DINAME 2017 - Proceedings of the XVII International Symposium on Dynamic Problems of Mechanics
A. T. Fleury, D. A. Rade, P. R. G. Kurka (Editors), ABCM, São Sebastião, SP, Brazil, March 5-10, 2017

Measurement of the Speed of Leak Noise Propagation in Buried Water Pipes: Challenges and Difficulties

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Abstract: To accurately determine the position of a leak in a buried plastic water pipe using acoustic correlation, a good estimate of the speed of noise propagation (wave speed) is required. The factors that affect this wave speed, and attenuation of the wave as it propagates along the pipe, include the pipe flexibility and the soil properties. These effects are discussed in this paper, and are illustrated by way of simulations for two different pipe sizes and two different soil types. It is shown that the soil type in Brazil can have a profound effect on the wave speed and hence the accuracy of leak location. Some practical problems in estimating the wave speed from in-situ measurements are also outlined. Although this is relatively simple to measure in principle, in practice it is extremely difficult to do, for a variety of reasons. Some of these are discussed and the reason why this measurement is particularly problematic with plastic water distribution pipes is illustrated.

Keywords: water leak detection, acoustic correlation, wave propagation

INTRODUCTION

Leakage occurs in buried water distribution systems through defective joints, or split pipes because of ground movement. It is estimated that 40-50% of drinking water is wasted through leakage in developing countries, and less than 10% is wasted in countries where the utilities are well-maintained, such as Japan (Kingdom et al., 2006), (Grant et al., 2012). It is costly to locate and repair these leaks.

To determine if a leak is present in a specific part of the network, pressure measurements together with flow measurements are used (Puust et al., 2015). To determine a more precise location of a leak, noise correlators are often used (Fuchs and Riehle, 1991). The cross-correlation function between two leak noise signals (acceleration, pressure or velocity) acquired at two different positions (generally hydrants) on the pipe is calculated. The peak in the correlation function is used to determine the difference in propagation times between the leak and the sensors. By combining this with knowledge of the speed at which the leak noise propagates, the location of the leak can be determined. Although correlators work well for metallic pipes, their performance on plastic pipes is more limited (Hunaidi et.al., 1999, 2000). The two main factors that affect correlator performance in this case, are the relatively high rates of attenuation experienced by waves propagating along the pipes and the variability in the speed at which they propagate along the pipe. The wave-speed is heavily influenced by the pipe properties and the surrounding soil (Muggleton et al., 2002, 2004, 2013), (Almeida, et al., 2014), (Gao et al., 2016). The accuracy with which the leak can be located is therefore directly linked to the accuracy with which the wave speed is known. For maximum accuracy, the wave speed should be measured in-situ on the section of pipe in which there is a leak, at the same time as the correlation measurement is made. In nearly all cases, however, the wave speed is estimated from a historical database determined from calculations made using assumed material properties and pipe geometry.

This paper shows why a good estimate of the speed of leak noise propagation is of paramount importance in obtaining an accurate estimate of the location of a leak. The factors affecting the speed of the wave responsible for leak noise propagation, as well as the attenuation of this wave are discussed. A simple expression to predict the wave speed, which is dependent upon both fluid loading and soil loading factors is presented. This shows why the wave speed is found to be very different from location to location, and motivates the need for measurement of the wave speed in-situ (Almeida et al., 2015). However, there are many practical problems, which make an accurate estimate of wave speed measurements difficult. Some of these issues are also outlined in this paper.

AN OVERVIEW OF LEAK DETECTION USING ACOUSTIC CORRELATION

Figure 1 shows a typical situation in which leak noise is used to detect and locate its position. Acoustic or vibration sensors are attached to convenient access points either side of the suspected leak position. The actuators shown in the figure are not normally used in the field for leak detection, but can be used to measure the speed of the wave responsible for leak noise propagation.

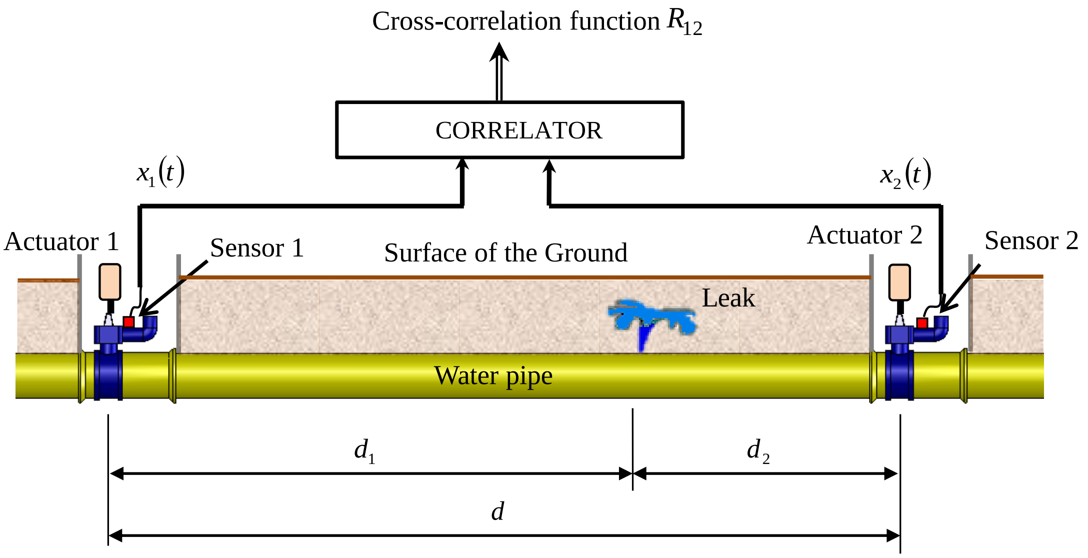

Figure 1 - Schematic of leak detection in a buried plastic water pipe using acoustic/vibration signals with a leak in between the two sensors. The actuators are used for the wave-speed measurement.

In Fig. 1 the leak position d_2 from the right-hand sensor is given by, (Gao et al., 2004),

$$d_2 = \frac{d - cT_0}{2}, \tag{1}$$

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). The wave that carries the leak noise in plastic pipes is predominantly a fluid-wave that is strongly coupled to the radial motion of the pipe-wall (Muggleton et al., 2002). The most widely used technique to determine the time delay between sensor signals uses the cross correlation function (CCF), $R_{12}(\tau)$, between the two measured signals $x_1(t)$ and $x_2(t)$, as shown in Fig. 1. The presence of a leak appears as a distinct peak in the CCF between the measured signals, which is given by, (Gao et al., 2004),

$$R_{12}(\tau) = F^{-1}\{S_{12}(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} S_{12}(\omega) e^{j\omega\tau} d\omega \tag{2}$$

where $F^{-1}\{\ \}$ is the inverse Fourier transform, $S_{12}(\omega)$ is the cross-spectral density function (CSD) between the measured signals, ω is circular frequency, and $j = \sqrt{-1}$. This peak in the correlation function gives the time delay estimate between the measured signals $x_1(t)$ and $x_2(t)$. Sometimes, it is preferable to express the cross-correlation function in a normalized form, which has a scale of -1 to +1. This is called the cross-correlation coefficient (CCC) and is given by $\rho(\tau) = R_{x_1x_2}(\tau)\big/\sqrt{R_{x_1x_1}(0)R_{x_2x_2}(0)}$, where $R_{x_1x_1}(0)$ and $R_{x_2x_2}(0)$ are respectively the autocorrelation functions at positions 1 and 2, when $\tau = 0$.

EFFECT OF THE WAVE-SPEED ESTIMATE ON LEAK LOCATION

It can be seen from Eq. (1) that accurate estimates of c and T_0 are required for an accurate estimate of the leak location. Much research into leak detection has concentrated on the estimation of the time delay, see Gao et al., (2006) and the references therein, for example. The greatest error, however, is likely to be in the estimate of the wave-speed as this varies dramatically depending on the geometry and material properties of the pipe and the surrounding soil. In most cases the wave-speed is estimated from tables, which are compiled from simple calculations or from a historical database. An error in the wave-speed estimate used in Eq. (1), will produce a corresponding error in the estimate of the distance d_2. The error can be determined from (Almeida et al., 2015),

$$\frac{\Delta d_2}{d} = \left(\frac{1}{2} - \frac{d_2}{d}\right)\frac{\Delta c}{c} \tag{3}$$

where Δc and Δd_2 are the differences between the measured and actual wave speed, and the estimated and actual distance respectively. Equation (3) shows that as the position of the leak becomes closer to one of the measurement points then the error in the wave-speed measurement has an increasing effect. By way of example, consider an extreme case of a length of pipe between the measurement positions of 100 m and a 10% error in the wave-speed estimate, with the leak being at one of the measurement positions. The resulting error in the location in this case is 5% of the length of the pipe, i.e. 5 m. Finding a way to reduce this error by more accurate wave-speed estimation is desirable, and some of the issues in doing this are discussed in this paper.

EFFECT OF FLUID-STRUCTURE-SOIL INTERACTION ON THE WAVE-SPEED

For a buried plastic water pipe, the surrounding soil and the material properties of the pipe can have a profound effect on the speed at which leak noise propagates along the pipe. This has been investigated in several papers as mentioned previously, and the key points are summarised here. It will be seen that it is desirable to measure the wave speed in-situ, wherever possible rather than rely on estimates as they are not likely to be very accurate. For a plastic pipe of mean radius *a* and pipe-wall thickness *h*, with complex Young's modulus $E^* = E(1+\mathrm{j}\eta)$, where η is the loss factor, and density ρ, containing water with bulk modulus B_w, which is buried in soil with bulk modulus B_s and shear modulus G, the speed of noise propagation is governed by the speed of a coupled fluid-structural wave in the pipe, which is given by (Muggleton and Yan, 2013)

$$c = \frac{\omega}{\mathrm{Re}\{k\}} \tag{4}$$

where k is a wavenumber given approximately by $k = k_f\left(1 + K_{\text{water}}\big/\left(K_{\text{pipe}} + K_{\text{soil}}\right)\right)^{\frac{1}{2}}$ in which $K_{\text{water}} = 2B_w/a$ is the dynamic stiffness (pressure/displacement) of the water in the pipe, $K_{\text{pipe}} = E^* h/a^2 - \rho h\omega^2$ is the dynamic stiffness of the pipe-wall and $K_{\text{soil}} = K_c + K_s$ is the dynamic stiffness of the surrounding soil, where K_c and K_s are the dynamic stiffnesses of the compressional and shear waves in the soil, and are given by

$$K_c = \left(B_s - \frac{2G}{3}\right)\frac{k_d^2}{k_d^r}\left(1 - 2\frac{k_1^2}{k_r^2}\right)\frac{H_0\left(k_d^r a\right)}{H_0'\left(k_d^r a\right)} - 2Gk_d^r\left(1 - 2\frac{k^2}{k_r^2}\right)\frac{H_0''\left(k_d^r a\right)}{H_0'\left(k_d^r a\right)} \quad \text{and} \quad K_s = -4Gk_r^r\frac{k^2}{k_r^2}\frac{H_1'\left(k_r^r a\right)}{H_1\left(k_r^r a\right)}$$

where the soil radial wavenumbers k_d^r and k_r^r are given by $k_d^r = \sqrt{k_d^2 - k^2}$ and $k_r^r = \sqrt{k_r^2 - k^2}$ respectively, and k_d and k_r are the compressional and shear wavenumbers in the soil respectively; $H_0(\bullet)$ and $H_1(\bullet)$ are Hankel functions and $'$ denotes a spatial derivative. Note that in this formulation, the axial stress at the interface between the pipe and the soil is considered to be negligible. The effect of this assumption was considered by Gao et al., (2016), who found that it had a negligible effect on the wave speed and only a small effect on the wave attenuation.

Two different pipe sizes are considered. One is found in the UK (Muggleton and Yan, 2013), and one is found in Brazil. As well as this, two soil types are considered for each pipe (soil type A is representative of much of the soil found in the UK, and soil type B is representative of the soil found in São Paulo). The properties of the pipes and the soils are given in Tabs. 1 and 2. The wave speeds for the two pipes and for the two soil types are shown in Fig. 2(a) and the attenuation in dB/m, which is given by $20\,\mathrm{Im}\{k\}/\ln(10)$, is shown in Fig. 2(b) for the frequency range 100 Hz to 1k Hz. This frequency range is chosen as this is the range in which measured leak noise is generally found. The following observations can be made.

- The flexibility of the pipe significantly reduces the wave-speed in the predominantly fluid wave (for a rigid pipe the fluid wave propagates at 1500 m/s). The stiffness of the soil counteracts this to some extent, increasing the wave speed.

- The attenuation of the wave increases with frequency. Some of the attenuation is due to damping in the pipe-wall, but the greatest part of the attenuation at high frequencies is due to the radiation of leak noise into the soil.

Table 1 – Pipe Properties

Properties	UK	BRAZIL
Young's modulus, E (N/m^2)	2×10^9	2×10^9
Density ρ (kg/m^3)	900	900
Loss factor	0.06	0.06
Pipe radius (mm)	84.5	35.8
Pipe-wall thickness (mm)	11	3.4

Table 2 –Soil and Water Properties

Properties	Soil type A	Soil type B	Water
Bulk modulus $B_{s,w}$ (N/m^2)	5.3×10^7	4.5×10^9	2.25×10^9
Shear modulus, G (N/m^2)	2.0×10^7	1.8×10^8	
Density ρ (kg/m^3)	2000	2000	

Because of the attenuation, a wave cannot travel for long distances along a buried plastic pipe and the measured vibration on the pipe tends to be at low frequency (Almeida et al., 2015). Although the wave speed is function of frequency it can be seen that it does not change dramatically, and a low frequency approximation to the wavenumber can be used to determine an approximate value. Unfortunately, the approximation cannot be used to predict the attenuation of the wave.

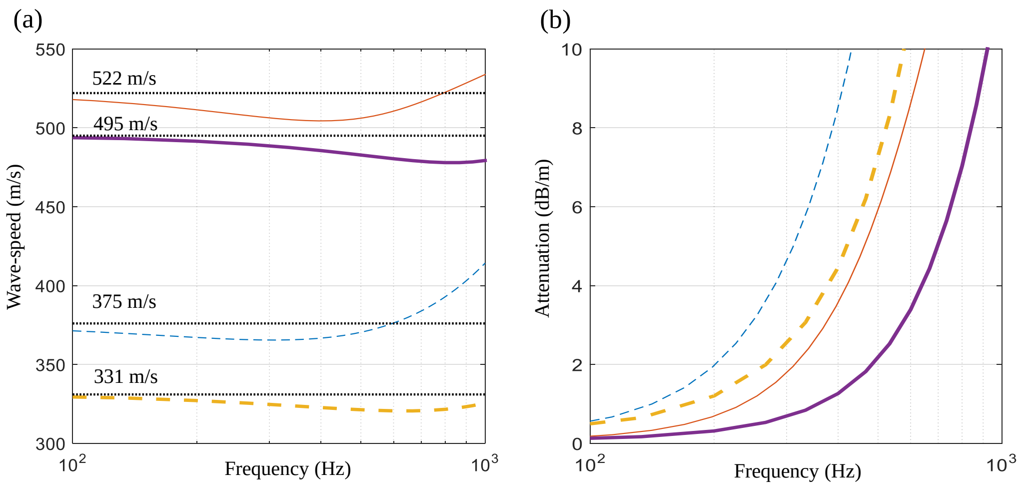

Figure 2 – Noise propagation characteristics (a) wave-speed (b) wave attenuation. Dashed thin line, UK pipe, soil type A; Solid thin line, UK pipe, soil type B; Thick dashed line, Brazil pipe, soil type A; Thick solid line, Brazil pipe, soil type B.

The approximation for the real part of the wavenumber is given by

$$\mathrm{Re}\{k\} = k_f \left(1 + \frac{\dfrac{2B_w}{Eh/a}}{1 + \dfrac{2G}{Eh/a}} \right)^{\frac{1}{2}} \tag{5}$$

where $2B_w/(Eh/a)$ and $2G/(Eh/a)$ are the fluid loading and soil loading terms respectively. It is clear that an increase in the fluid loading term increases the wavenumber, and hence decreases the wave-speed, and an increase in the soil loading term (due to the shear stiffness of the soil), decreases the wavenumber and hence increases the wave-speed. These effects are illustrated in Fig. 3, which shows the wave-speed normalised by the wave-speed in water (1500m/s) as a function of the soil loading term, for the UK pipe and the Brazilian pipe whose parameters are given in Tab. 1. It can be seen that both the fluid and the soil loading terms can have a profound effect on the wave-speed. As mentioned previously accurate knowledge of the wave-speed is needed for an accurate estimate of the leak location. This motivates the need to measure the wave-speed in-situ.

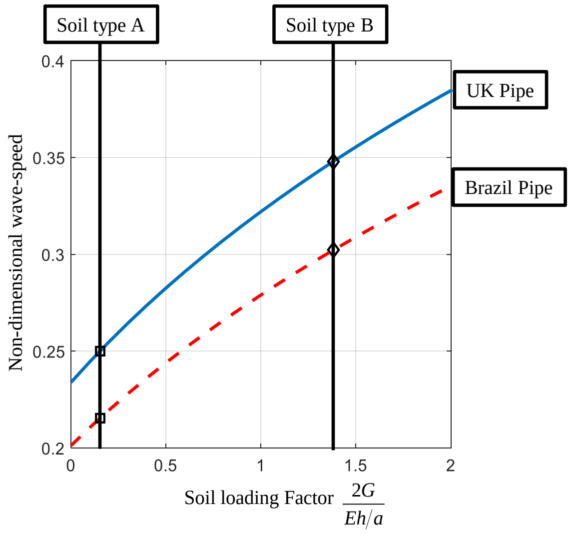

Figure 3 – Non-dimensional wave speed (wave-speed divided by 1500 m/s – wave-speed in water in a rigid pipe) as a function of the soil loading factor for the Brazil pipe (*h*/*a*=0.095), solid blue line and for the UK pipe (*h*/*a*=0.132), dashed red line.

MEASUREMENT OF WAVE SPEED

To measure the wave speed in a buried pipe, a wave has to be generated in the pipe and two signals measured which are of a known distance from the excitation point. The excitation can be done with shakers as in (Almeida et al., 2015) in a configuration as shown in Fig. 1 or by creating a leak at a known position. Typical processed signals are shown for measurements made on a buried plastic pipe rig in the UK using accelerometers. Figure 4(a) shows the modulus of the CSD normalised by its maximum value, and Fig. 4(b) shows the phase. Also shown in Fig. 4(b) is a straight line corresponding to $\phi = -\omega T_0$. The coherence is shown in Fig. 4(c), where it can be seen that the bandwidth over which there is potentially time delay information is about 20-120 Hz corresponding to the frequency range at which the coherence is not close to zero. Finally, Fig. 4(d) shows the cross-correlation coefficient in which the time delay is indicated. Referring to Fig. 1, $d_1 = 30$ m, $d_2 = 20$ m, and the measured time delay was about 25 ms, which results in a wave speed of about 400 m/s. Of particular note in Fig. 4(b) is the deviation of the measured phase from the phase that would be measured purely due to a time delay. The deviation of the phase from that due to the time delay can be due to several reasons, including noise, structural dynamics of the pipe system (Almeida et al., 2013), and wave reflections from discontinuities in the pipe system (Gao et al., 2009). The effect of a resonance due to structural dynamics is to significantly reduce the bandwidth over with the time delay is estimated by correlation. The effect of reflections is to cause a confusing picture in the cross-correlation function. The effect of bandwidth and the centre frequency of this bandwidth on the ability to determine an accurate estimate of time delay in the presence of reflections is further discussed here.

For simplicity the attenuation in the pipe is neglected (which is equivalent to using the PHAT estimator (Gao et al, 2006)), so that the cross-correlation function is given by

$$R_{12}(\tau) = \frac{\Delta\omega}{\pi} \frac{\sin\left(\Delta\omega(\tau - T_0)/2\right)}{\Delta\omega(\tau - T_0)/2} \cos\left(\omega_c(\tau - T_0)\right) \quad (6)$$

where $\Delta\omega = \omega_{\text{upper}} - \omega_{\text{lower}}$ is the bandwidth over which there is leak noise and $\omega_{\text{centre}} = \left(\omega_{\text{upper}} + \omega_{\text{lower}}\right)/2$ is the centre frequency of the band. This can be written in non-dimensional form as

$$\hat{R}_{12}(\hat{\tau}) = \frac{R_{12}(\tau)}{\Delta\omega/\pi} = \frac{\sin(\hat{\tau})}{\hat{\tau}} \cos(\alpha\hat{\tau}) \quad (7)$$

where $\hat{\tau} = \Delta\omega(\tau - T_0)/2$ and $\alpha = 2\omega_{centre}/\Delta\omega$. Equation (7) is plotted in Fig. 5 for $\alpha = 4$.

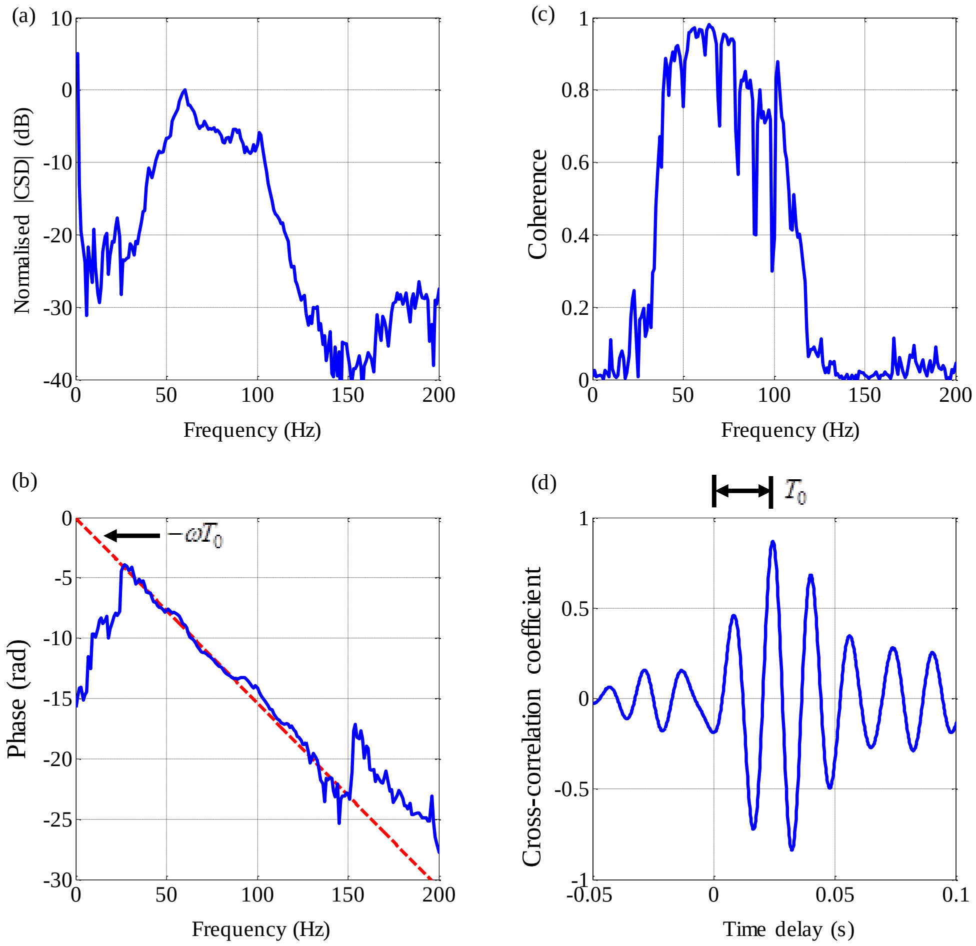

Figure 4 - Processed leak signals from the test-rig shown in Fig. 2 (a) Modulus of CSD normalised by the maximum value, (b) phase, (c) coherence, (d) cross-correlation coefficient.

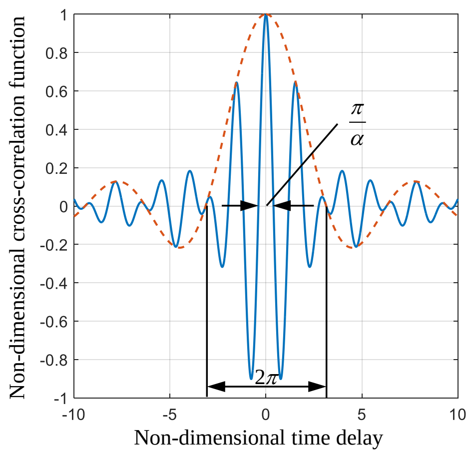

Figure 5 – Normalised cross-correlation function with the time delay set to zero.

The envelope $\sin(\hat{\tau})/\hat{\tau}$ is also plotted. It can be seen that the normalized cross-correlation function has a peak at $\hat{\tau} = 0$, which corresponds to $\tau = T_0$. It can also be seen that the normalized cross-correlation function oscillates within the envelope. The non-dimensional time of the first crossing point in this function can be determined by setting $\cos(\alpha\hat{\tau}) = 0$, which occurs when $\alpha\hat{\tau} = \pi/2$. Hence the non-dimensional time between the zero crossing points either side of $\hat{\tau}=0$ is given by π/α. The first zero crossings in the envelope, which governs the shape of the cross-correlation function occur when $\sin(\hat{\tau})=0$, which is when $\hat{\tau}=\pi$ so the non-dimensional time between the first zero crossings in the envelope is 2π. For two time delays to be detected in the cross-correlation function (which correspond to the arrival of two waves, one being the original wave and the second being a reflected wave) requires that the non-dimensional difference in the arrival times $\Delta\hat{T}$ should be such that $\Delta\hat{T}>\pi/\alpha$. Preferably, it should occur after the first zero crossings of the envelopes so that $\Delta\hat{T}>2\pi$. In dimensional terms this is when $\Delta T>1/(2f_{\text{centre}})$, where f_{centre} is the centre frequency of the band in Hz, or preferably when $\Delta T>2/\Delta f$, where Δf is the bandwidth in Hz.

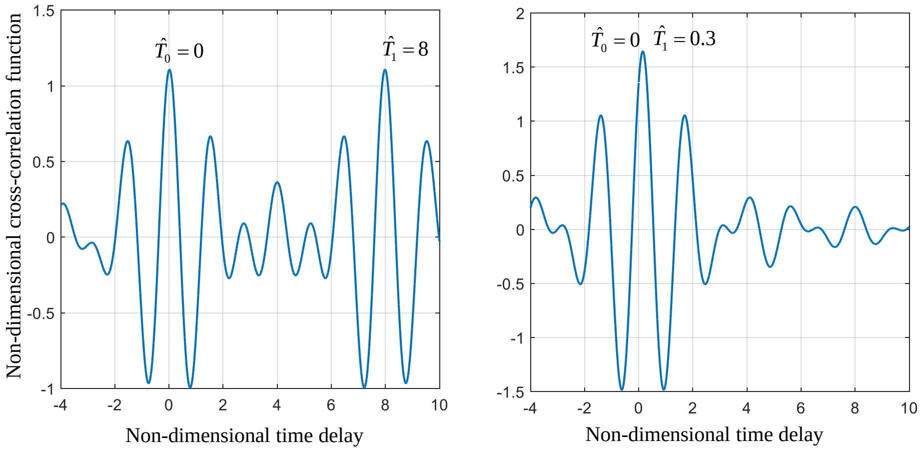

Figure 6 – Illustration of the effect of the signal parameters on the estimation of time delay with system with two time delays (reflections). (a) Two time delays are discriminated (b) time delays are not discriminated.

The discrimination of two time delays is illustrated in Fig. 6 for $\alpha=4$. Figure 6(a), shows the cross-correlation for a signal where the difference between the two time delays is $\Delta\hat{T}=8$. In this case the criteria given above is fulfilled and hence there are two clear peaks corresponding to $\Delta\hat{T}=0$ and $\Delta\hat{T}=8$. Figure 6(b) shows a cross-correlation function where the non-dimensional difference between the two time delays is only 0.3. It can be seen that only one peak is apparent and the time delay corresponding to this peak is 0.15. This does not correspond to either time delay. In fact, as the signals corresponding to the two time delays have the same amplitude then the peak occurs at the mean of the two time delays as discussed in (Almeida et al., 2015). However, this is unlikely to occur in practice and so a signal that contains a wave reflection in which $\Delta T<2/\Delta f$ can cause a considerable error in the estimate of time delay and hence the estimate of a wave speed.

CONCLUSIONS

This paper has discussed the importance of obtaining a good estimate of the speed of leak noise propagation in buried water pipes so as to determine an accurate estimate of the location of a leak. The factors affecting the speed of the wave responsible for leak noise propagation, as well as the attenuation of this wave, as it propagates have been described. A simple expression to predict the wave speed, which is dependent upon both fluid loading and soil loading factors, has been derived (No simple expression is possible for wave attenuation). It has been shown that while the flexibility of the pipe slows down the wave compared to a rigid-wall pipe, the shear stiffness of the soil plays an important role in counteracting this effect, increasing the wave speed. This has been found to be particularly relevant for the type of soil found in Brazil.

Concerning the estimation of wave speed by measurement, some dynamic effects that can cause inaccuracies in the estimate have been highlighted. Among them are resonance effects that can severely limit the bandwidth over which the time delay is estimated using correlation, and the effect of wave reflections in the pipe. The relationship between the bandwidth and the centre frequency of the bandwidth on the ability to differentiate between a direct wave and a reflected wave has been discussed. It has been found that if more than one wave is dominant in the pipe, then a wide bandwidth is necessary in order to obtain an accurate time delay estimate, and hence an accurate estimate of the leak location.

ACKNOWLEDGMENTS

The authors would like to thank Dr Jen Muggleton from the ISVR, University of Southampton, UK, for helpful discussions on the effects of soil loading on leak noise propagation. The authors would also like to acknowledge the financial support from FAPESP, Process No. 2013/50412-3.

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