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Abstract: In many water distribution systems, metallic pipes are being replaced by plastic pipes due to their deterioration and age. Although acoustic methods are effective in finding leaks in metallic pipes, they have been found to be problematic with plastic pipes due to the high damping within the pipe-wall. In acoustic correlation methods, sensors are placed either side of a suspected leak, and the peak in the cross-correlation function of the measured signals gives the time difference (delay) between the arrival times of the leak noise at the sensors. To convert the time delay into a distance, the speed at which the leak noise propagates along the pipe (wave-speed) needs to be known. It has been found the structural dynamics of the system can corrupt time delay estimates. In this paper, data from test-rigs in the United Kingdom and Canada are used to demonstrate the problems encountered, and a model is developed to further investigate which of two commonly used correlation algorithms are more robust to the presence of resonances in buried pipe systems. It is found that this is highly sensitive to the bandwidth over which the analysis is conducted. Moreover it is further found the Phase Transform (PHAT), which is frequently used for leak noise detection, is particularly sensitive to the presence of resonances, whereas the basic cross-correlation (BCC) function is found to be more robust.

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Cover Letter

UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
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Journal of Sound and Vibration 31 January 2017

Dear Editor

I would be grateful if would consider our paper "The effects of resonances on time delay estimation for water leak detection" by myself, Michael John Brennan, Phillip Frederic Joseph, Gao Yan, and Amarildo Tabobone Paschoalini for publication in the Journal of Sound and Vibration.

The paper has not been submitted to any other journal for publication.

I look forward to hearing from you in due course.

Yours faithfully

Fabrício C. L. Almeida

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Statement of Author Contribution

UNIVERSIDADE ESTADUAL PAULISTA
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Dear Editor

This letter is to confirm the participation of me and my colleagues in the paper whose title is "The effects of resonances on time delay estimation for water leak detection in plastic pipes". Furthermore, it is also highlighted the contribution from each author as follow:

- Fabrício Almeida: This author collected the data in Blithfield, performed simulations and wrote the original (first draft) paper
- Michael Brennan: The main idea (model) used in this paper was introduced by this author. He participated actively in the discussions, modelling and amending the paper.
- Phillip Joseph: This author has been involved in the discussions and amendments carried out until the final version of this paper.
- Gao Yan: The idea was first discussed during her PhD studies. She contributed to the model and analyse the Canadian data together with helping in the amendments of the paper.
- Amarildo Tabone: This author gave computational support during the simulations.

This paper has been revised and approved by the authors mentioned above.

Best Regards

Fabrício Almeida (first and corresponding author).

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The effects of resonances on time delay estimation for water leak detection in plastic pipes

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Abstract

In acoustic correlation methods for water leak detection, sensors are placed at pipe access points either side of a suspected leak, and the peak in the cross-correlation function of the measured signals gives the time difference (delay) between the arrival times of the leak noise at the sensors. Combining this with the speed at which the leak noise propagates along the pipe, gives the location of the leak with respect to one of the measurement positions. It is possible for the structural dynamics of the pipe system to corrupt the time delay estimate, which results in the leak being incorrectly located. In this paper, data from test-rigs in the United Kingdom and Canada are used to demonstrate this problem, and analytical models of resonators are coupled with a pipe model to replicate the experimental results. The model is then used to investigate which of the two commonly used correlation algorithms, the Basic Cross-Correlation (BCC) function and the Phase Transform (PHAT), is more robust to the undesirable structural dynamics. It is found that this is highly sensitive to the bandwidth over which the analysis is conducted. Moreover, it is found that the PHAT is particularly sensitive to the presence of resonances and can give an incorrect time delay estimate, whereas the BCC function is found to be much more robust, giving a consistently accurate time delay estimate for a range of dynamic conditions.

Keywords：leak detection; water pipes; resonance; cross-correlation; time delay estimation.

1. Introduction

Buried water pipelines are susceptible to leakage. To repair these pipe-systems, the ground generally must be excavated to allow access to the damaged pipe section, resulting in significant financial loss [1]. Many techniques can be used to detect and locate leaks, and the choice of which one to use depends on the cost, stage of the leak, personnel involved (technical level of knowledge), area to be covered, etc. Common non-acoustic methods used in detecting leaks include the measurements of flow rates and pressures in pipe networks [2], thermography [3] and ground-penetrating radar [4], which detect regions of the soil whose properties have been modified by the presence of the leak.

Ben-Mansour et al [5] and Puust et al [6] have provided good reviews on the classical techniques used to locate and detect leaks, and outline the main advantages and disadvantages of each. One of the simplest and most common acoustic techniques is the use of “listening sticks”. This technique has limited effectiveness, however, since it depends greatly on operator experience and only provides an empirical estimate of the leak position [2, 3]. Leak noise correlators have been used for many years [2]. These devices calculate the cross-correlation function between the signals obtained from two transducers attached to the pipe, whose peak is then used to detect and locate the leak. Although correlators are effective for metallic pipes [3, 7], the range over which they can detect leaks is significantly less for plastic pipes [3, 7, 8]. This is because of the relatively high level attenuation of leak noise due to damping in the pipe system, and the influence of the pipe properties on the speed at which the noise propagates along the pipe [8, 9]. Recent research on improving leak detection has thus focussed on plastic pipes.

In leak detection, the most widely used correlators utilise the so-called Basic Cross Correlation (BCC) function. The BCC may be performed by taking the inverse Fourier transform of the cross spectral density (CSD) function of a leak signal, measured either side of the leak. However, there are other options in some types of commercial correlators [10, 11]. One of them uses the phase transform (PHAT) as discussed by Gao et al [12]. The PHAT correlator is used to sharpen the peak in the cross-correlation function and to suppress other additional peaks unrelated to the time delay information. In this process, the modulus of the CSD between the signals is "flattened" or "whitened" prior to the transformation to the time domain. Only the phase information is therefore used to determine the time delay estimate. However, recent experimental work has shown that the PHAT correlators, in which time delay estimate is obtained from the peak in the cross-correlation function can, in some circumstances, be in significant error.

The aim of this paper is to investigate the effect of pipe resonances on the accuracy of the PHAT correlator, and to compare its performance with that of the BCC function. It will be shown that measurements made on water distribution pipes can include the effects of resonances. Another objective of this paper is to speculate on the reasons for these resonances based on experimental data from two test-rigs. The data demonstrates that the most likely cause of the resonance behaviour is due to the structural dynamics of the pipe system. A model is then developed to systematically investigate the sensitivity of the BCC and PHAT correlators to the system dynamics and to determine when there are likely to be errors with the time delay estimate.

2. Overview of leak detection using the cross-correlation function

This section describes the use of cross-correlation of vibration and acoustic signals as a tool for leak location in water distribution pipes, further details of which can be found in [7] and [13] and the references cited therein. A typical measurement set-up is depicted in Fig. 1. The noise generated by the leak propagates along the pipe and is measured by sensors placed at two different positions (access points), typically hydrants or valves either side of the leak. The distance between the sensors is $d = d_1 + d_2$, where d_1 and d_2, are the respective distances between the leak and the access points. To determine the position of the leak, the cross-correlation function between the measured signals $z_1(t)$ and $z_2(t)$ is calculated. The peak in this function, which is a measure of similarity between the two measured signals, occurs at time delay T_0, and the distance of the leak from sensor 1, d_1, can be estimated from [13],

$$d_1 = \frac{d - cT_0}{2}, \tag{1}$$

where c is the speed of propagation (wavespeed) of the leak noise. The wavespeed is generally determined from standard tables provided by manufacturers of commercial correlators [14], or calculated using theoretical equations, such as the one given by Gao et al [13]. It can also be measured in-situ [15]. The generalised cross-correlation function between $z_1(t)$ and $z_2(t)$, is given by [12]

$$R_{z_1 z_2} = F^{-1}\{\Lambda(\omega) S_{z_1 z_2}(\omega)\} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \Lambda(\omega) S_{z_1 z_2}(\omega) e^{i\omega\tau} d\omega, \tag{2}$$

where $F^{-1}\{\ \}$ is the inverse Fourier transform, $\Lambda(\omega)$ is a frequency-dependent weighting function for the different correlators, and $S_{z_1z_2}(\omega)=\left|S_{z_1z_2}(\omega)\right|e^{i\phi(\omega)}$ is the CSD function between the signals $z_1(t)$ and $z_2(t)$, $i=\sqrt{-1}$ and $\phi(\omega)$ is the phase spectrum. In the case where there is a pure time delay then $\phi=\omega T_0$, where T_0 is the difference between the arrival times at the two sensors. The weighting function $\Lambda(\omega)$ varies for each correlator [12], but in this paper, only two are considered. They are the BCC and the PHAT, for which $\Lambda(\omega)\big|_{\mathrm{BCC}}=1$ and $\Lambda(\omega)\big|_{\mathrm{PHAT}}=1\big/\left|S_{z_1z_2}(\omega)\right|$. Note that for a pure delay, $\phi=\omega T_0$, the cross-correlation function calculated using the PHAT becomes $R_{z_1z_2}^{\mathrm{PHAT}}=\delta(\tau-T_0)$, i.e., a delta function at time T_0.

An example of processed high quality leak noise data is shown in Fig. 2. These data were collected on a test rig located in Ottawa in Canada [7], a schematic of which is shown in Fig. 3(b). A description of this test-rig is given in Section 3. The data has also been analysed by Gao et al [13], and further details on the data from the test-rig can be found in this reference. The leak measurements were acquired using accelerometers, where the distance between these sensors (d) is about 102 m and the distance d_1 from the leak is 29.1 m. Figures. 2(a-c) show the normalised modulus of the CSD with respect to its maximum value, the coherence function, and the phase spectrum related to the CSD between a leak signal measured either side of its position, respectively. Straight-line behaviour of the phase in Fig. 2(c) can be observed over a reasonably large frequency range, which is indicative of high quality leak-noise data. Lower quality leak-noise data measured using hydrophones also obtained on the Ottawa test-rig is discussed later in the paper.

To determine the frequency range over which leak noise can be detected, the approach taken by Muggleton et al [16] is adopted. It is related to the ability to unwrap the phase in the cross spectrum, which in turn is related to the coherence between the two signals. In order to unwrap the phase, its variance, which is given by $\mathrm{Var}[\phi] \approx 1/(2\gamma^2 N)$ [17], where N is the number of averages over which the estimate is obtained and γ^2 is the coherence function, should be less than $(2\pi)^2$. In the work carried out by Muggleton et al, the number of averages used was 10, hence the coherence is required to be greater than 10^{-3} to successfully unwrap the phase. In the cases used in this work, the phase can also be unwrapped if the coherence is greater than 10^{-3}, and this was found to be independent of the number of averages. This value of coherence is therefore used to define the bandwidth over which the leak noise is significant. This bandwidth was found to be 34 Hz – 118 Hz in the data presented in Fig. 2 and is shown in Figs. 2(a-c). This bandwidth arises because below about 34 Hz correlated background noise is dominant, and at frequencies greater than about 118 Hz the leak noise reaching the sensors is very weak due to the filtering properties of the plastic pipe [8,13]. Figure 2(d) shows the corresponding BCC and PHAT correlators calculated after the data has been passed through a band-pass filter with upper and lower cut of frequencies of 34 Hz and 118 Hz respectively to suppress background noise. It can be seen that both correlators give a similar result, especially in the region close to the time delay of 90 ms.

3. Experimental arrangements and leak data

3.1 Description of the experimental test-rigs

The data from two pipe systems were used in this work. One is in the UK (the Blithfield pipe system), and the other is in Canada (the Ottawa pipe system). The reason for using data from these pipe systems is because the signals obtained from both pipe systems broadly exhibit similar features, even when different approaches were used to simulate the leak. In the Blithfield pipe system, the leak was created by opening a valve in a stand-pipe, and in the Ottawa system the leak was due to a crack in the buried pipe.

The Blithfield pipe system is shown in Fig. 3(a). It is a 120 m long pipe network buried at a depth of about 0.8 m, and is assembled from pipe-sections of 20 or 30 m long, each of which has an outer radius of 80 mm and wall thickness of 9.85 mm. Each pipe section has an accessible valve. The leak can be generated at any of the 5 access points, which also correspond to possible measurement locations, although only three of these locations were used in this work. The measurement points are labelled as P1 and P2, and the leak position is located between these two points. Figure 3(a) shows a plan view of the Blithfield pipe system in which the access points and position of the leak are indicated. More information about the Blithfield pipe system can be found in [18]. Table 1 depicts the characteristics of the Blithfield pipe rig which were also used for the simulations.

The Ottawa pipe system is 200 m long and it is buried at a depth of about 2.4 m. The pipe has an outer radius of 75 mm, and the measurement positions are hydrants connected to the pipe. Figure 3(b) shows a plan view of the Ottawa pipe system together with the leak position, and the two hydrants (measurement positions). More information about the Ottawa pipe system can be found in [7]. Table 1 depicts the Ottawa pipe system characteristics, which were also used to carry out the simulations.

As mentioned above, leak noise was generated in the Blithfield pipe system by using a stand-pipe connected to the hydrant as shown in Fig. 4a(i). At the end of the stand-pipe a pressure gauge and a small valve were connected. The small (secondary) valve was used to control the size of the leak and hence the level of leak noise, which was measured using accelerometers attached to the valves at points P1 and P2. One of these points is shown in Fig. 4a(ii). In the Ottawa pipe system, the leak was caused by a crack in the pipe which is shown in Fig. 4b(i). Hydrophones were used as sensors in this case, and were attached to hydrants either side of the leak. One of the hydrants is shown in Fig. 4b(ii). The corresponding results for accelerometer measured data are shown in Fig. 2.

3.2 Data collection

The time duration of the leak noise signals acquired in the Blithfield and Ottawa pipe systems were 60 seconds and 66 seconds, respectively, with corresponding sampling frequencies of 5 kHz and 500 Hz respectively. A Hanning window was used with 50% overlap for the determination of the coherence and CSD functions. For convenience, the frequency resolution of the spectra presented is 1 Hz. The graphs corresponding to those shown in Fig. 2 are plotted for accelerometer data from the Blithfield pipe rig in Figs. 5a(i-iv) and for hydrophone data from the Ottawa pipe rig in Figs. 5b(i-iv). The bandwidths for analysis (19 Hz - 166 Hz and 6 Hz - 94 Hz respectively) were chosen in each case by considering a coherence threshold of 10^{-3} as discussed in the previous section. The modulus of the CSD for the Blithfield pipe rig was normalized by its maximum value located within the limits of the bandwidth used for the analysis, and the modulus of the CSD for the Ottawa pipe rig was normalized by the amplitude of the first resonance peak at about 55 Hz.

3.3 Data analysis

One striking difference between the data shown in Fig. 2 and Fig. 5, is that in addition to the monotonic decay in the phase, there are significant deviations in the phase at low frequencies, which are due to acoustic reflections as discussed in [19]; there are also additional phase shift(s) at higher frequencies. These additional phase shifts, which are indicated in Figs. 5a(ii) and b(ii), are present in leak data from many water pipe systems, and thus should be considered when deciding how to interpret the cross-correlation function. In the Blithfield pipe, there is a single additional phase shift at about 88 Hz, and in the Ottawa pipe rig there are two additional phase shifts occurring at about 55 Hz and 79 Hz.

Figures 5a(iv) and 5b(iv) indicate that the additional phase shift(s) can have a pronounced effect on the cross-correlation functions. Specifically, it is found that in both test-rigs the PHAT correlator is greatly affected by the presence of resonances in the pipe system, but not the BCC. The time delay estimates for the Blithfield pipe system are 22.8 ms and 24.4 ms, for the BCC and PHAT functions respectively (about a 6% difference), and for the Ottawa pipe system they are 94 ms and 11.2 ms for the BCC and PHAT functions, (an 11% difference), respectively.

4. Possible causes of the additional phase shifts

From the results shown in the previous section, it is clear that the additional phase shifts affect the time delay estimate determined from the peak in the BCC and PHAT functions. It is thought that the additional phase shifts are due to the structural dynamics of the pipe system. In this section, some experimental evidence to support this hypothesis is presented, and in the following section a phenomenological model is derived to give further insight into the effects of the resonances on the cross-correlation function.

4.1 Blithfield test rig

Frequency response measurements were made at three access points on the Blithfield test rig to determine the structural dynamics of the pipe test rig. The measurement positions were P1 and P2 (access points), and at the position where the leak is simulated, as shown in Fig. 3(a). Figure 6(a) shows the general set-up for one of the measurement positions. A Wilcoxon type F4/Z820WA inertial shaker was fitted on the hydrant, and a B&K type 4383 accelerometer was mounted on the valve next to it. The force was measured using a force gauge integrated into the inertial shaker, which was driven by a white noise signal. The signals from the accelerometer and shaker (force gauge) were measured using the DATs acquisition system at a sampling frequency of 5 kHz for one minute.

The measured accelerances at the three positions are shown in Fig. 7. The labels “a”, “b”, and “c” correspond to the measurements at P1, the leak position and P2, respectively, and the labels “i” and “ii” denote the modulus and phase, respectively. Also plotted are simulations obtained using the models described in Appendix A. The model described in the appendix is used to support the hypothesis concerning the resonances in the system, and later, in section 5.1 and 5.2 to investigate how the resonance behaviour affects the time delay estimate. The models were developed based on experimental observations. For example, two peaks observed in the spectra suggests the need for a two-degree-of-freedom system. The model parameters were chosen by curve fitting to the data. Table 2 shows the parameters for the resonators used in the simulations. The characteristics for each pipe rig are depicted in Table 1, as already mentioned in subsection 3.1. To calculate the accelerances, x_3 (shown in Fig. A1) was set to zero, and the system was excited by f_1 (the shaker). For points P1 and P2, which exhibit single-degree-of-freedom behaviour, k_2 was also set to infinity. At the leak position the system behaved as a two-degree-of-freedom system.

Figure 7 shows reasonable agreement between the simulations and the experimental data, in both the modulus and the phase. The predicted natural frequencies are also in the range where the additional phase shifts occur in the leak data, as shown in Fig. 5. This provides strong evidence that these additional phase shifts are due to structural resonances. The reason why that, in some cases, the hydrant behaves as a single-degree-of-freedom system and in another case behaves as a two degree-of-freedom is currently not known, but it is most probably due to the way in which the pipe is connected to the hydrant and how it is attached to the ground. The number of degrees of freedom in the system is therefore likely to vary from case to case. A schematic of a hydrant in the Blithfield test rig is shown in Fig. 6(a). It is probable that the resonance(s) are due to the mass-like behaviour of the valve, which is made from brass and is relatively massive, and interacts with the stiffness-like behaviour of the plastic pipe and the surrounding soil.

4.2 Ottawa test rig

Structural dynamic measurements were not made on the Ottawa test rig, but the reason for the additional phase shifts is also thought to be resonance behaviour. The physical layout of the hydrants is very different to the Blithfield test rig. The pipe is buried very much deeper than at the Blithfield site and there are large risers to which the hydrants are connected. Figures. 8(a) and (b) show photographs of the two risers (measurement positions), where their different lengths can be observed. The instrumentation fitted to the hydrant is shown in Fig. 4b(ii). As mentioned above, the signals from the accelerometers, which sense the vertical motion of the hydrant, do not exhibit resonance effects, as can be seen in Fig. 2. By contrast, the hydrophones, which sense the acoustic pressure in the riser do, as shown in Fig. 5. It is possible that a lateral structural mode of the riser is responsible for a resonance in each of the risers. To support this conjecture, it is observed that lowest resonance frequency occurs in the longer (less stiff) riser and the highest resonance frequency occurs in the shorter (stiffer) riser. The accelerometers do not sense lateral motion and hence do not sense the resonant responses, but the acoustic pressure is influenced by the lateral motion of the riser, and hence is detected by the hydrophones.

5. Model of the pipe systems including resonators and sensors

The previous section has provided evidence to suggest that additional phase shifts are caused by structural resonances in the pipe system coupled to the transducers. These resonance effects can be accounted for in a model for the CSD by incorporating a frequency response function (FRF) of a resonator(s), as shown in Fig. 9. Following Gao et al. [13,20], the model of the CSD is given by

$$S_{z_1 z_2}(\omega) = S_0 E(\omega) D_1^*(\omega) H_1^*(\omega, d_1) H_2(\omega, d_2) D_2(\omega) E(\omega) \quad (3)$$

where * denotes the complex conjugate, $H(\omega, d_n) = e^{-\omega\beta d_n} e^{-i\omega d_n / c}$ for positions n=1, 2 is the FRF of the pipe system between the pressure at the leak position and the measurement positions 1 or 2, in which $c = c_f \Big/ (1+2Ba/Eh)^{\frac{1}{2}}$ is the speed of the wave responsible for leak noise propagation and $\beta = (\eta Ba/Eh) \Big/ \left(c_f \left(1+(2Ba/Eh)\right)^{1/2} \right)$ is the attenuation factor, where c_f and B are the free-field wavespeed and bulk modulus of water respectively; E, a, h and η are the Young's modulus, the mean pipe radius, the pipe-wall thickness, and loss factor of the pipe-wall respectively; S_0 is the PSD of the leak pressure, which is taken to be a constant; D_n is the FRF of the additional resonator(s) at the measurement position used to capture the structural dynamics discussed in the previous section; the FRF for a hydrophone is $E(\omega)=1$ and the FRF for an accelerometer is $E(\omega)=-\omega^2 a^2/(Eh)$. Note that in this model it is assumed that the resonator is weakly coupled to the pipe, i.e., that the resonator has no effect on the pipe vibration.

5.1 Blithfield system

It can be observed in the phase data for the Blithfield pipe system, shown in Fig. 5a(ii), a phase deviation of about 270° from the straight-line behaviour due to the leak noise propagation. To predict this phase shift, the two degrees-of-freedom system described in Appendix A is computed with position x_3 corresponding to position P1 only. The accelerometer is attached to mass m_1 only and therefore f_1 is set to zero. As accelerometers were used in this pipe rig, the FRF for the sensors is given by $E(\omega)=-\omega^2 a^2/(Eh)$ [20]. Table 3 lists the parameters used to obtain a good fit to the experimental data. The simulated results using Eq. (3) are plotted in Fig. 10 (a), together with the experimental results. It can be seen that there is a good fit between the predicted and measured phase data, and a moderate fit with the modulus data.

5.2 Ottawa system

For the Ottawa pipe system, two single-degree-of-freedom resonators, one at each measurement position, are needed to predict the measured phase spectrum. The simulated results using Eq. (3) are plotted in Fig. 10(b), together with the experimental results. Table 3 shows the parameters used to simulate this case. It can be seen that there is a good fit between the predicted and measured results for both the modulus and phase. A phase shift of 180° at frequencies greater than the natural frequency of one resonator is obtained. The second resonator , however, is positioned on the other side of the leak, so that the phase shift is in the opposite sense compared to the first resonator.

5. Effects of resonators on the time delay estimate

To determine the effect of resonances in the pipe systems on time delay estimation, the model described in the previous section is investigated together with Eq. (2) to assess the influence of a different number of resonances. The pipe properties in the Ottawa pipe system are input to the pipe model. Four different situations are studied as shown in Figs. 11c(i-iv). In each case the BCC and PHAT are calculated as shown in Figs. 11a(i-iv) and 11b(i-iv) respectively. The first is a benchmark case where no resonators are present. The second case is where one resonator is present, the third case is where two resonators are present, both on the same side of the leak (as in the Blithfield pipe system). The final case is when there are two resonators present, one on each side of the leak (as in the Ottawa system). Note that it is assumed that the resonator has no effect either on the pipe vibration or the resonator to which it is attached. An ideal band-pass filter (10 Hz – 150 Hz) is applied prior to calculating the cross-correlation functions. Moreover, the cross-correlations functions are adjusted so that the time delay due to the leak is compensated for so that the correct time delay due to leak noise occurs at $\tau - T_0 = 0$.

For the case with no resonators present, it can be seen from Figs. 11a(i) and 11a(ii), that there are advantages in using the PHAT correlator as it sharpens the peak in the cross-correlation function, as discussed in [12]. However, it can also be seen from the remaining plots in Fig. 11, that the BCC is largely insensitive to the effects of the resonators, unlike the PHAT correlators. Thus, in situations when there are system resonances, the PHAT can give an incorrect time delay estimate if the bandwidth is chosen incorrectly. To clearly illustrate this effect an animation (video) is provided for the case shown in Fig. 11c(ii). In this animation, the lower frequency limit of the band-pass filter is set to 10 Hz, and the upper frequency limit is increased systematically to 150 Hz. The effect of this can be seen in the animation on the BCC and the PHAT. It is clear that, in terms of the PHAT, the choice of bandwidth is crucially important to correctly estimate the time delay. If the upper frequency is set below the resonance frequency, then the time delay will be correctly estimated. If it is set above this frequency then this will not be the case.

The reason why the BCC is not affected to the same extent as the PHAT is because the time delay is estimated using the BCC by weighting the data by the modulus of the CSD [21]. The CSD generally decays away rapidly above a resonance frequency, as shown in Figs. 10a(i) and 10b(i), so the data above this frequency has much less influence on the time delay estimate compared to the data below this frequency. To illustrate the three cases with resonators attached shown in Fig. 11, the time delay is estimated using the BCC and PHAT as the bandwidth is increased incrementally from 10 Hz - 20 Hz to 10 Hz - 200 Hz. The results can be seen in Fig. 12. It can be seen that the effect on the PHAT is much more dramatic than for the BCC, with the maximum error of about 5% occurring when there are two resonators attached to the pipe at each side of the leak (see Fig. 12(c)), as in the Canada case.

6. Conclusions

This paper has investigated the way in which resonances in a buried pipe system affect time delay estimation due to a leak calculated using the BCC and PHAT correlation functions. Experimental data from two test rigs has been presented which has shown that resonances can occur in practical systems. It is the phase change associated with the resonance(s) that causes an appreciable error in the time delay estimation calculated using the PHAT. To further investigate this phenomenon, a model of a pipe system, which includes the noise propagation through the pipe, the sensors and resonators, has been developed.

Simulations have been conducted using the model, which have been validated by experimental data, to quantify the effect of the resonances and the bandwidth over which the time delay is estimated. It has been shown that the BCC is relatively insensitive to the system resonances and is a more robust correlator to use for leak detection in plastic pipes. This is because it effectively limits the bandwidth over which the time delay is estimated to frequencies below the lowest resonance frequency. The PHAT correlator, however, is sensitive to additional phase shifts due to a resonance(s), and so extra care should be taken over the choice of bandwidth for this correlator for time delay estimation in plastic water pipes.

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The authors would like to thank South Staffs Water plc for supporting the project, and to FAPESP project number 2013/50412-3 and FEPISA for partial financial support. The authors would also like to thank the National Research Council of Canada for supplying the data from the Ottawa pipe test rig.

APPENDIX A – Lumped parameter model

In this appendix, the models used to (a) predict the measured accelerances given in Section 4, and (b) the resonators used in the pipe model for leak noise, given in Section 5 are described. The models are based on the lumped parameter system shown in Fig. A1. The equation of motion for this system is given by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f} \qquad \text{(A1)}$$

where

$$\mathbf{M} = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1 + c_2 & -c_2 \\ 0 & -c_2 & c_2 \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix}, \quad \mathbf{x} = \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix},$$

$$\mathbf{f} = \begin{Bmatrix} f_1 \\ 0 \\ f_3 \end{Bmatrix}$$

Assuming a harmonic force of the form $f = Fe^{i\omega t}$ and a response $x = Xe^{i\omega t}$ results in

$$\mathbf{x} = \left[\mathbf{K} - \omega^2\mathbf{M} + i\omega\mathbf{C}\right]^{-1}\mathbf{f} \qquad \text{(A2)}$$

A1 Measured accelerances on the Blithfield test rig

To determine the point accelerance for a single-degree-of-freedom system, as is observed for points P1 and P2, k_2 can be set to infinity and x_3 is set to zero in Eq. (A2). The point accelerance is then given by $\ddot{X}/F_1$ where $\ddot{X} = -\omega^2 X$. To determine the point accelerance for the two-degrees-of-freedom system, as observed for the leak position, x_3 is simply set to zero in Eq. (A2). The system parameters for the single-degree-of-freedom system and for the two-degree-of-freedom are given in Table 2 located in section 4.1.

A2 Resonators for the leak noise model

When the lumped parameter system is used to model a resonator, it is attached to pipe at position x_3, and f_1 is set to zero. For the two degrees-of-freedom system used for the Blithfield test rig, the FRF is given by $D(\omega) = X_1/X_3$, and the system parameters are given in Table 3 located in section 5.1. For the Ottawa test rig, the resonators are two single-degree-of-freedom systems. To achieve a single-degree-of-freedom system k_2 is again set to infinity (or can also be achieved by setting m_1 to zero) and $D(\omega) = X_1/X_3$ is calculated. the system parameters are given in Table 3 located in section 5.1.

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Figure(s)

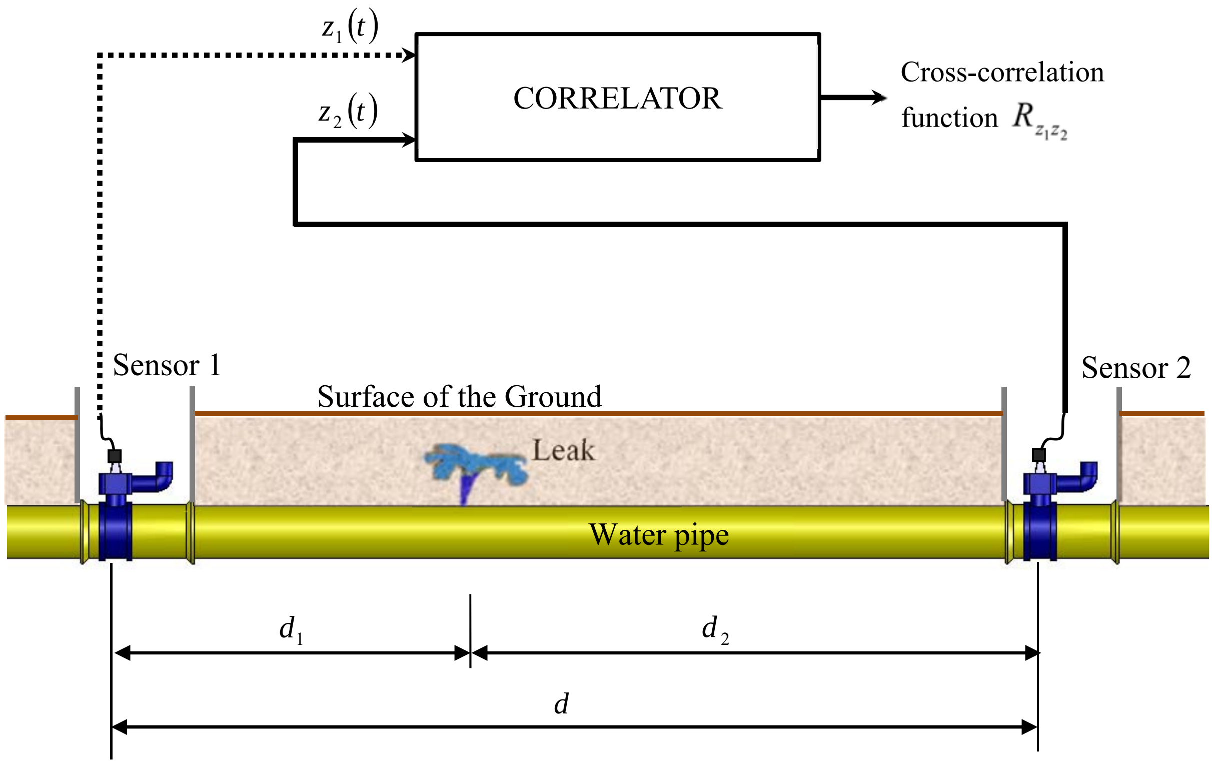


Figure 1 - Schematic of leak detection in a buried water pipe using acoustic/vibration signals with a leak bracketed by two sensors.

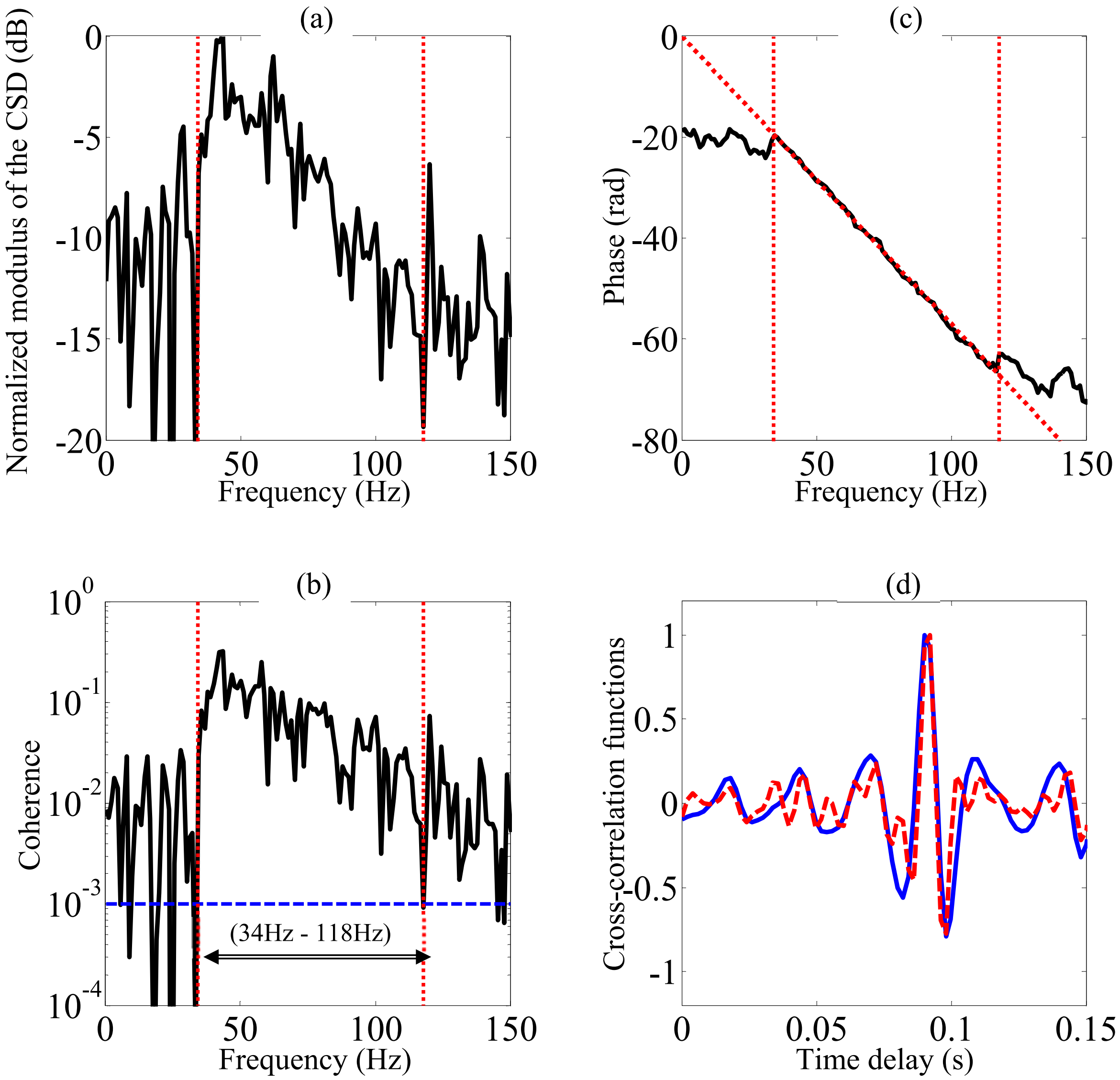
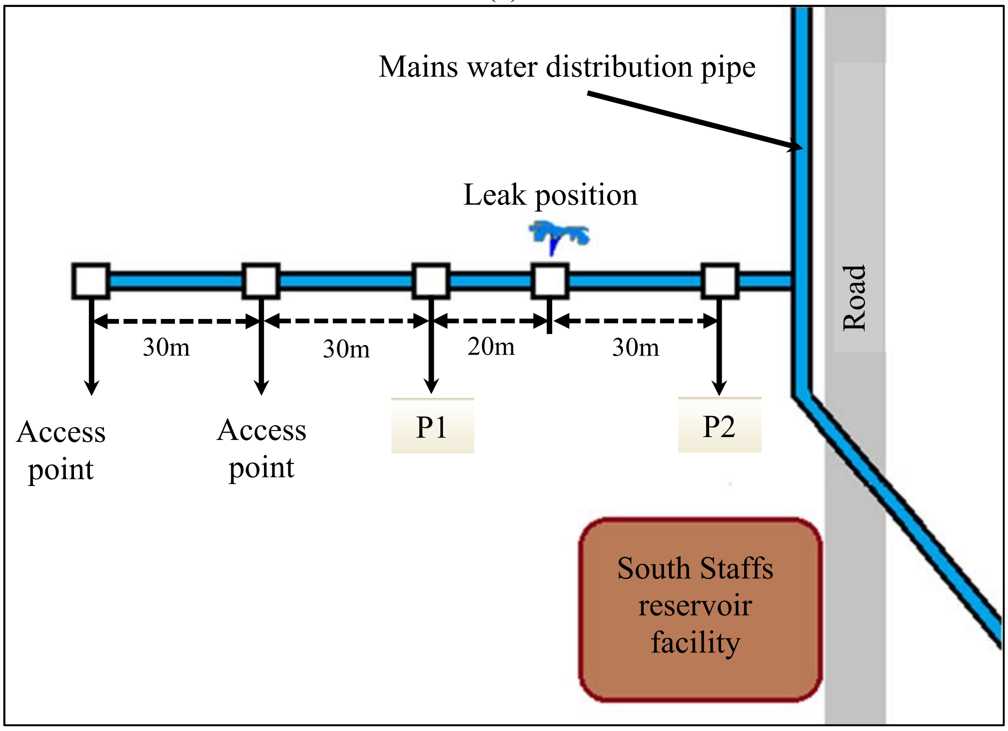


Figure 2 – A typical leak signal in the frequency and time domains measured using accelerometers. (a) Normalized modulus of the CSD with respect to its maximum value; (b) Coherence; (c) Phase of the CSD; (d) Cross-correlation functions — BCC;- ----- PHAT.

(a)



(b)

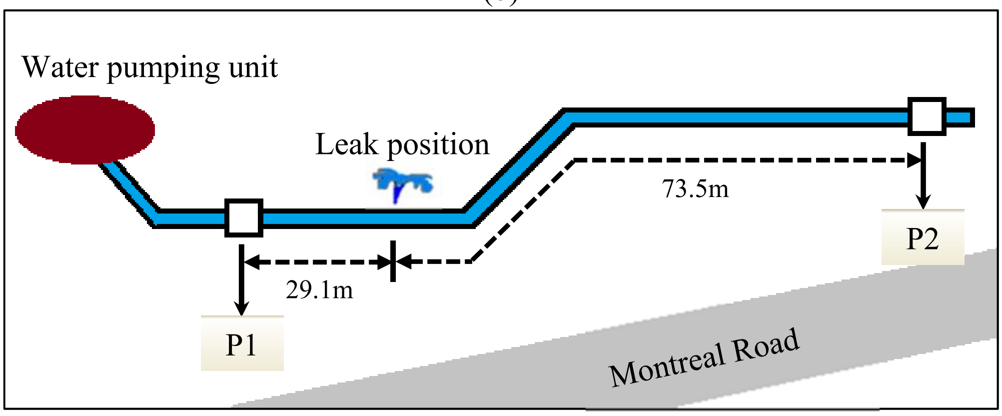


Figure 3 – Schematic of the pipe systems used to simulate leaks under controlled conditions. The drawings are not to scale. (a) The Blithfield system. (b) The Ottawa system. The access points where the measurements were taken are given by P1 and P2.

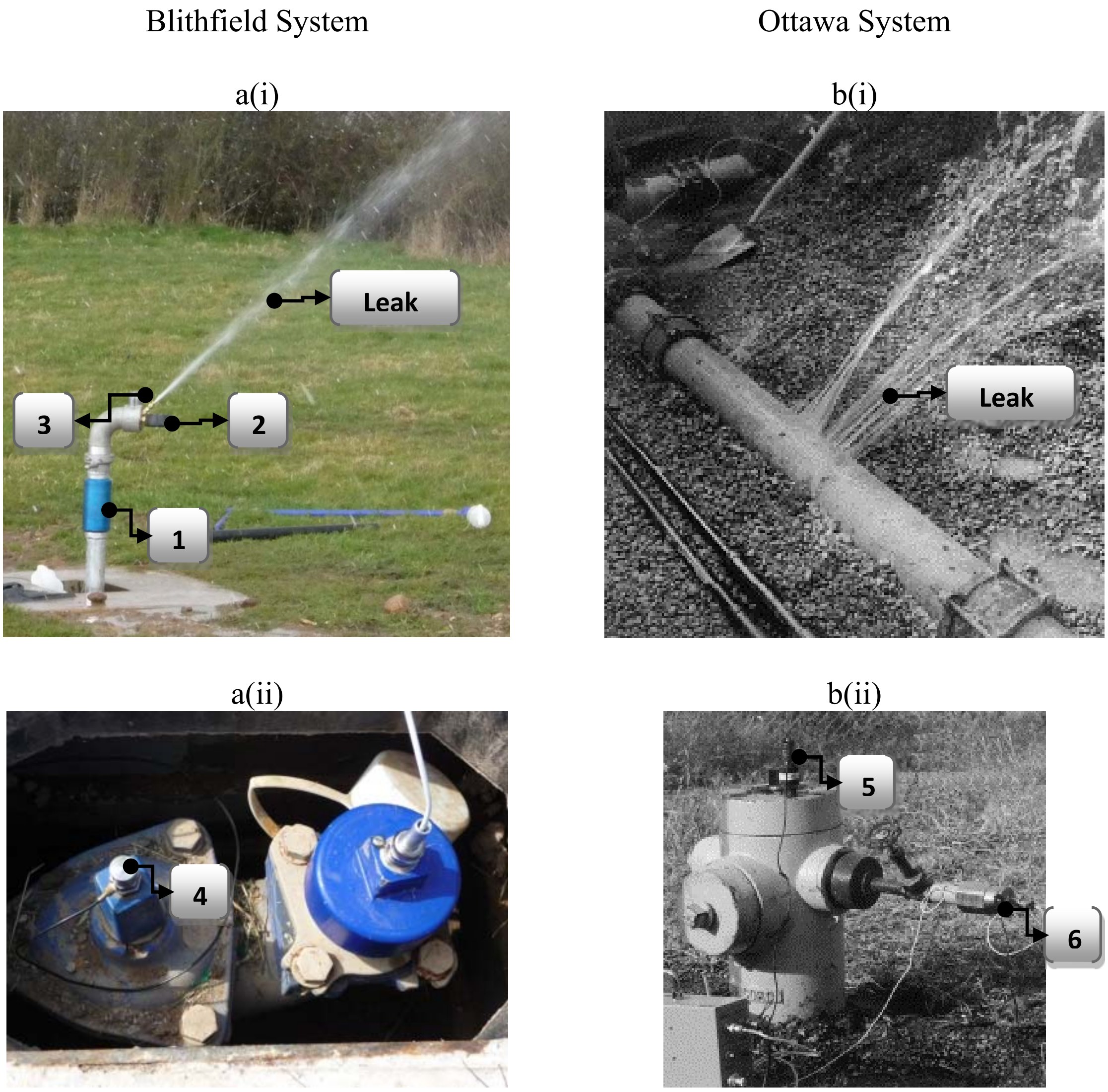


Figure 4 - Photographs showing how the leaks were generated and measured. a(i) Leak generation in the Blithfield system; a(ii) Accelerometer attached to the valve in the Blithfield system to measure the leak; b(i) Leak generation in the Ottawa system [7]; b(ii) Hydrophone attached to the hydrant to measure the leak noise in the Ottawa system [7]. (1) Stand pipe; (2) Pressure gauge; (3) Secondary valve; (4) Accelerometer; (5) Accelerometer; and (6) hydrophone.

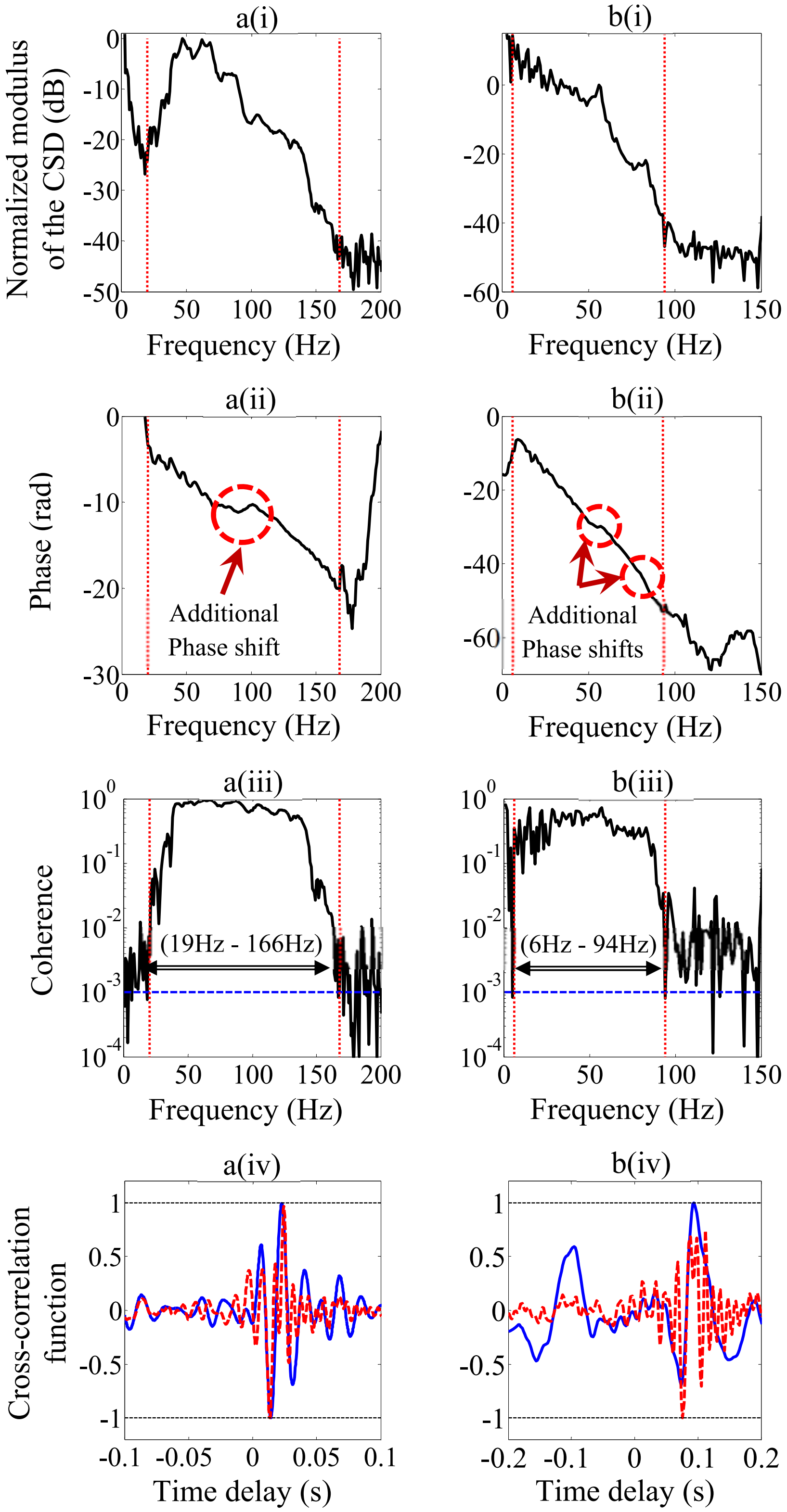
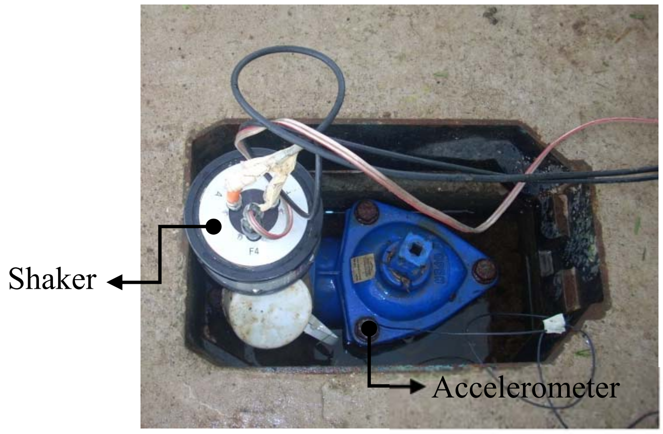


Figure 5 – Leak noise signals. (a) Acceleration-measured signals acquired in the Blithfield pipe system. (b) Acoustic pressure-measured signals acquired in the Ottawa pipe system. Subplots (i), (ii), (iii) and (iv) are the normalized modulus of the CSD, phase of the CSD, coherence and the cross-correlation functions, respectively. The modulus of the CSD for the acceleration signals is normalized by its maximum value and the modulus of the CSD for the hydrophone signals is normalized by the peak located at about 55 Hz.

(a)



(b)

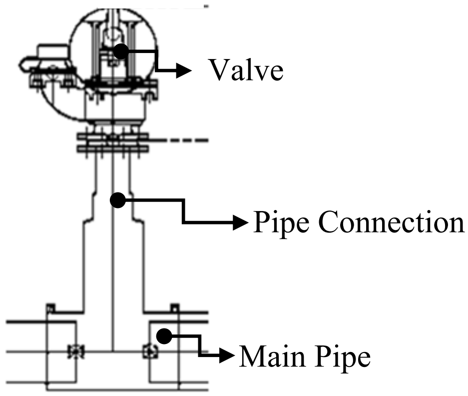


Figure 6 – One of the access points where the accelerance was measured (a) Photograph of one showing the position of the shaker and the accelerometer. (b) schematic showing the arrangement of the hydrant (access point).

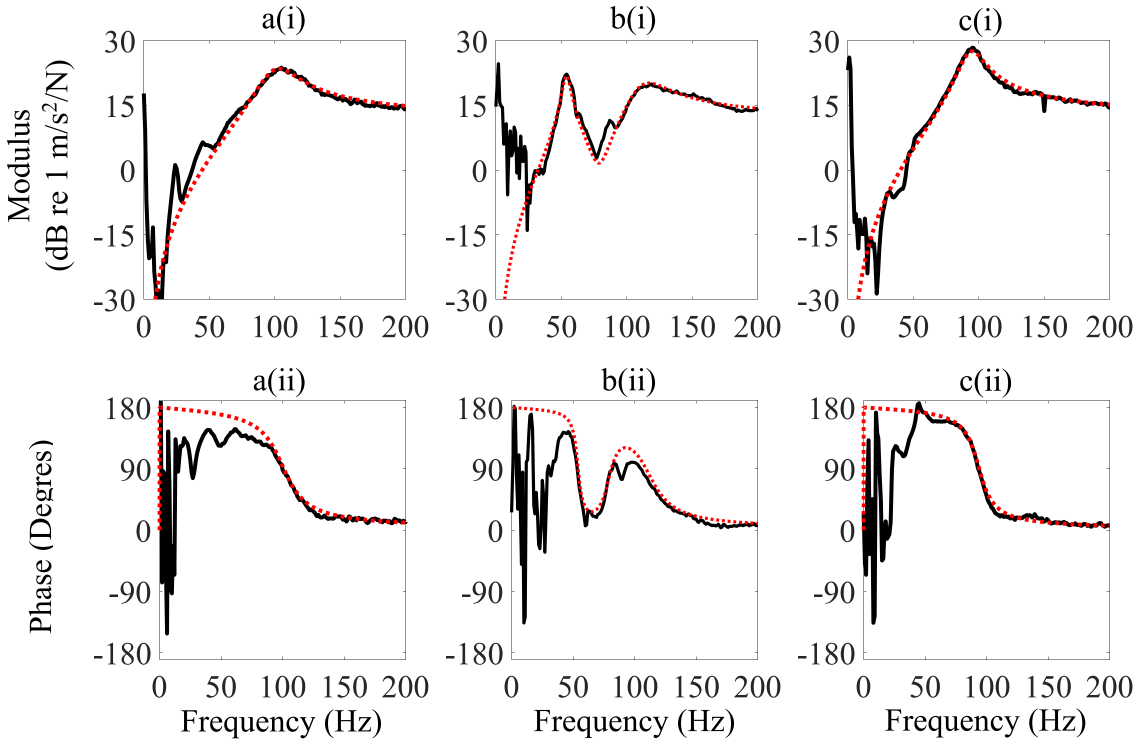


Figure 7 – The accelerances measured at three access points. The labels (i) and (ii) denote the modulus and phase, respectively. (a) Point P1. (b) Leak position. (c) P2. ━ measurement; ······ simulations.

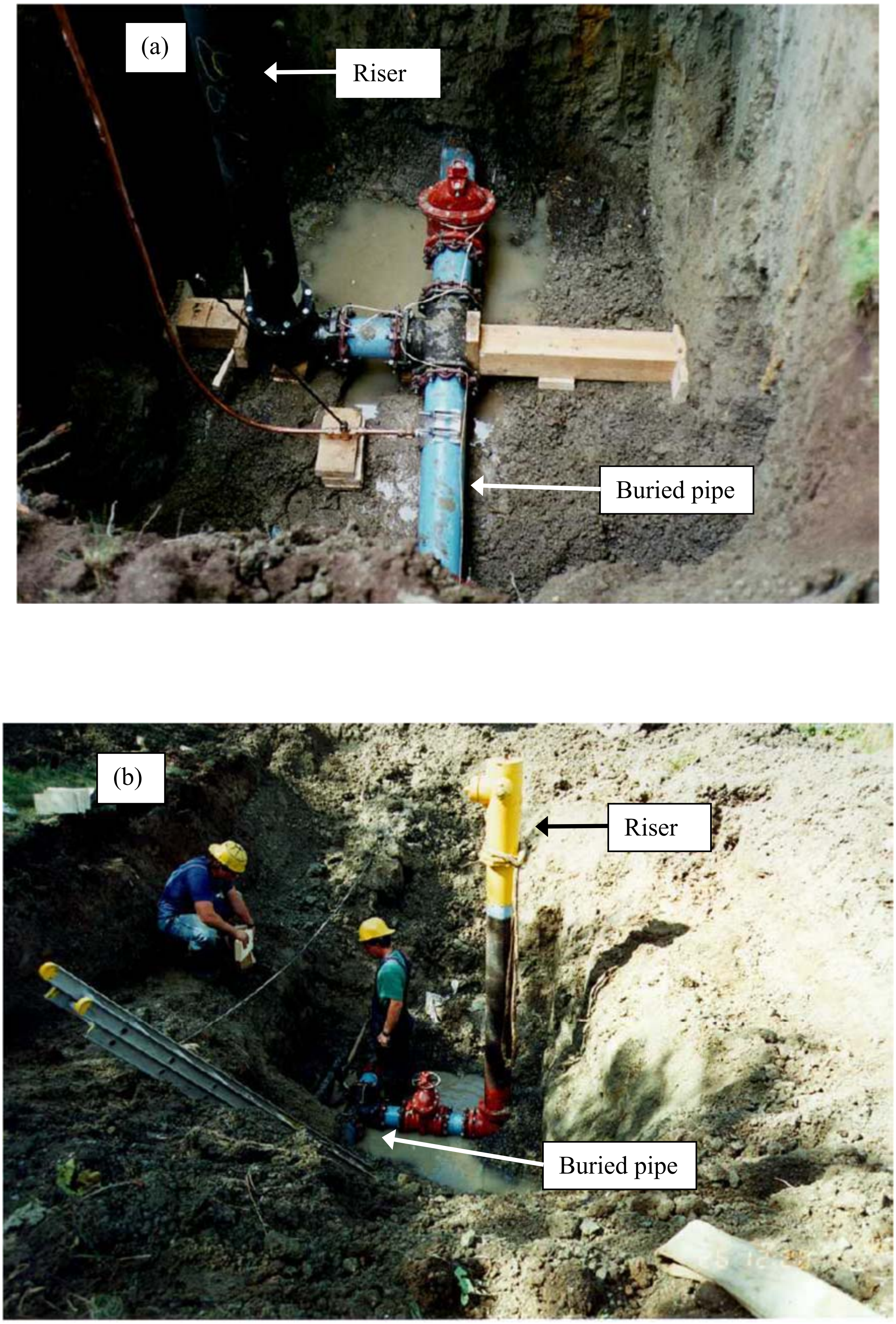


Figure 8. Arrangements for the hydrants of the Ottawa site before reinstatement [3]. (a) upstream, and (b) downstream.

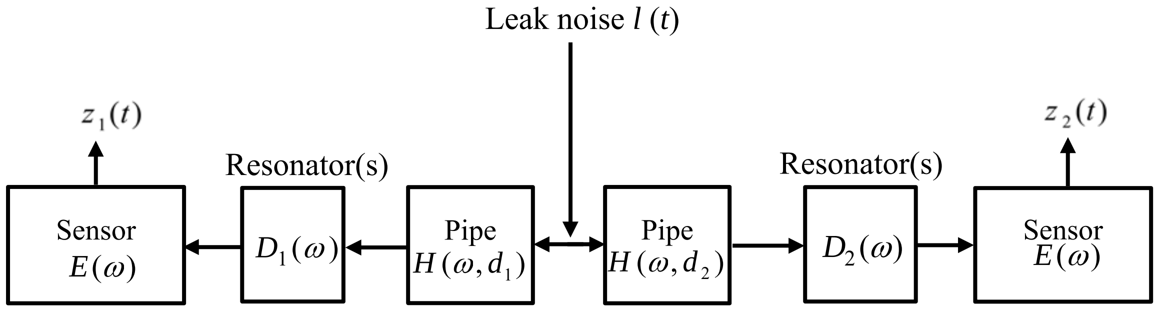


Figure 9 – Model of the pipe including resonators and sensors.

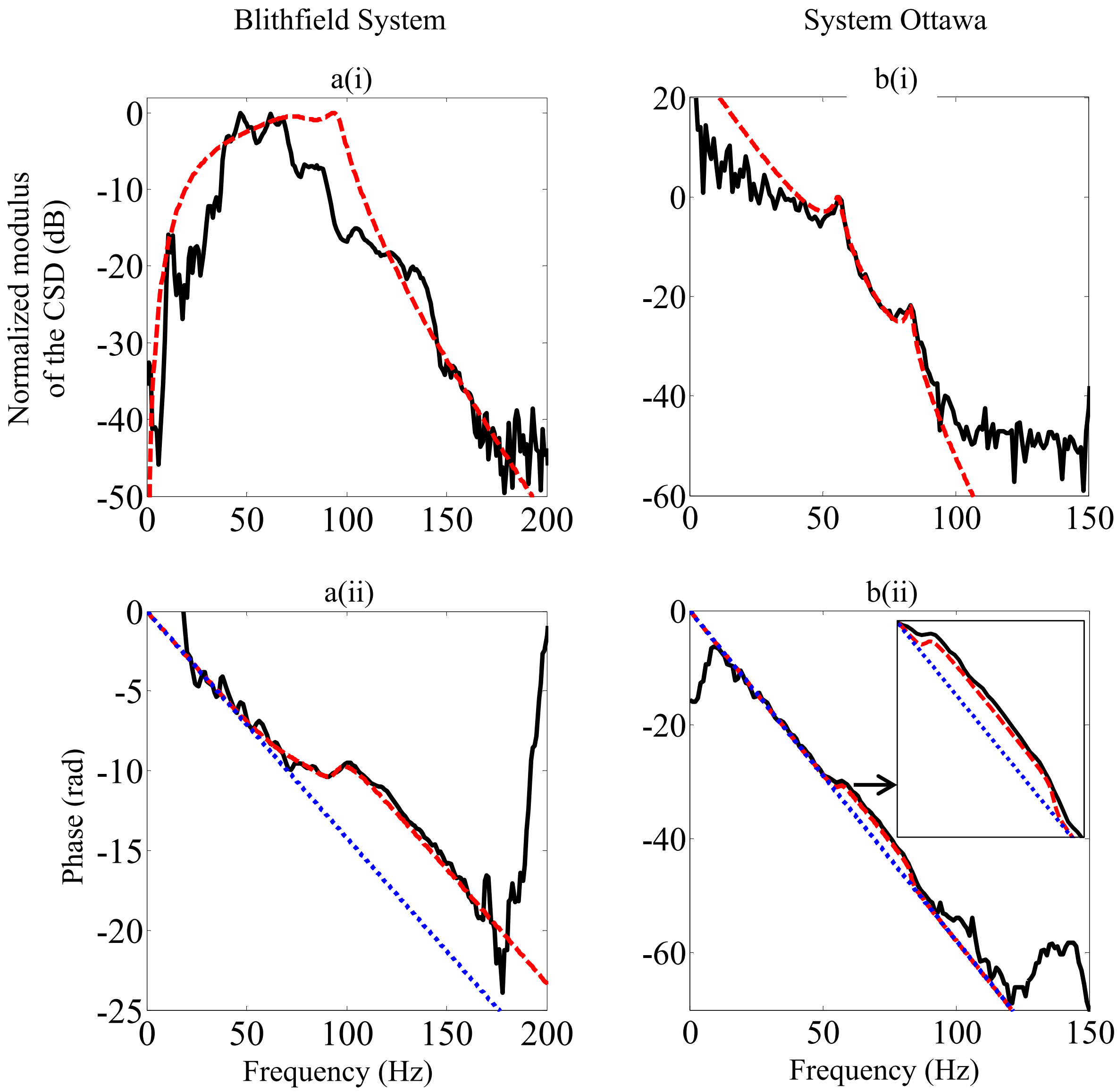


Figure 10 - Comparison between the actual data and simulations using the phenomenological model. The label (ii) and (ii) stands for the normalized modulus of the CSD and its unwrapped phase, respectively. These are the same cases shown in Fig.5. (a) Data acquired in the Blithfield pipe system. (b) Data acquired in the Ottawa pipe system. — actual leak data; ····· simulated phase with no resonator attached to the pipe ; – – simulated phase with resonators attached to the pipe.

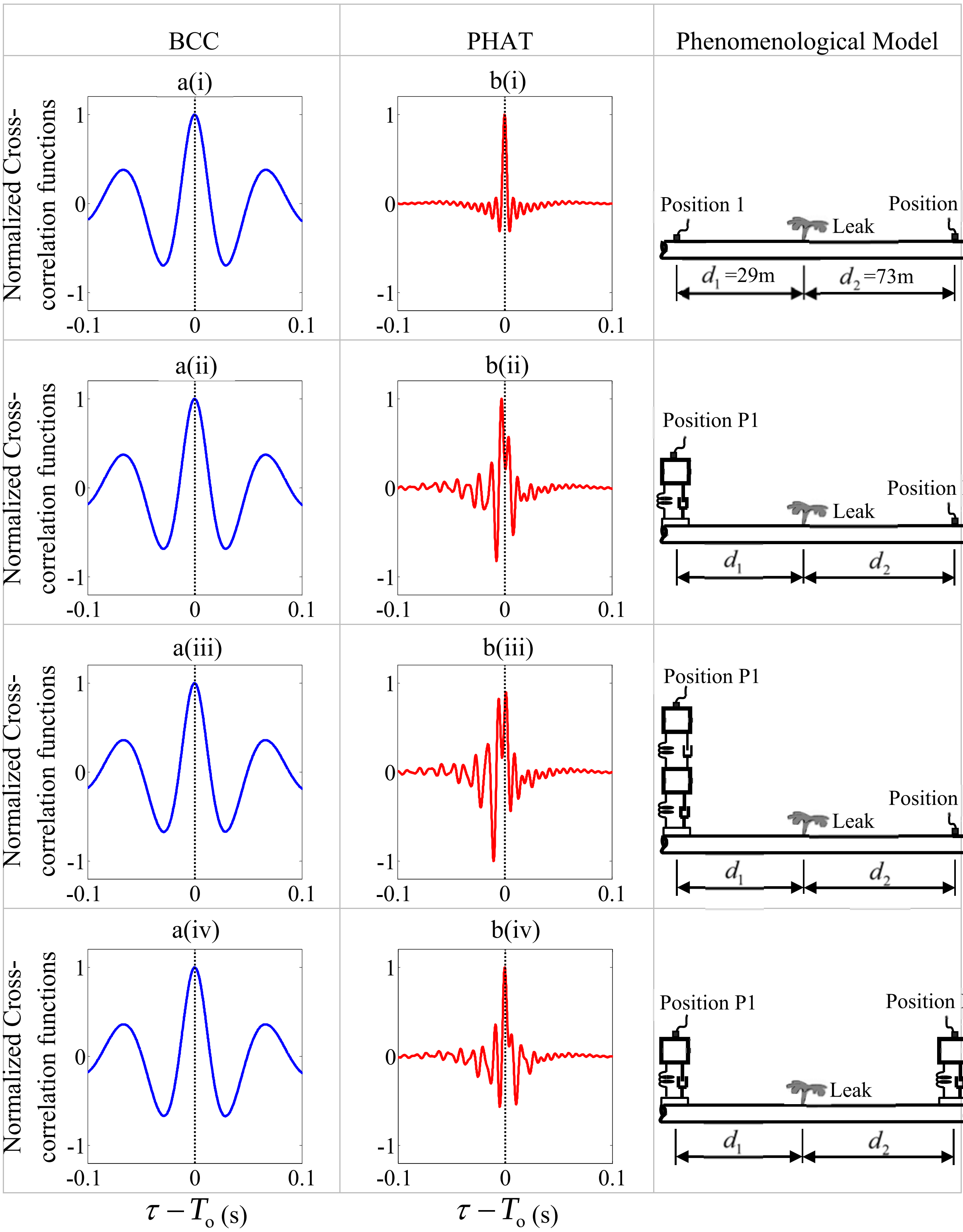


Figure 11. The effects of additional dynamics on the shape of the simulated BCC and PHAT correlators. The cross-correlation functions are normalized to their maximum value. A band-pass filter was used, which lower and upper limits set at 10Hz and 150Hz, respectively. The labels (i), (ii), (iii) and (iv) stand for the cases with no resonator, one resonator, two resonators in series being one resonator highly damped and the other resonator lightly damped, and two resonators at each measurement position attached to the pipe, respectively. (a) BCC (b) PHAT.

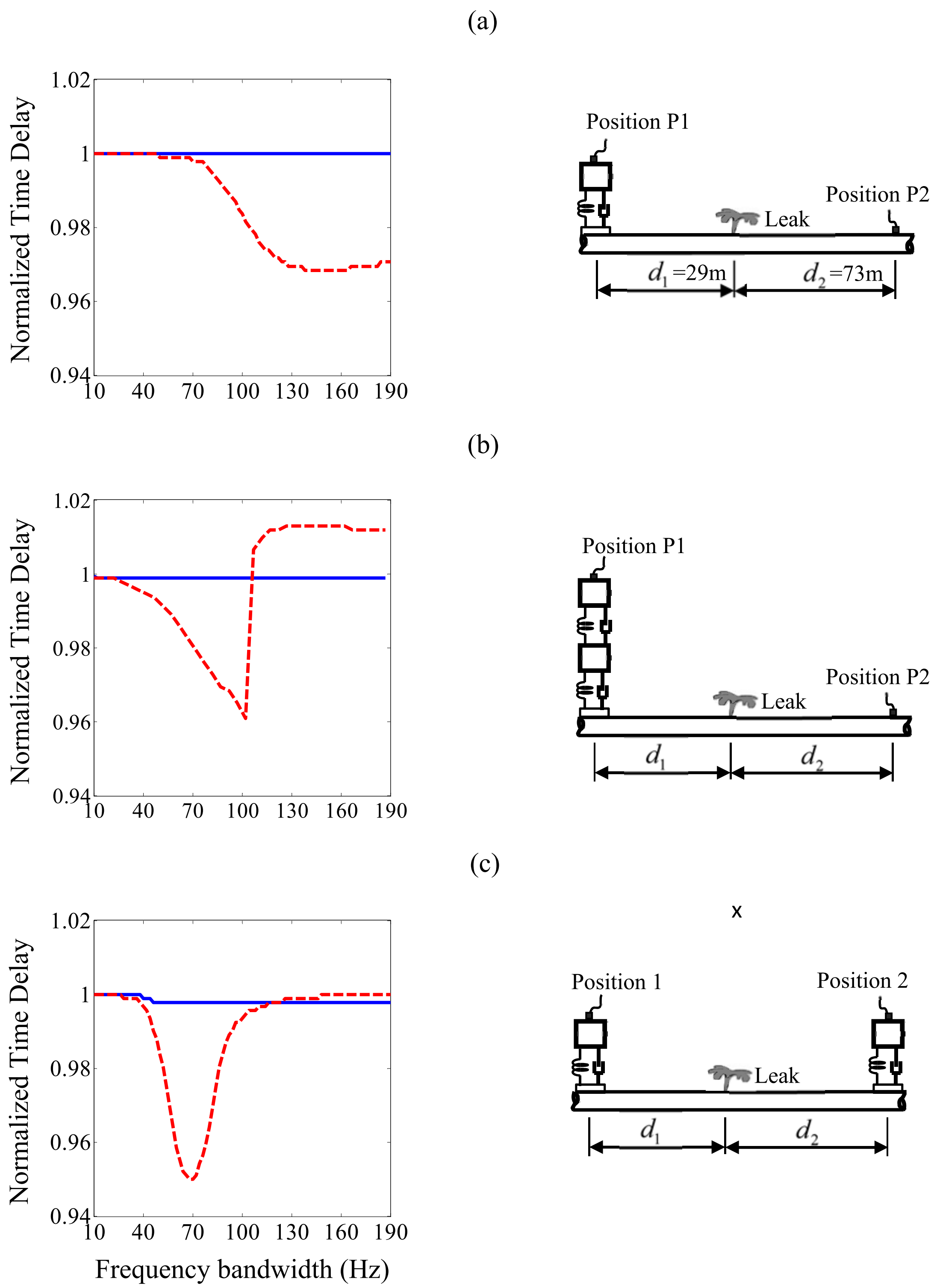


Figure 12 – The normalized time delay estimate given by the peak in the BCC and PHAT correlation functions as a function of the bandwidth. The time delay is normalized with respect to the actual time delay, which is known in the simulation. The lower limit of the band-pass filter is fixed at 10 Hz while the upper limit increases from 20 Hz to 200 Hz. (a) One resonator attached to the pipe. (b) Two resonators in series attached to the pipe. (c) Two resonators attached to the pipe, one each side of the leak. — BCC; ----- PHAT.

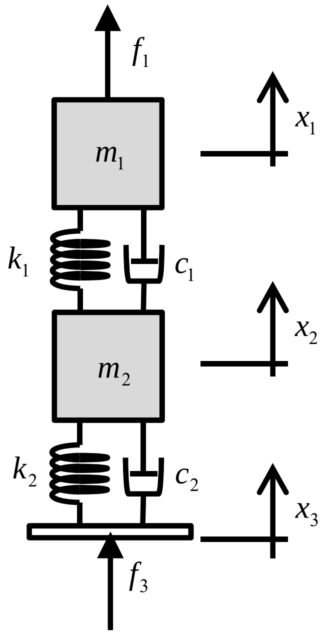


Figure A1 – Lumped parameter model used for the accelerance of the access points in the Blithfield test rig, and for the resonators in the pipe leak-noise model.

Table(s)

Pipe system	Blithfield	Ottawa
d_1 (m)	20	29
d_2 (m)	30	73
Outer radius (mm)	80	75
Wall Thickness (mm)	9.85	9.85
Young Modulus of the pipe(Nm^{-2})	2×10^{9}	2×10^{9}
Bulk modulus of the water (Nm^{-2})	2.2×10^{9}	2.2×10^{9}
Attenuation factor (sm^{-1})	2.9×10^{-4}	1.99×10^{-4}
Loss factor	0.19	0.22

Table 1 – Blithfield and Ottawa pipe system characteristics used to carry out the simulations

Parameters	Position 1	Leak position	Position 2
m_1 (kg)	0.22	1	0.24
m_2 (kg)	-	0.25	-
k_1 (Nm^{-1})	0.77×10^{5}	1.56×10^{5}	0.96×10^{5}
k_2 (Nm^{-1})	∞	0.91×10^{5}	∞
c_1 (Nsm^{-1})	25	51.5	43
c_2 (Nsm^{-1})	-	36.2	-
x_3 (m)	0	0	0
f_1 (N)	1	1	1
f_3 (N)	-	-	-

Table 2 – Parameters used to simulate the FRF using the two-degree of freedom for the model of resonances

Parameters	Position 1		Position 2	
	Blithfield	**Ottawa**	**Blithfield**	**Ottawa**
m_1 **(kg)**	-	1	1	1
m_2 **(kg)**	-	-	5×10^{-4}	-
k_1 **(Nm^{-1})**	-	1.26×10^5	2.4×10^5	2.72×10^5
k_2 **(Nm^{-1})**	-	∞	1.82×10^2	∞
c_1 **(Nsm^{-1})**	-	14.2	147	9.4
c_2 **(Nsm^{-1})**	-	-	0.02	-
f_1 **(N)**	-	0	0	0
f_3 **(N)**	-	-	-	-

Table 3 – Parameters used to simulate the resonances for the leak model

Letter to the editor
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animation of how ressonances affect the BCC and PHAT correlation - jsv_animation_res.mp4

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The effects of resonances on time delay estimation for water leak detection in plastic pipes

By Fabrício Almeida, Michael Brennan , Phillip Joseph , Gao Yan, Amarildo Paschoalini.

Manuscript ID: JSV-D-15-01274

The authors would like to thank the reviewers for their helpful comments, specially reviewer one who gave important notes on this paper. We have attended to all the comments from reviewer 1; we have either changed/inserted text or have clearly stated why we have chosen not to make the changes suggested. We are at odds with reviewer 2, but have given a detailed response to his comments.

Our detailed responses are given below. We have also taken the opportunity to make some minor changes to the English in places where there was room for improvement. We believe that we have addressed all the points raised and also have provided evidence of the presence of structural resonances in pipe systems, which may affect some algorithms used to perform correlation functions. We hope that it is now acceptable for publication.

Rebuttal

Reviewers' comments:

Reviewer #1: *The study investigates the effects of resonances on common cross-correlation-based methods for pinpointing burst leaks in water supply networks. Numerical models including additional resonances are developed and validated with experimental data. Simulations are then performed for primarily assessing the effects on time delay estimation generated by variations in the filter bandwidth, in presence of such resonances.*

The study provides valuable results for practical applications concerning leak pinpointing. Interesting information on the possible nature of vibro-acoustic signals generated by water leaks (a topic frequently disregarded by works dealing with leak detection) are reported as well.

Since the physical nature the resonances is not identified and only two sets of experimental data are taken into account, the study may partially lack of generality. However the paper may be suitable for publication after addressing the following questions and comments.

The authors welcome the supportive comments from the reviewer. We acknowledge the deficiency noted by the reviewer concerning the physical nature of the resonances. This is a particularly difficult problem and is hard to generalise, because of the nature of the system. It is a buried water-filled plastic pipe to which several fittings are connected. It is likely that the structural dynamics will vary from each of the access points on a single pipe system. It is also probable that there will be differences from system to system. In the paper it is accepted that the structural dynamics (specifically resonances) could have adverse effects on the determination of the location of a leak using acoustic correlation. These effects are demonstrated on two test rigs and then a model is developed to determine the sensitivity of two commonly used correlators to resonance effects. To address the specific concerns of the reviewer concerning the physical nature of the resonances, the authors have included some measurements on the Blithfield test rig, which are then compared to a simple model. This is contained in a new section 4 in the paper. Concerning the Ottawa test rig, the physical nature of the resonances is suggested, by comparing accelerometer and hydrophone data. To describe this additional work three new figures (Figs 6-8), one table (Table 2) and an appendix have been included.

Main remarks

I) Resonances are assumed as the probable cause of the phase shifts observed in the analyzed experimental data. The hypothesis is supported by the implemented numerical models, which replicate quite well the observed phenomena. However, the physical source of these resonances is not clearly identified, as stated by the authors in Sections 4. Assessing the resonances of the test rigs at the measuring points (e.g. by performing

Experimental Modal Analysis) should permit to check rather straightforwardly the validity of the assumptions. Such verification would significantly increase the generality and the relevance of the study. If such verification cannot be performed, the authors should provide and discuss a physical interpretation of the resonances, based on the experimental setup. In particular the authors should discuss the behavior of the accelerometers installed in the Ottawa pipe (on the same hydrants of the hydrophones), whose measurements are reported as example in Section 2, which results completely unaffected by the supposed resonances. In addition, both the Abstract ("The objective of this paper [..] buried pipe systems.") and the Conclusions ("Experimental data from two test rigs has been presented which has shown that resonances can occur in practical systems.") apparently assume resonances to be already identified as the sources of phase shifts, which is not completely true, unless further experimental verifications are performed. Hence, depending on the modifications of the other sections possibly carried out by the authors, they may require to be updated.

It is believed that the authors have addressed these points in the revised manuscript- see comments above.

II) In Section 4, two distinct models (one for the Ottawa and one for the Blithfield pipe systems respectively) are developed and validated, for supporting the hypothesis of resonances possibly causing phase shifts. However, apparently, simulations reported in Section 5 are not directly performed on the validated models (except for the model in Fig. 4c(iv)), the values of the validated models (natural frequencies and damping) being only taken as references for setting the model parameters. Exploring different situations through simulations may indeed result interesting and profitable. In such an instance, varying the parameters of the resonators (other than the filter bandwidth) may provide valuable results as well. I strongly encourage the authors to expand this section with new simulations for taking into account at least the variation of the natural frequencies of the resonators (within a reasonable range), which is likely to occur in different pipe systems (as confirmed by the remarkable differences between the Ottawa and the Blithfield parameters). In any case, Section 5 should be reorganized for providing a clearer description of models and simulation conditions, results obtained from simulations and related discussion. Using subsection may be advisable.

It is hoped that the authors have now presented sufficient evidence to support the physical nature of the resonances. It is clear that, regardless of the nature of the resonant behaviour – see for example the two situations presented, then if a resonance occurs in the bandwidth over which the analysis is conducted, then this will be problematic for the PHAT correlator. The BCC correlator is not affected in the same way because of the reasons given in the paper. Given the clarity of the physical nature of the system, the authors believe that Section 4 and 5 present sufficient evidence in the way in which a resonance affects time delay estimation, at least for buried plastic water pipes. The authors do not think that additional simulations would add any new insight into the problem.

Minor remarks

a) A more concise abstract would emphasize the achievements of the paper. The abstract may focus on the activities performed within the presented study, whereas most of the details concerning problems related to detection and location of water leaks in plastic pipes can be provided in Section 1.

The abstract has been shortened significantly and is now more focussed

b) Section 1 may introduce more rigorously the topic of leak detection in water supply networks. In particular, a clearer distinction between leak detection (getting aware of the presence of leaks) and location (i.e. leak pinpointing, which is the primary aim of this study) should be provided. Moreover, further methods investigated and successfully tested on experimental facilities and/or real pipes for detecting and/or locating water leaks (other than cross-correlation, which is for sure the most widespread technique adopted for leak location in practical applications) may deserve a mention. As for techniques based on vibro-acoustic signals only, the following works may be added to the references as examples:

[1] W. Li, W. Ling, S. Liu, J. Zhao, R. Liu, Q. Chen, Z. Qiang, and J. Qu, Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: a case study, Journal of Environmental Sciences 23(11) (2011), 1816-1822.
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[5] M.F. Ghazali, S.B.M. Beck, J.D. Shucksmith, J.B. Boxall, and W.J. Staszewski, Comparative study of instantaneous frequency based methods for leak detection in pipeline networks, Mechanical Systems and Signal Processing 29 (2012) 187-200.

The introduction has undergone significant change. There are many references to methods of leak detection. Rather than cite many papers and hence lengthen the introduction disproportionally, the authors have cited three review papers [4,5,6], which provide the background described by the reviewer.

b.1) Since cross-correlation methods can generally operate on signals from both accelerometers and hydrophones (this study itself takes into account both) the expression "vibro-acoustic" instead of "acoustic" would be more rigorous.

The authors accept the point made by the reviewer. However, the water industry uses the word “acoustic” rather than “vibro-acoustc” and so the authors prefer to retain the word “acoustic” so as not to confuse the industry professionals.

c) Section 2 specifically describes the use of cross-correlation for leak location. I suggest to change the first sentence ("In this section an overview [..] water distribution pipes is presented") in "This section describes the use of cross-correlation of vibration and acoustic signals as a tool for leak location in water distribution pipes". The section heading should be updated accordingly.

This has been changed as suggested.

c.1) Equations 3a,b; 4a,b. As far as I know, equations should be numbered consecutively, without sub-indexation.

These equations have been removed in the amended manuscript.

d) Section 3 includes a large amount of information (experimental setup, test procedure, results, discussion). Using subsections (e.g. 3.1 Setup; 3.2 Analysis; 3.3 Discussion; etc.) may result in a clearer exposition.

This has been subdivided into subsections as suggested.

d.1) The effectiveness of using two distinct sub-indexes in subplots (from the clarity point of view) may result questionable. The authors may consider using only one sub index in all figures throughout the paper and/or splitting the figures. In any case, using two sub-indexes in Figure 4 does not appear strictly required for clarity purpose. The use of more concise captions would be advisable as well (also in the other figures).

The authors have retained the sub-indices as it is felt that they are more appropriate for the two pipe systems considered. The captions have been shortened in the cases where the authors think it is beneficial.

e) Section 4, 1st sentence: "To further investigate [..] a phenomenological model of the pipe system together with the frequency responses of the sensor used to measure leak noise is proposed." The FRF of a sensor that is used within its proper range of measurement should not affect signals. Reasonably the FRF between source and measuring point depends on the quantity that is being monitored (pressure vs. acceleration), but is not affected by the sensor itself. Please, clarify.

The reviewer is correct. The term FRF is used to describe the relationship between the pressure in the pipe and the output. For example, for the hydrophone it is pressure/pressure, which is unity, and for the accelerometer the input is pressure and the output is acceleration. It is assumed that there are no sensor dynamics involved.

f) Section 5 may be expanded with further simulations, as discussed at point (II) *f.1) "To clearly illustrate this effect an animation is provided [..] in the animation on the BCC and the PHAT." Since supplementary (optional) material only available online is not visible in the printed article, probably referring such material in this way is not advisable. I suggest moving this sentence to a footnote, and explicitly declaring that the animation will be available for download as supplementary material.*

It is believed that the reference to the supplementary material is now clear. As mentioned previously, the authors believe that the simulations presented cover the cases that are likely to be encountered in practice.

f.2) "It is clear that, in terms of the PHAT, the choice of bandwidth is crucially important to correctly estimate the time delay. If the upper frequency is set below the resonance frequency, then the time delay will be correctly estimated. If it is set above this frequency then this will not be the case.". This statement apparently conflicts with the results shown in Fig. 9, where time delay estimation by using PHAT is never correct for both case (a) and case (b). Please reformulate or add some clarifications.

The authors accept the point that the sentence above follows on from the animation. The authors have changed the sentence to read……”. To clearly illustrate this effect an animation (video) is provided....” so that the reader will not be confused as to how this conclusion is reached.

f.3) "It can be seen that the effect on the PHAT is much more dramatic than for the BCC, with the maximum error of about 5% occurring when there are two resonators attached to the pipe on one side of the leak (as in the Blithfield case)." Doesn't the maximum error occur in case (c), i.e. the configuration with one resonator on each side?

The reviewer is correct. This was a typo and has been corrected.

g) Please check typos and grammar throughout the manuscript (and in the keywords as well).

Mm m

Some typos were found and amended.

Reviewer #2: *This work is one in series on leak detection in pipes by the same core authors. It shows similarities with the preceding papers without bringing any new major result.*

This paper discussed the way in which the dynamics of the access points can affect the time delay estimates calculated using correlation. To the authors knowledge this has never been reported in the literature.

The leak detection method analysed is a simple correlation technique as used in some commercially available detectors. The focus of the manuscript is on the effect of resonances in the piping system on the leak detection performance. This is done by looking at the slope of the CSD function phase which should be proportional to frequency in the case of reflections-free propagation, i.e. in the case of an ideal delay line. As reflections from the discontinuities lead to resonances, the phase exhibits jumps which is turn affect the cross-correlation function. In order to analyse the phenomenon the authors use a model of delay line with fictitious SDOF resonators added to simulate the resonances. By adjusting the resonator parameters the model is shown to produce phase effects on the correlation function in tune with the observations.

The reviewer’s summary is a fair representation of the paper.

This reviewer has not managed to understand clearly the purpose of the analysis done in the manuscript. The sound propagation in pipes is a well known subject and the (large) number of already published papers on leak detection by correlating pipe waves has covered the subject to a depth - by often repeating some of the findings. Curiously enough the authors do not mention an earlier JSV paper by the same main authors aimed at the same topic: analysis of effects of reflections on correlation function: JSV 325, 649-663, 2009. The model used in that paper, based on repeated reflections, is much more physical than the "ad hoc" one used in the present manuscript. Besides, the former paper provides conclusions about how to improve correlation readings which is not the case with the present work.

The authors believe that the reviewer has confused the effects due to reflections and the effects due to structural dynamics. This is probably our fault because we did not make this sufficiently clear in the original manuscript. We have hopefully clarified this in the revised manuscript and have cited the JSV paper [19] that the reviewer mentions. In short, the reflections are an acoustic phenomenon that results in additional deviations from straight-line phase behaviour at low frequencies – this was covered in detail in the cited JSV paper. The effects considered in this paper are quite different and are due to the structural dynamics of the access points. They have a very different effect on the cross-correlation function. It is hope that this is now clarified in the revised paper. As mentioned above, the authors do not believe that this phenomenon is well known, and there are no papers in the literature that discuss this problem.

Some specific remarks:

- The technique assumes sound propagation at a constant, frequency independent velocity. Such an approximation holds for long pipes below the first cut-on frequency and away from discontinuities. It probably holds for the pipes concerned in view of relatively

small diameter of and of fairly low frequency basebands used, but this should be checked out.

The reviewer is correct. The paper is focussed on cases where the sound propagates at a constant phase velocity. As plastic pipes act as a low pass filter, then then the signals measured in such pipes generally contain only low frequencies, and hence the frequency range over which there is time-delay information is well below the first cut-off frequency, as can be seen by the phase spectra presented in the paper. The authors have not made any measurements where the frequency range has been so wide that dispersive behaviour has been observed.

- What does justify the stated condition about the limit of variance of the phase estimate, < (2pi)^2, needed to allow phase unwrap ? This leads to ridiculously low threshold of coherence function, like 10-3 used in the paper. Such a low coherence indicates the absence of common origin of the two signals which is in contradiction with the principle of the detection method.

A coherence value of 10-3 may appear ridiculously low, but the authors have found that the phase can be unwrapped until this value is reached, and hence time delay information is preserved within the measured signals up to the frequency where the coherence drops below this value. The authors have seen this in all of their work on leak detection and have cited reference [16] as the basis for this. Although the value of 10-3 is small it does not indicate the absence of a common origin of the two signals as the reviewer suggests, it simply means that the signal to noise ratio is very small – but it is still just large enough for the purposes of time delay estimation.

- The model including the added resonators, leading to Eq. 7, is not justified by any scientific argument. Eq. 6 does indeed represent the model of a SDOF in a general sense, but how is this coupled to the pipe and what does it physically represent ?

It is believed that his point has been addressed in the responses to reviewer 1. As to how the resonator(s) is coupled to the pipe is easy to see with the accelerometer. It is simply attached to the pipe wall. For the hydrophone it is not possible to state so clearly. What can be stated is the pressure signals are passed through a resonator. As shown in the block diagram in Fig. 9. It should be emphasised, that the authors do not consider this to be the main point of the paper. The main point is that structural resonances can occur in some pipe systems, and the effects of these resonances can be such that the estimated time delay can be incorrect, unless the bandwidth is chosen appropriately.

The present manuscript seems not to result in any substantial new knowledge neither it provides any improvement of the detection procedure. I therefore propose rejection.

The authors respectfully disagree with the reviewer. We believe that we have shed some insight into a phenomenon that can result in incorrect time delay estimation. In the revised manuscript we have added supporting evidence to the assertion that the source of the deviation of the phase is due to the structural dynamics of the access points. To the authors' knowledge the work reported in this paper cannot be found elsewhere in the literature.