

Abstract. Leak detection is a major concern for large urban centres and water utilities. Various techniques are applied to detect and locate leaks at an early stage, with vibro-acoustic methods being among the most widely used. These techniques rely on the pipe's response to a leak to determine its position. One of the most effective approaches, leak noise correlation, utilizes two transducers to measure pipe vibrations at different positions, estimating the time delay between signals and using the leak velocity to calculate the leak location. However, leak velocity depends on the mechanisms through which leak noise propagates along the pipe. Recent studies have identified two possible mechanisms responsible for leak energy propagation in plastic pipes. However, these findings were based on different test rigs and boundary conditions. This paper aims to investigate the mechanisms governing leak energy propagation in plastic water pipes used in the interior of São Paulo state under consistent boundary conditions, including leak excitation and the type of flooring beneath the pipe. Multiple transducers will be used to measure the pipe's response: hydrophones, which measure sound pressure in water (invasive measurement); geophones and accelerometers, which are placed on the pipe wall (non-invasive); and laser vibrometers, which are non-contact sensors for measuring pipe wall vibrations. Classic signal processing techniques will be applied to analyse the pipe response and confirm the presence of these mechanisms, including Coherence, the phase of the Cross-Power Spectral Density (CPSD), and the Cross-Correlation Coefficient (CCC). Finally, actual leak velocity values will be compared to those estimated using analytical equations from the literature, based on wave models associated with leak-induced excitation. This comparison aims to support the hypothesis that multiple propagation mechanisms contribute to leak noise transmission.

Keywords: Leak detection, pipe response, leak noise, propagation, transducers.

1 Introduction

Climate change and ecosystem preservation have become pressing concerns for future generations [1]. Among these issues, the responsible use of potable water stands out as one of the most critical challenges faced by contemporary society. Water distribution infrastructure plays a vital role in delivering piped water to urban and peripheral areas. However, deficiencies in such installations and the emergence of small defects, particularly leaks, undermine the system's efficiency and contribute to broader environmental degradation [1]. One promising approach involves capturing vibration waves due to a leak along the pipe using transducers [2]. This technique offers several advantages, particularly the ability to detect leaks without requiring excavation. It relies on analysing the time delay between signals captured by two sensors placed at different locations along the pipe. By combining this delay with knowledge of wave propagation speed, determined by the pipe material, fluid properties, and installation conditions, it becomes possible to estimate the leak's location [3]. However, the accuracy of this method depends heavily on understanding the propagation characteristics of leak-induced acoustic signals. These characteristics are influenced by the physical mechanisms and boundary conditions governing energy transmission along the pipe. Recent studies, such as Quartaroli [4], provide experimental evidence for the existence of multiple propagation modes in plastic pipes. These modes can vary according to material properties and installation conditions, highlighting the need for further investigation using different sensors and pipe configurations.

In this context, the present study aims to investigate energy propagation mechanisms from leaks in plastic pipes, focusing on conditions representative of typical installations in the interior regions of São Paulo State, Brazil. To this end, a variety of sensors were employed to capture the vibration response of the system and compare it with models reported in the literature. The sensors used in this research include accelerometers, geophones, hydrophones,

and laser vibrometers, each offering distinct measurement capabilities. For example, laser vibrometers allow non-contact vibration acquisition, which is particularly advantageous in scenarios where physical access to the pipe is limited. On the other hand, hydrophones measure pressure fluctuations directly within the fluid, making them more intrusive but valuable for capturing fluid-borne wave components. Using the collected data, classical signal processing tools were applied, such as Power Spectral Density (PSD), Frequency Response Function (FRF) magnitude and phase, coherence, and Cross-Correlation Function (CCF). These analyses were instrumental in identifying propagation patterns associated with different signal types and transducers characteristics.

2 Test rig and instrumentation description

The experimental test rig schematic and photos are highlighted in figure 1. This is the same test described by [4]. The test rig is provided by the water company SABESP and connected to the municipal water supply. The facility consists of an unburied plastic pipe (PVC) and includes two control valves and one drain valve for removing air from the line. The process for taking measurements involves opening the control valves, using the drain valve to remove any bubbles that could affect the measurement, and opening the leak before recording vibrations. The pipe has an external diameter of 60 mm, and a wall thickness of 3.3 mm. Data collection was performed at different positions, 3 meters apart, on a straight section of pipe, approximately 45 meters long. The signals were captured at a sampling rate of 12kHz, synchronized, and the transducers used are depicted in table 1.

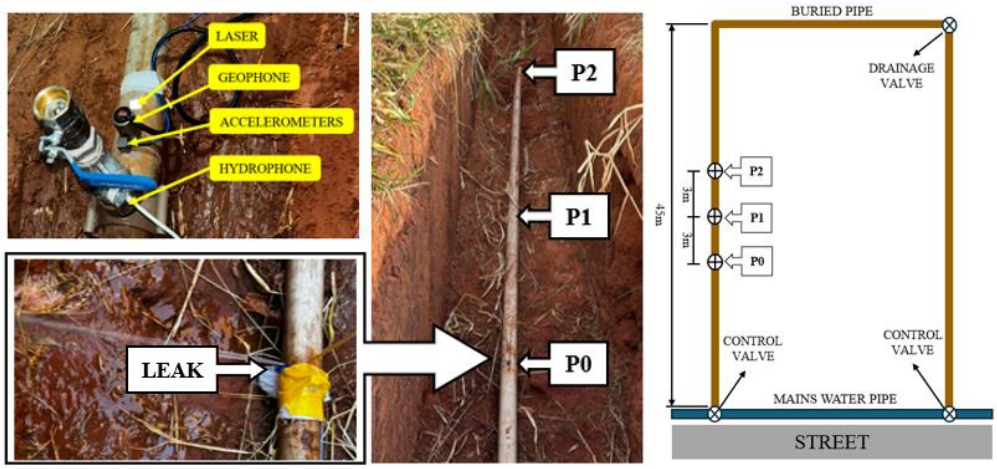


Figure 1. Test rig schematic (right), sensors positioned on the tube and test field assembled (center), and sensors on the tube with the leak location indicated (left).

Table 1. Sensors and parameters

Sensors	Manufacturer	Type	Sensitivity
Accelerometer (ACC)	PCB	333B40	500 mV/g
Geophone (GEO)	SM24	-	24 V/ms^{-1}
Laser (LAS)	Polytec	Vibro Go 200	400 mV/mm/s
Hydrophone (HYD)	Bruel and Kjaer	8103	30 uV/Pa

3 Results

Classic signal processing tools are used here to characterize the pipe response due to a leak. The coherence $C_{P_0P_i}(f) = \left|S_{P_0P_i}(f)\right|^2 \Big/ \left(S_{P_0P_0}(f)S_{P_iP_i}(f)\right)$, phase of the CPSD $\arg(S_{P_0P_i})$ and the Cross Correlation Coefficient $\mathrm{CCC} = R_{P_0P_i}(t) \Big/ \left(R_{P_0P_0}(0)R_{P_iP_i}(0)\right)$. It is important to note that P_0 is the pipe response at the leak position and P_i any measurement position where the pipe response can be measured, where i =1,2, for 3 metres (P_1) and for 6 metres (P_2) measurement positions, respectively. Furthermore, $S_{P_0P_i}(f)$ is the CPSD, $S_{P_0P_0}(f)$ the Power Spectral Density (PSD) at the leak, $S_{P_iP_i}(f)$ the PSD at any measurement position, $\arg(S_{P_0P_i})$ is the phase of the CPSD,

$R_{P_0P_i}(t)$ is the cross-correlation as a function of time lag t , $R_{P_0P_0}(0)$ the auto correlation of the signal collected at the leak when $t = 0$, and $R_{P_0P_0}(0)$ the auto correlation of the signal collected at any other measurement position when $t = 0$. The coherence is performed to visualized the linear relation in the frequency domain between two measurement position, i.e. 0-3 metres (P_0P_1) or 0-6 metres (P_0P_2). The phase of the PSD is to visualize the time delay between two measurement positions, so that, a straight line is an indication of pure delay, i.e. leak noise mechanism of propagation. The CCC is used to estimate the time delay in the time domain given by a peak. Figure 2 shows the results obtained via processing the measured data described in the previous section. The label "a" and "b" stand for 0-3 metres and 0-6 metres, respectively. The laves "i", "ii", "iii" and "iv" stand for coherence, phase, cross-correlation performed below 2kHz and cross-correlation calculated above 2kHz, respectively.

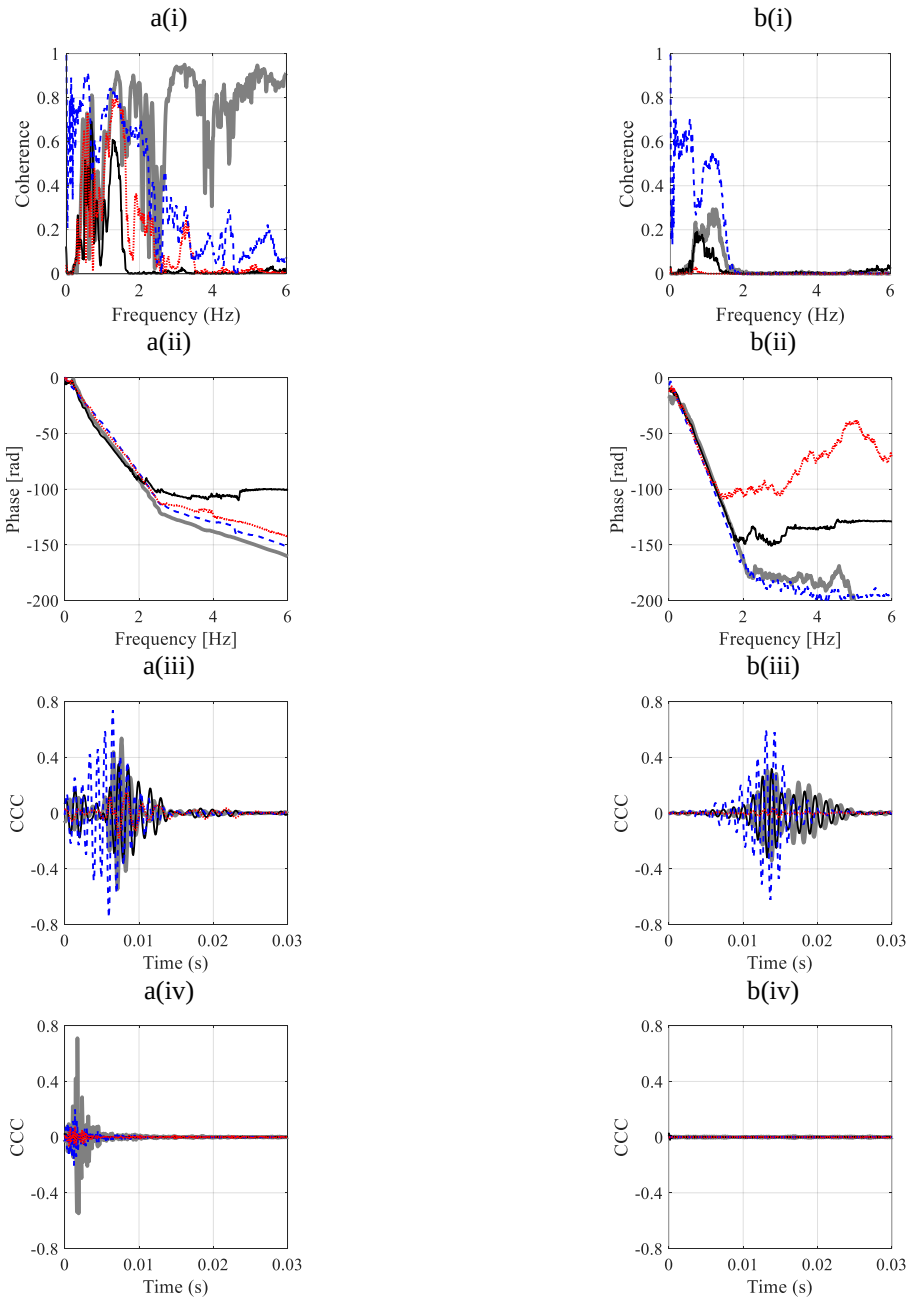


Figure 2. Results of the measurements conducted at (a) 0-3 metres and (b) 0-6 metres. The labels "i", "ii", "iii" and "iv" stand for the Coherence, phase, CCC performed using filtered signals below 2kHz and CCC performed using filtered signals above 2kHz, respectively

It is possible to observe in the coherence that the pipe filters out high frequency content for the pipe response measured away from the leak. This is also observed as a coherence drop in the low frequency content, which is located mostly below 2kHz. Moreover, the phase presents two different slopes, being one below at about 2kHz and the other one above such frequency. In the "low frequency content", the phase presents a higher gradient than the one above. This is related to the s=1 mechanism (below 2kHz), which that the s =2 mechanism is related to the steeper gradient (above 2 kHz) as already investigated by Quartaroli et al., 2023 [7]. It is possible to notice that the steeper slope is well-spotted between 0-3 metres, but this is not the case for 0-6metres reinforcing that the amplitude of the s=2 mechanism id smaller than for the s=1 mechanism and further filtered away due to the pipe dynamics. The signals are filtered within these two frequency regions and the cross-correlation performed to estimate the time delay and the speed of each mechanism. The theoretical wave speed for the s=1 and s=2 mechanisms are $c_1 = c_f\left(1 + 2Ba/Eh\right)^{-1/2}$ and $c_2 = \sqrt{E/r(1 - n^2)}$, respectively. It is important to note that c_f, B, a, E, h r and u, are the speed of sound in a free water, the bulk modulus of the water, mean radius of the pipe, Young's modulus of the pipe material, pipe thickness, density of the pipe material and Poisson of the pipe material, respectively. They can be found in [7] for the test rig used. The measured wavespeed for the s=1 and s=2 waves are 420 m/s and 1800 m/s, respectively. The theoretical for the same waves are 403 m/s and 1.627 m/s, respectively.

4 Conclusions

This paper investigated the pipe response due to a leak using 4 different transducers: 2 non-invasive contact sensors (accelerometers and geophones), one invasive sensor (hydrophone) and on non-contact sensor (laser). These transducers were able to measure the pipe response due to a leak at the leak position and two other positions away 3 metres and 6 metres, respectively. The hydrophone presented the lower frequency content among the tested transducer and the accelerometer presented the best higher frequency content characteristic. The two leak noise mechanisms were captured for the measurement position closer to the leak (3 metres). The laser was not effective for the 6 metres, but it seems a problem with the preparation of the measurement position.

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