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An Experimental Study into the Effects on Leak Noise Propagation of using Extension Rods at Measurement Points on a Pipe

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Abstract: The cross-correlation technique is generally used in leak noise correlators to pinpoint the position of a leak in a pipe. The procedure involves the placement of two sensors at known positions and estimating the difference in time that it takes for the leak noise to reach the two sensors. However, sensors are placed at access points, which are generally hydrants, and these are not always close to a leak position. This can cause problems in plastic pipes because leak noise attenuates rapidly with distance. A solution to the problem could be to connect extension rods to the pipe at regular intervals, that terminate on the ground surface. This motivated the study described in this paper, which involves an experimental investigation into leak noise propagation along a water pipe and a connected extension rod. It is shown that for a one-meter-long metallic rod, the water pipe response to a leak excitation is reduced in the vicinity of the rod, but the propagation delay estimated using measurements on the pipe is not affected. However, this is not the case for measurements made at the top of the extension rod. For the case studied, there is an additional propagation delay (around 6%). The relative propagation delay between the extension rod and the water pipe can be reduced if the distance between the measurement positions is increased, assuming that the buried depth of the pipe is fixed. Of course, this is limited by the rate at which the leak noise is attenuated as it propagates along the pipe.

Keywords: leak detection, water piper, one-dimensional waveguides

INTRODUCTION

Water pipes are susceptible to leakage, which can lead to infrastructure and environmental damage. Moreover, water companies are under pressure to reduce water wastage as this source is becoming scarce with the increase of population in large centres together with the high distances that potable water needs to be transported. In Brazil the average water loss is about 38%, however, it can reach 70% in some states, such as Maranhão (O Globo, 2018). In developed countries, such as Japan, where the water loss is about 2% (O Globo, 2018), acoustic techniques are extensively used, with the cross-correlation technique being one of the most used (Fuchs and Hiehle, 1991). Another well-known technique is to measure the ground vibration using a geophone (Puust et al., 2010) "to listen" for the leak noise that propagates through the soil above the pipe. Listening sticks/rods are also used to aid leak search and detection by placing a metal rod at measurement positions, so that the pipe response can be "listened to" even at difficult access points, such as valves in buried pipes (Hu et. al, 2021). This paper intends to demonstrate how one-dimensional waveguides, such as metallic rods, can be used as an alternative to the current access points to collect the vibration response of the water pipe. An experimental study is carried out initially to investigate the feasibility of this method. A theoretical investigation using the model developed by Gao et. al (2004), which represents the in-air pipe response, will be presented in the full paper to investigate the coupling with the one-dimensional waveguide.

LEAK NOISE PROPAGATION IN PLASTIC PIPES

Leak noise propagates along a water pipe in a predominantly fluid-borne wave called the s=1 wave. This wave type is well-coupled with the pipe wall, so that there is a direct relationship between the sound pressure generated by the leak in the fluid to the radial vibration of the pipe wall. The pipe response to the leak is then measured at two known positions and used to detect the leak location, This is done by estimating the difference in the time it takes for the leak noise to reach the two sensors (time delay T_o) and combining this with knowledge of the speed c at which the wave s=1 propagates along the pipe. Gao et. al (2004) modelled the in-air pipe response to the leak excitation considering the pipe geometry and material properties. The Frequency Response Function (FRF) between the acoustic pressure at the leak position and the pipe wall displacement at the measurement position is given by

$$H(\omega,l)=\frac{a^2}{Eh}e^{-j\omega l/c}e^{\omega\beta l}\,, \tag{1}$$

where $c=c_f\left(1+\left(2Ba/Eh\right)\right)^{-1/2}$, $\beta=1/c_f\left[\eta Ba/Eh/\left(1+2Ba/Eh\right)^{1/2}\right]$ is the loss within the pipe wall, ω is the frequency in rad/s, $j=\sqrt{-1}$, l is the distance from the leak to the measurement position, $c_f\approx 1500\,\mathrm{ms}^{-1}$, B, a, E and

h are the free-fluid speed of sound, Bulk modulus of the water, nominal radius of the pipe, Young's modulus of the pipe and wall thickness of the pipe, respectively, and η is the loss factor. It is possible to observe from Eq. (1) that the attenuation of the wave in the pipe is a function of β, ω and l. Figure 1 shows a schematic of the *s*=1 wave decaying away from the leak position along the pipe together with a one-dimensional waveguide connected to the water pipe. This decay is very large for plastic pipes, especially for pipes with large diameters.

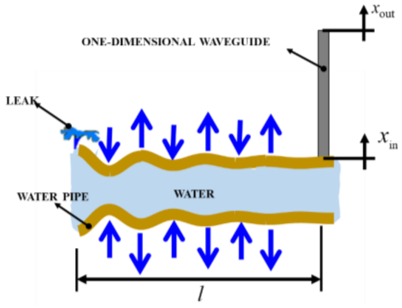

Figure 1 – Illustration of the *s*=1 wave (predominantly fluid borne) which is well-coupled with the pipe wall together and one waveguide connected to the plastic water pipe (schematic not to scale)

The pipe response at the position where the one-dimensional waveguide is placed gives the input to such a waveguide. Hence the total system response may be given by

$$H_{sys}(\omega) = H(\omega, l) H_{wg}(\omega, x)\,, \tag{2}$$

where $H_{wg}(\omega, x) = e^{-j\omega x / \sqrt{E_{wg}/\rho_{wg}}}$ is the transmissibility of the waveguide coupled to the pipe with length x and, E_{wg} and ρ_{wg} are the Young's modulus and density of the waveguide material, respectively. This model takes into account that the rod is well coupled to the pipe and its mass has little effect on the pipe response, so it can be neglected. The waveguide used in this work is a one-meter-long metallic standpipe. This will be measured in the lab and added to the model in the full paper to investigate how this waveguide affects the system response when using cross-correlation techniques.

DESCRIPTION OF THE TEST RIG AND VIBRATION CHARACTERIZATION

The test rig used to conduct experiments presented in this work is located in the city of Tupã in Brazil and it was provided by the water company SABESP. It is composed of a non-buried (in-air) plastic PVC pipe with a length of 45 meters connected to the water mains network where the system can be filled and pressurized via opening a control valve as depicted in Figure 2. Moreover, there is also a drainage valve which is used to remove any air bubbles present in the system that could affect the coupling between the pipe wall and the water (fluid). The plastic pipe has an outside diameter of 60 mm and a wall thickness of 3.3 mm.

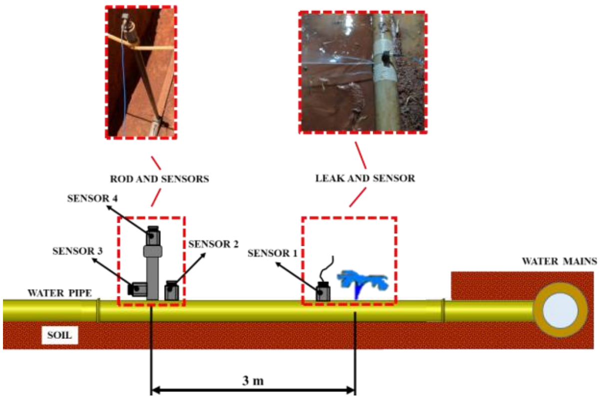

Figure 2 – Schematic of the test rig used to conduct the experiments (not to scale)

The leak is simulated by a hole in the pipe wall in a way that a sensor next to it (sensor 1) can be placed to measure the response. A one-meter-long metallic rod, which is a one-dimensional waveguide, located 3 meters away from the leak is connected to the plastic pipe using beeswax and a sensor next to it (sensor 2) is placed to measure the pipe response adjacent to the standpipe. Moreover, two other sensors are placed on the extension rod, one located next to the pipe (sensor 3) and the other one at the top (sensor 4). The instrumentation used is given in table 1. Signals were collected for one minute with a sampling frequency of 12 kHz. The measurements on the pipe were taken in the radial direction of the pipe and the measurements on the standpipe in the axial direction of the rod.

Table 1 – Instrumentation used to collect the experimental data

Description	Manufacturer	Model
Sensor 1 - High sensitivity accelerometer (500 mV/g)	B&K	4506-B-003
Sensor 2, 3 and 4 - High sensitivity accelerometer (500 mV/g)	PCB	356A17
Data acquisition system	SIEMENS	SCADAS XS

MEASURING THE TIME DELAY

The power spectral density (PSD) at the leak position and at the other measurement positions were evaluated, as well as the coherence and, the modulus and phase of the cross-power spectral density (CPSD) between these measurement positions. A Hanning window and an overlap of 50% were applied, resulting in a frequency resolution of 10 Hz. Figures 2 (i), (ii), (iii) and (iv) show the respective PSDs (blue solid line and dotted red line stand for the leak position and the measurement positions, respectively), coherence, modulus of the CPSD and phase of the CPSD for (a) the measurement at the leak position (sensor 1) and on the pipe (sensor 2) without any standpipe placed on the water pipe, (b) the measurement at the leak position (sensor 1) and on the pipe (sensor 2) with the standpipe placed next to sensor 2, and (c) the measurement at the leak position (sensor1) and on the top of the rod (sensor 4).

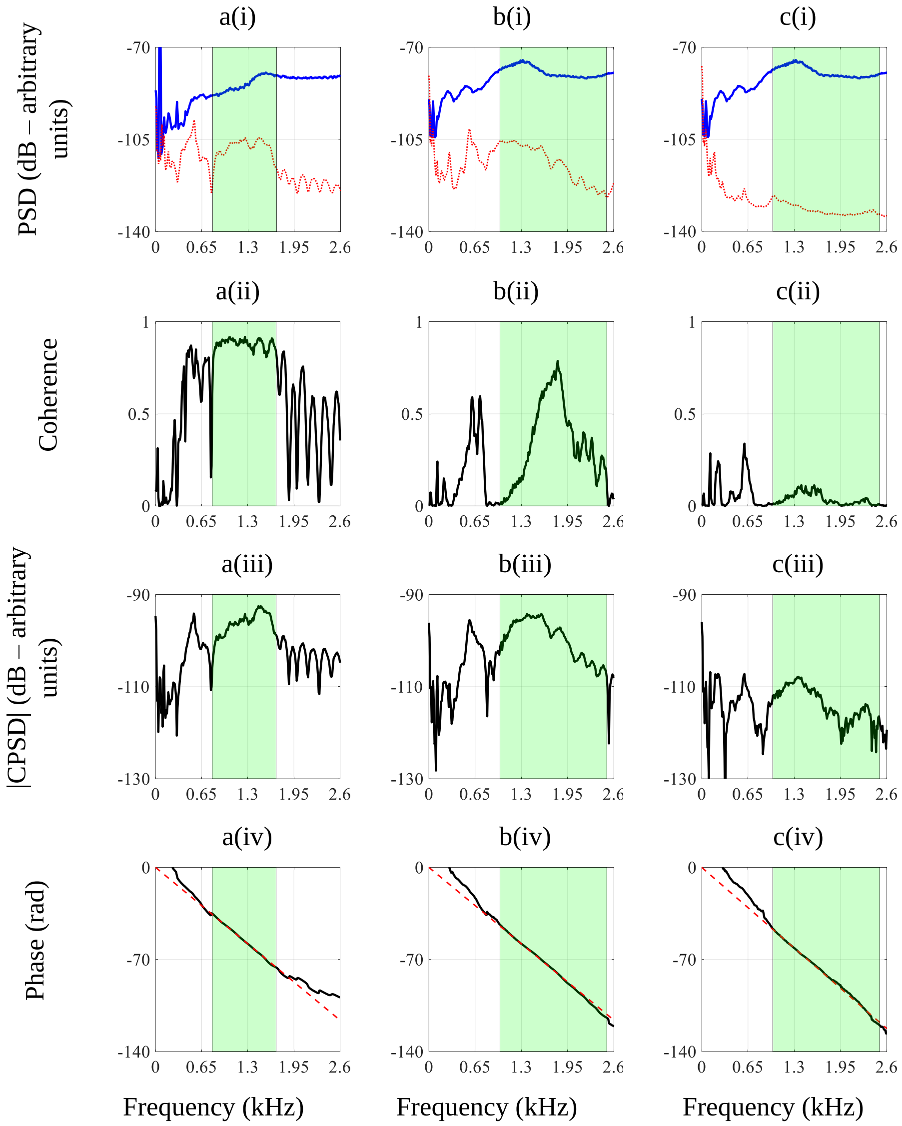

Figure 3 – The "i" PSD, "ii" coherence, "iii" |CPSD| and "vi" the phase of the CPSD between (a) sensor 1 and sensor 2 with no standpipe, (b) sensor 1 and sensor 2 with standpipe and (c) sensor 1 and sensor 4. Blue solid line: PSD of the leak signal; Red dotted line: PSD of the signal acquired at the measurement position

The shaded area is the frequency range over which the phase presents a good linear behaviour (straight line). This is defined as the filtering bandwidth over which the correlation is performed. Besides, the red dashed line in the phase is given by the ideal case $-\omega T_o$ where T_o is given by the peak of the cross-correlation function shown in Figure 3. It can be observed that the leak has a similar spectrum for the three cases depicted. However, this is not the case for the PSD at the measurement positions, especially the one on the top of the standpipe where the PSD shows that there is a large decrease in energy. Although there is this reduction in vibration, the coherence shows that there are correlated signals between the two measured positions. Furthermore, in both coherence and modulus of the CPSD the presence of peaks and troughs at frequencies above 1.95 kHz can be seen, especially for the case with no standpipe placed on the water pipe. This is due to the dynamics of the system. This can also be observed in the phase, when for the case of the water pipe only (no standpipe) the phase starts to change its gradient above approximately 1.95 kHz.

The effects on the time delay is better observed when the cross-correlation is calculated, and this is shown in Figure 3 as the cross-correlation coefficient (CCC). It can be observed that there is a reduction in the peak when the standpipe is placed on the water pipe, but there is no change in the time delay of 7.1ms. There is a further amplitude reduction when the measurement is conducted at the top of the standpipe and there is a small change in the time delay to 7.5ms. This gives an error of about 6% when compared to the estimation based on the measurements on the pipe. This suggests that it is possible to measure time delay using this one-dimensional waveguide, but perhaps not very far from the leak as the amplitude is drastically reduced. Moreover, this additional time delay becomes less important as the length of the water pipe gets longer compared to the rod extension.

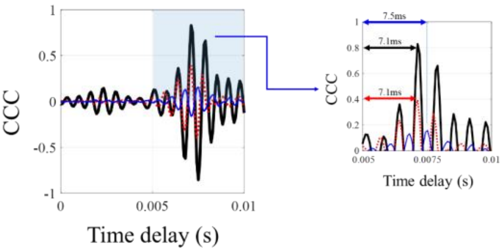

Figure 3 – The Cross-Correlation Coefficient (CCC) calculated for the cases depicted in Fig.(2). Thick Solid Black line: response leak-water pipe only; Dotted red line: response leak-aside the standpipe; Thin blue solid line: response leak-top of the standpipe

CONCLUSION

This extended abstract has presented some experimental results to demonstrate the effect of measuring leak propagation noise in a water pipe using an accelerometer on the top of a rod extension connected to the water pipe which was excited by a leak. Here, the waveguide was a one-metre-long metallic rod coupled to the water pipe by beeswax. One of the effects of the rod is to reduce the amplitude of the pipe response next to it, but increase the frequency range over which the cross-correlation can be performed (information on time delay) pushing the system dynamics to higher frequencies. Moreover, the measurement conducted on the top of the rod involves a propagation time, which was around 6% compared to that in the water pipe. However, this can be reduced if the distance from the leak to the rod extension is increased compared to the length of the rod.

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REFERENCES

Fuchs, H.V., and Riehle, A., 1991, “Ten years of experience with leak detection by acoustic signal analysis”, Applied Acoustic, Vol. 33, pp. 1-19.

Gao, Y., Brennan, M.J., Muggleton, J.M. and Hunaidi, O., 2004, “A model of the correlation function of leak noise in buried plastic pipes”, Journal of Sound and Vibration, Vol. 277, pp. 133-148.

O Globo, 24th of March 2018, printed version.

Puust, R., Kapelan, Z., Savic, D.A., and Koppel, T., 2010, “A review of methods for leakage management in pipe networks”, Urban Water Journal, Vol. 7, No. 1, pp. 25-45.

Hu, Z., Tariq, S., Zayed, T., 2021, “A comprehensive review of acoustic based leak localization method in pressurized pipelines”, Mechanical Systems and Signal Processing, Vol. 161, pp. 107994.

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