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ON THE DIFFERENCE BETWEEN GROUND AND PIPE VIBRATION MEASUREMENTS OF LEAK NOISE FOR LEAK DETECTION PROBLEMS

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Abstract. *Leak location in a buried water pipe can be carried out by measuring the vibration of the pipe or via the ground vibration above it. This is possible due to pipe-soil interaction and wave propagation caused by the excitation due to the leak. To measure the ground vibration due to a leak, sensors are placed on the ground and signals are then collected. However, for the vibration measurements in the pipe, the sensors can only be placed at available positions. The measured phase between these sensors can be used to locate the leak. For ground vibration measurements, however, two types of waves, shear and compressional waves, propagate into the soil. The interaction between these waves is observed as two different phase gradients in distinct frequency ranges due to the differences in the speeds of these waves. Moreover, the pipe vibration due to the leak, which is a fluid-borne type wave, has a straight-line-like behaviour. Hence, this paper shows these differences by using actual leak data collected in a special test rig to simulate leak conditions. The coherence together with the modulus and phase of the Cross Spectral Density (CSD) are used to show how these measurements can differ from each other.*

Keywords: *Leak detection, Ground Vibration, Pipe Vibration, Vibro-acoustic Techniques*

1. INTRODUCTION

Potable water is vital for the well-being of the population. However, water stress in big centers allied with climate change, has put in danger the water distribution in these areas. As a result, water companies have been under constant pressure to reduce water loss in their water distribution systems. In this context, acoustic techniques have been used extensively to find and locate leaks in buried water pipes (Fuchs and Riehle, 1991; Gao et al., 2004; Hunaidi et al., 2004). These techniques can involve measurements directly on the pipe (Gao et al., 2005; Gao et al., 2006) or on the ground (Muggleton, Brennan and Gao, 2011), because leak noise can propagate along the pipe and also radiate into the soil (Brennan et al., 2018; Scussel et al., 2019).

Leak noise energy is mostly carried by the predominantly fluid-borne wave. Several models have been developed to determine the mechanisms by which leak noise energy radiates into the soil, and how the coupling between the pipe-wall and the surrounding soil affects the propagation characteristics of a leak noise in the pipe (Muggleton, Brennan and Pinnington, 2002; Muggleton, Brennan and Linford, 2004; Gao, Muggleton and Yan, 2016; Gao, Liu and Muggleton, 2017). Leak noise radiates as shear and compressional waves into the soil. These waves are modelled using Hankel functions of the first order and second kind and their first derivative (Gao, Liu and Muggleton, 2017). This paper shows actual leak data collected in a bespoke test rig, where different leak conditions can be simulated, to show the differences between the measurements carried out on the ground and on the pipe. The same sensors were used for the two types of measurements. Moreover, the leak was also induced by the same mechanism. The Coherence and the modulus of the Cross Spectral Density (CPSD) function is used to highlight the frequency bandwidth over which there is leak data. The phase of the CPSD is used to show the time difference between the two data sets collected. This is given by the slope of the unwrapped phase; the slower the wavespeed the steeper the phase gradient and vice-versa.

2. AN OVERVIEW OF SIGNAL PROCESSING FOR LEAK DETECTION IN BURIED WATER PIPES

Vibro-acoustic sensors are used to sense the noise generated by the fluid-structure interaction due to the presence of a leak. These measurements can be conducted either by placing sensors directly to the pipe or on the ground right above to the pipe. Figure 1 shows the schematic of the measurements set-up used for pipe and ground vibration measurements. The labels "P" and "G" stand for Pipe and Ground, respectively.

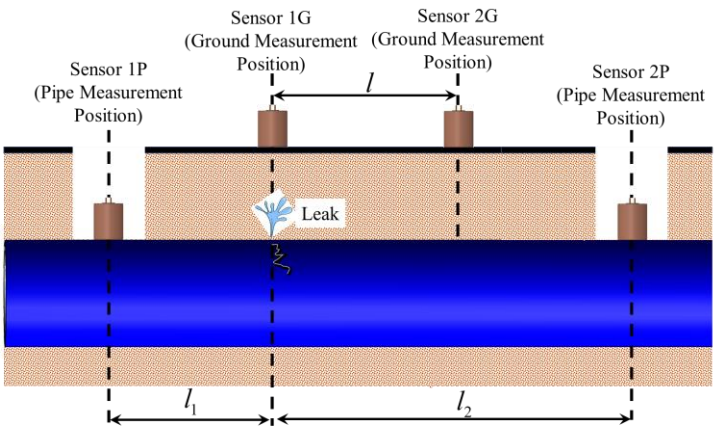

Figure 1. Schematic of the measurements conducted in the bespoke test rig

The Cross-Correlation Function (CCF) and the CPSD are the main signal processing techniques used in the analysis of leak detection and location for buried water pipes. The first is a measure of similarity between two sensors with synchronized time histories $x_1(t)$ and $x_2(t)$, and it can be calculated by (Oppenheim and Schafer, 2011)

$$R_{x_1x_2}(\tau)=\frac{1}{T}\int_0^{T-\tau} x_1(t)x_2(t-\tau)\mathrm{d}t\ ,\ \ \tau>0\ ,$$
$$R_{x_1x_2}(\tau)=\frac{1}{T}\int_{-\tau}^{T} x_1(t)x_2(t-\tau)\mathrm{d}t\ ,\ \ \tau<0\ , \quad (1)$$

where, T and τ are the time length and time lag, respectively. The peak of the CCF is used as a measure of the time delay estimation to calculate the leak position. The CPSD can be determined by calculating the Fourier Transform of the CCF, hence

$$S_{x_1x_2}(\omega)=\int_{-\infty}^{\infty} R_{x_1x_2}(\omega)\mathrm{e}^{i\omega\tau}\mathrm{d}\tau\ , \quad (2)$$

where ω is the circular frequency and $i=\sqrt{-1}$. The CPSD can be also written as

$$S_{x_1x_2}(\omega)=\left|S_{x_1x_2}(\omega)\right|\mathrm{e}^{i\phi}\ , \quad (3)$$

where $\left|S_{x_1x_2}(\omega)\right|$ is the modulus of the CPSD and ϕ is the phase between the signals whose gradient is related to the time delay. Hence, the estimation of the phase gradient is the estimation of the time delay in the frequency domain. The advantage of using the CPSD instead of the CCF is that distortions in the data can be easily observed, such as reflections (Gao et al., 2009) and resonances (Almeida et al., 2017). Hence, this paper will use "frequency domain" analysis using the CPSD to show the difference between measurements conducted on the pipe and on the ground, especially by analyzing the phase gradient. Furthermore, the coherence is also used to check the frequency bandwidth over which the leak noise is located. The coherence is calculated by

$$\gamma(\omega)=\frac{\left|S_{x_1x_2}(\omega)\right|}{\sqrt{S_{x_1x_1}(\omega)S_{x_2x_2}(\omega)}}\ , \quad (4)$$

where $S_{x_1x_1}(\omega)$ and $S_{x_2x_2}(\omega)$ are the Power Spectral Densities (PSD) of the time histories $x_1(t)$ and $x_2(t)$, respectively. The coherence varies from "0" to "1" with "0" corresponding to no correlation and "1" corresponding to complete correlation.

3. CLASSICAL WAVE MODEL TO UNDERSTAND LEAK PROBLEMS IN BURIED WATER PIPES

Simulations for leak detection problems are generally used to give physical insight of the problem. These simulations are conducted mainly by using Finite Element Methods (FEM) and Wave Propagation Models (WPM). Gao et al. (2004) were the first to give physical insight into leak detection problems in buried plastic pipes by estimating the Frequency Response Function (FRF) via a WPM for a pipe filled with water. Brennan et al (2018) investigated the use of FEM models together with WPM to understand the mechanism in which leak noise energy propagates along the buried pipe and through the soil. However, for the purpose of this work, the model used by Almeida et al. (2019), which is based on the work from Brennan et al. (2018) is used. This is a classical nondispersive plane wave model, where a simple wavenumber can be derived and used to give a better understand of leak problems. This wave model can be written as

$$w(x,t) = W(\omega)\mathrm{e}^{\pm ikx}\mathrm{e}^{i\omega t}, \tag{5}$$

where $W(\omega)$ is the frequency dependent amplitude at the leak position, x is the distance from the leak to the measurement position and k is the so-called wavenumber. The wavenumber in the pipe can be written as, (Brennan et al., 2018)

$$k = \frac{\omega}{c}\left(1 - \frac{i\eta}{2}\right), \tag{6}$$

where c and η are the speed at which the wave propagates in m/s and the loss factor, respectively. The loss factor is the parameter responsible for the wave attenuation, and the wavespeed is a function of the pipe material and its geometry, together with the surrounding medium (Brennan et al., 2018). Assuming that $W(\omega) = W_0$ is constant (white noise), the right propagating wave and neglecting the time dependency, so that $w(x) = W_0\mathrm{e}^{-ikx}$, the FRF between the acoustic pressure of the leak and the acoustic pressure at a measurement position x is given by

$$H(\omega) = e^{-ikx}. \tag{7}$$

Moreover, considering that the leak spectrum is flat (Gao et al., 2004), the CPSD is given by

$$S_{x_1x_2}(\omega) = H_1^*(\omega)H_2(\omega), \tag{8}$$

where "$*$" denotes the complex conjugate, $H_1(\omega) = e^{-ikl_1}$ and $H_2(\omega) = e^{-ikl_2}$ as shown in Fig.1 for the sensors placed on the pipe at the distances l_1 and l_2 respectively, for example. However, measuring the leak noise on the pipe or the leak noise on the ground above the pipe results in different CPSDs. This is because the leak noise propagates only as a compressional wave along the pipe, while that, compressional and shear waves radiate through the soil due to the pipe and soil interaction (Brennan et al., 2018). Figure 2(a) and 2(b) show how these mechanisms are responsible for leak noise energy propagation along the pipe and radiating through the soil, respectively.

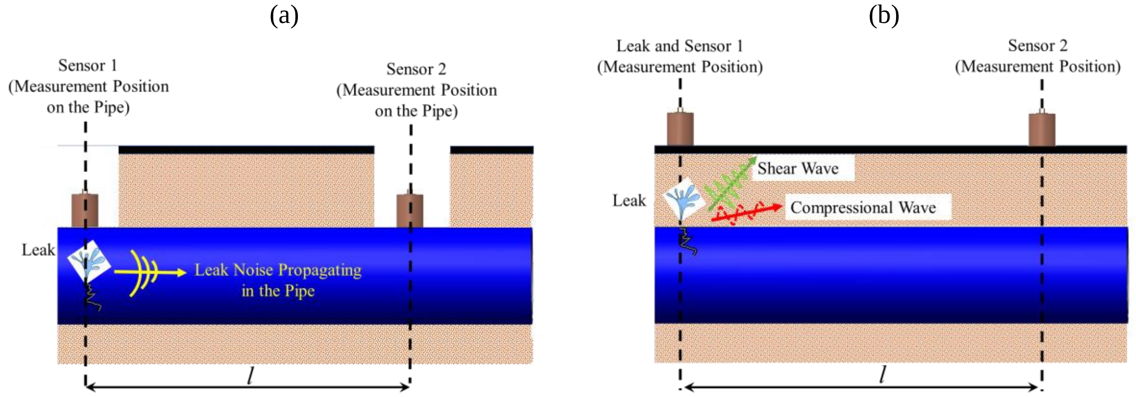

Figure 2. Schematic of the way in which leak noise (a) propagates along the pipe (compressional wave) and (b) radiates through the soil (compressional and shear waves)

Generally, accelerometers are used as sensors for leak detection problems. This, however, gives a FRF of $H^{(a)}(\omega) = -\omega^2 H_{\text{pipe}}(\omega)$, where the superscript "a" denotes acceleration and $H_{\text{pipe}}(\omega)$ is given by Eq. (7). Considering the situation illustrated in Fig. 2(a), which is the leak noise propagating along the pipe, the CPSD is given by

$$S_{x_1x_2}(\omega)\Big|_{\text{pipe}} = \omega^4 e^{-ikl}. \tag{9}$$

Figure 3(a) shows the phase of the CPSD given by Eq.(9). As can be seen, the phase has a straight-line behavior highlighting that only one wave propagates along the pipe (one time delay/wavespeed, which is related to the phase gradient). For this simulation the parameters η, c, and l are set to 0.15, 380 m/s and 1 meter, respectively. Although the leak noise propagates as spherical waves in the soil (compressional and shear waves), the plane wave model will be here used to give only an idea of how these waves interact and its effects on the phase of the CPSD. This is only a phenomenological model as an attempt to reproduce the main features given by the model developed by Gao et al. (2017) in a simpler way. Likewise for the problem for the leak noise radiating through the soil, such as the one shown in Fig.2(b), the shear wave $w_s(x)=W_0^s e^{-ik_s x}$ and the compressional wave $w_c(x)=W_0^c e^{-ik_c x}$ can be used to calculate the FRF $H^{(a)}(\omega)=-\omega^2 H_{\text{ground}}(\omega)$, where $H_{\text{ground}}=\left(w_s(l)+w_c(l)\right)/\left(w_s(0)+w_c(0)\right)$, so that the CPSD for this case can be written in a simplified way as

$$S_{x_1x_2}(\omega)\Big|_{\text{ground}}=\omega^4\frac{W_0^s e^{-ik_s l}+W_0^c e^{-ik_c l}}{W_0^s+W_0^c}. \tag{10}$$

It can be seen in Fig.3(b) that there are two slopes present in the simulated data. This is due to the interaction between the two waves, which travel at different wavespeeds resulting in different time delays related to those two slopes in the phase gradient. The shear (c_s) and compressional (c_c) wavespeeds are set to 280 m/s and 1550 m/s, respectively. The loss factor and distance between the sensors are kept as for the case shown in Fig.3(a). Actual leak data will be shown in the next section to give a real illustration of the problem

Figure 3. Simulated phase gradient via (a) Eq.(9) and via (b) Eq.(10).

4. TEST RIG DESCRIPTION

The test rig is located in Brazil and belongs to a Brazilian water company. The buried plastic pipe is buried at a depth of 0.5 m, and has a radius and pipe wall thickness of 35.8 mm and 3.4 mm, respectively. The leak is generated by a small hole in the pipe. There is a flexible hose connected to the pipe via a plastic collar, where water from the leak can flow out from the main pipe via the small hole avoiding soil degradation. As mentioned previously, the measurements for pipe vibration can be carried out only at places where there is access to the buried pipe only, such as hydrants and access points provided. For the ground vibration, however, the measurements can be conducted at any point on the ground, but the sensors need to be placed next to the leak position in order to be effective in “listening” the leak noise. This is the fundamental reason why the pipe vibration and ground vibration should be used together. The first estimates the leak position, whereas the second confirm its position by measuring the ground vibration. Figure 4(a) and 4(b) show the photos of the ground and pipe measurements, respectively carried out in the bespoke rig.

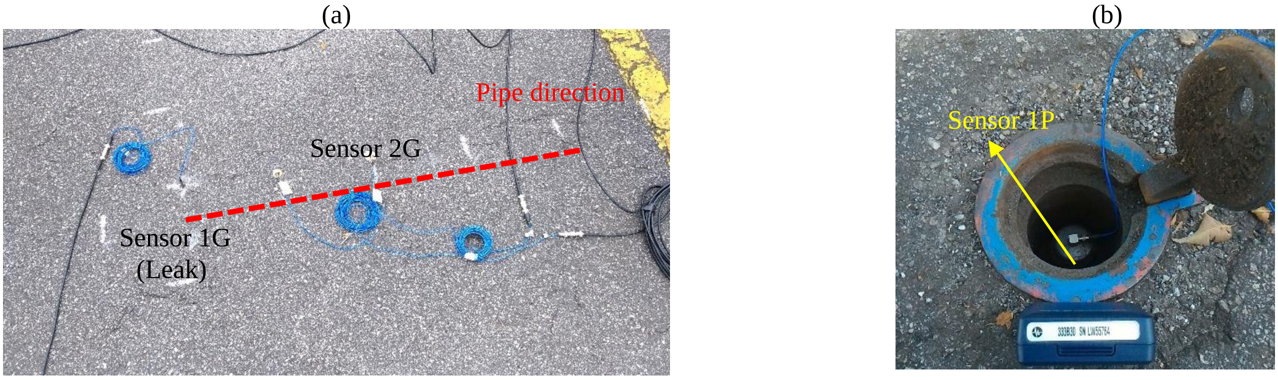

Figure 4. Photos taken in the test rig (a) Ground vibration measurement (b) Pipe vibration measurement

Figure 4(a) shows the position of the sensor 1G right above the leak together with some marks along the asphalt (ground) where the measurements were taken (sensor 2G). The maximum distance between sensors 1G and 2G, where measurements could be taken (for good coherence), is about 1.25 m. For the pipe, however, the measurements were conducted with the sensors away from 7 meters apart. Figure 4(b) shows an access point where an accelerometer is placed at. The other access point is similar to this one, so the figure is not shown. The results are given in the next section.

5. LEAK DATA: PIPE AND GROUND MEASUREMENTS

An LMS Scada acquisition system was used to acquire the signals. Two accelerometers PCB model 333B30 were also used. The data was acquired for 1 minute. The data was processed using a Hanning window, a frequency resolution of 2 Hz was selected and an overlap of 50% was set. Figure 5(a), (b) and (c) show the Coherence, the modulus and phase of the CPSDrespectively. The labels “(i)” and “(ii)” stand for the measurements conducted on the pipe and on the ground, respectively.

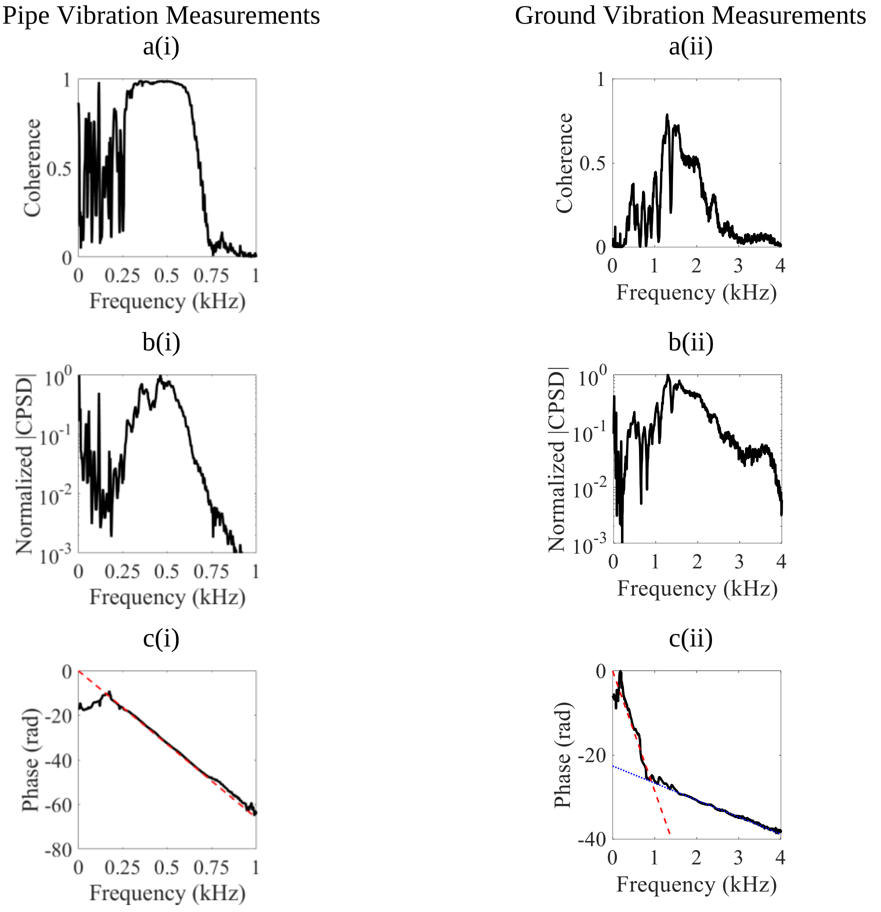

Figure 5. The measurements carried out on the pipe (i) and on the ground (ii). (a) Coherence. (b) The modulus of the CSD. (c) The phase of the CSD.

As observed, the leak energy has broader frequency bandwidth for ground vibration data than for pipe vibration data. This is because one sensor is right above the leak and the other one is just 1 m away from the source (this is the case for the ground vibration). The phase, however, shows the difference which maters for leak location problems. The phase gradient for the pipe vibration has a straight-line-like behavior highlighting that there is only one type of wave travelling along the pipe, which is the fluid-borne wave. However, for the ground vibration it is clear that there are two different slopes at different frequency ranges. This is the evidence of two waves propagating at the same time, but for different frequency ranges. The shear wave is the slower one where the phase has a steeper behavior at “low” frequencies (below around 1 kHz). On the other hand, the compressional wave is faster and the phase has a flatter behaviour at higher frequencies (above around 1 kHz).

6. CONCLUSIONS

This paper has shown the difference between vibration measurements for leak detection problems. Actual leak data collected in a special facility to simulate leaks in buried plastic pipes has been presented. The phase gradient for the vibration measurements on the pipe has a straight-like-behaviour, which is related to the predominantly fluid-borne wave responsible to carry most of the leak noise energy along the pipe. However, for the ground vibration measurements there are two slopes present in the phase gradient. These slopes are evidence of the presence of two different wave types propagating in the ground. These waves are the shear and compressional waves. Generally, pipe vibration and ground vibration are performed together, the first being used to estimate the leak position and the second to confirm the location of the leak. To understand the difference between the mechanisms at which the leak noise propagates along these media is fundamental for the effectiveness of vibro-acoustic techniques used in leak detection problems.

7. ACKNOWLEDGEMENTS

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