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On the signum function and its effect on acoustic correlation for leak location in buried plastic water pipes

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Abstract

Water loss through leakage in water pipeline distribution systems is a serious issue due to the increasing scarcity of water, such as the recent problem faced by São Paulo State in Brazil. Although older metallic pipes are now being replaced by plastic pipes they still suffer from leakage. Unfortunately, correlation techniques, which are used to locate leaks by correlating signals from two vibration sensors attached to the pipe, are less effective in plastic pipes because of higher leak noise attenuation. Hence, the gain setting of the sensors used to collect leak signals have to be carefully selected to enhance the effectiveness of correlation techniques when applied to plastic pipes. However, this is not simple in practical situations, so that the acquired data can become saturated (clipped) or be very small. This paper describes the effects of clipping on the estimation of time delay by severely distorting the signals by using the signum function. It transpires, that although this adds some noise to the original signals, and potentially reduces the bandwidth of which there are measurable leak noise signals, it does not have a profound effect on time delay estimation and hence the accuracy of the leak location. Leak noise signals measured in controlled conditions on a bespoke test-rig constructed by South Staffs Water plc, are used to demonstrate how this process works.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Water distributions systems are susceptible to leakage, which results in substantial wastage of water. A leak generates noise that can be used for its detection and location. One of the simplest and most common techniques used for leak detection is the use of “listening sticks”. To increase the sensitivity of the device, a wooden section is attached to one end of the stick to transmit vibrations more effectively, or a digital acoustic amplifier is used. This technique has limited effectiveness since it depends greatly on operator experience, and provides only an empirical estimate of

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the leak position [1-3]. Processing of the signals from acoustic and vibration sensors is now commonly carried out in order to improve the localization accuracy of leaks. These techniques have been applied extensively to metallic and plastic water pipes. Typically, acoustic or vibration sensors (hydrophones and accelerometers) are connected to access points either side of the location of the suspected leak. The most widely used technique involves the correlation between the measured signals at the two different access points [4]. Ideally, the peak in the cross-correlation function occurs at an instant which is the difference in time that it takes for the leak to propagate to each sensor position. The leak location is then deduced using knowledge of the speed at which the noise propagates. The effectiveness and accuracy of the estimated leak location in plastic pipes is affected by problems such as background noise, small signals due to high attenuation levels in the pipe, poor instrumentation sensitivity, inaccurate wave speed estimate and unknown pipe properties [1,2]. Here in this paper, however, the time delay estimation is the main concerned issue.

Because of noise issues the gain setting of the sensors used to collect leak signals care is taken to select appropriate gain settings to enhance the effectiveness of the correlation technique in leak detection and location. However, this is not always simple in practical situations, and in some cases the acquired data can become saturated (clipped).

This paper describes the effects of clipping on the estimation of time delay by severely distorting the signals by using the signum function. Leak noise signals measured in controlled conditions on a bespoke test-rig constructed by South Staffs Water plc, are used to demonstrate how this process works.

2. Leak detection using acoustic correlation

A typical situation where noise from a leak is used to detect and locate its position is shown in figure 1. Acoustic or vibration sensors are attached to access points, which are typically hydrants or valves, either side of the suspected leak position. In figure 1, the leak position d_1 from the left-hand sensor is given by [1] $d_1 = (d - cT_0)/2$ 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 most widely used technique to determine the time delay between sensor signals uses the cross-correlation function $R_{x_1x_2}(\tau)$ between the two measured signals $x_1(t)$ and $x_2(t)$ as shown in Fig. 1 [5]. The presence of a leak appears as a distinct peak in the cross-correlation function (CCF) between the measured signals, which is given by [1]

$$R_{x_1x_2}(\tau) = F^{-1}\left\{W(\omega)S_{x_1x_2}(\omega)\right\} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} W(\omega)S_{x_1x_2}(\omega)e^{i\omega\tau}d\omega \tag{1}$$

where $F^{-1}\{\ \}$ is the inverse Fourier transform, $W(\omega)$ is the weighting function for the different correlators, $i = \sqrt{-1}$, $S_{x_1x_2}(\omega) = \left|S_{x_1x_2}(\omega)\right|e^{i\phi(\omega)}$ is the cross spectrum density (CSD) function of the signals $x_1(t)$ and $x_2(t)$, and ϕ is the phase between the signals. In the case when there is a pure time delay, then $\phi = \omega T_0$. The weighting function can take various forms [1] but in this paper, only two are considered. They are $W(\omega) = 1$, $W(\omega) = 1/\left|S_{x_1x_2}(\omega)\right|$

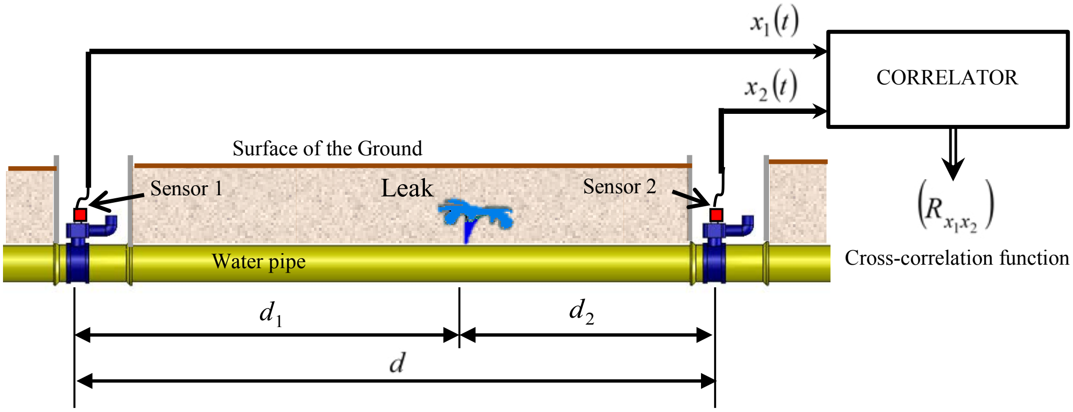

Fig. 1. Schematic of leak detection in a buried plastic water pipe using acoustic/vibration signals with a leak in between the two sensors

When the frequency weighting function is one, then equation (1) corresponds to the so-called basic cross-correlation BCC function as described by Knapp and Carter [5], which is simply given by

$$R_{x_1x_2}^{\mathrm{BCC}}(\tau) = F^{-1}\{S_{x_1x_2}(\omega)\} \tag{2}$$

If the frequency weighting function is $1/\left|S_{x_1x_2}(\omega)\right|$ then equation (1) corresponds to the Phase Transform (PHAT), which is given by [1]

$$R_{x_1x_2}^{\mathrm{PHAT}}(\tau) = F^{-1}\left\{\frac{1}{\left|S_{x_1x_2}(\omega)\right|} S_{x_1x_2}(\omega)\right\} = \delta(\tau + T_0) \tag{3}$$

where $\delta(\tau)$ is the delta function. It can be seen from Eq. (3), that the result of the PHAT is a perfect delta function located at the time delay T_0. For leak detection problems, the water flow inside the pipe is neglected compared to the speed of leak noise (time delay is a function of leak noise only). However it has the disadvantage that noise can be enhanced, thereby corrupting the estimate of the time delay [1]. The choice of the gains in the measurement system used to measure leak noise is perceived as being important to obtain good signals for further processing. However this is not always easy to set in the field and can result in the signals being clipped due to saturation of electronic equipment. The effect of severe clipping is simulated by using the signum function [6] (also known as sign function) on the measured time histories. This results in a signal that is 1 when the acquired signal is positive, -1 when the signal is negative, and zero when the signal is also zero. The two modified time series are given by $s(t) = \mathrm{sgn}\big(x(t)\big)$, $s(t) = \mathrm{sgn}\big(x(t)\big)$ where $\mathrm{sgn}(\;)$ is the signum function. Figure 2(a) shows a typical time history measured from a plastic water distribution pipe. Figure 2(b) shows the same time history modified by the signum function. In the following section the effect of severe clipping is investigated on the BCC and PHAT correlators by applying the signum function to leak noise signals collected from a bespoke test-rig in the UK.

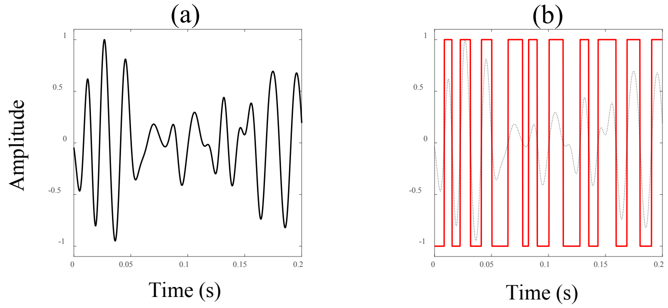

Fig. 2. Accelerometer-measured leak data (a) Normalized to its maximum value. (b) Clipped by using the signum function.

3. Experimental work

The leak noise signals were measured on the Blithfield pipe rig, which is a bespoke test rig in the UK, provided by South Staffs Water plc. Figure 3 shows a schematic of the pipe rig highlighting the distances between the access points, along with the positions where the leak was generated and, measurements taken (Positions 1 and 2). The pipe extremity close to Position 1, where sensor 1 was placed, is connected to the mains water distribution pipe, which supplies water at a pressure of about 6 bar. At the other extremity the pipe is terminated with a blank.

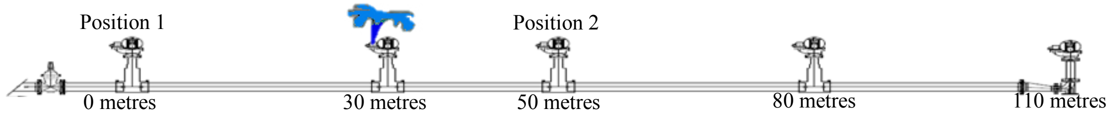

Fig. 3. The pipe rig used for the experimental work.

All the access points are set in concrete to provide rigid supports for the pipe connections, while the pipe sections are buried at a depth of about 0.8 m. Figure 4(a) shows one of the access points. Leak noise was generated by opening a secondary valve fitted to a blanking piece attached to the hydrant as shown in the sketches in figures 3(b) and (c). The main valve shown in these figures allowed the water contained in the buried pipe to enter the hydrant. The leak was 30 metres away from Position 1. A pressure gauge was also attached to the hydrant as shown in Figure 3(c). Details of the transducers at Positions 1 and 2, and the instrumentation used are given in table1.

Table 1. Transducers and instrumentation used in the experiments.

Device	Manufacturer	Type
Accelerometer	Bruel and Kjaer	4384
Charge amplifier	Bruel and Kjaer	2635
Acquisition system	Prosig	5680

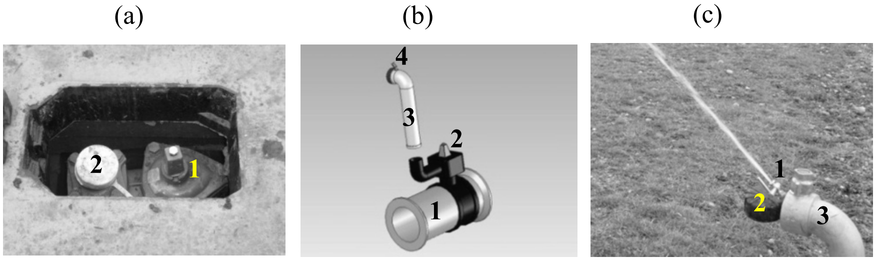

Fig. 4. Some components of the pipe test-rig. (a) The pipe access point and its main valve. (1) Main valve; (2) connection point. (b) Sketch of the device used for generating the leak conditions. (1) Plastic pipe; (2) Main valve; (3) Metal hydrant; (4) Secondary valve. (c) Pressure gauge and secondary valve attached to the hydrant. (1) Secondary valve; (2) Pressure gauge; (3) Hydrant.

4. Results

In this section, some results are investigated for the actual and “clipped” leak data of cases where no resonances (measurements at Position 1 and leak position) and resonances (measurements at Position 1 and Position 2) are present in the system. The characteristics of these data is first shown in the frequency domain. After that, the BCC and PHAT correlators will be performed using the inverse Fourier Transform of the described data in the frequency domain. The modulus and phase of the CSD, and the coherence calculated using typical strong leak noise-signals (black-solid line), and the modified time histories (red-dotted line) measured at the leak position and at position 1 using two accelerometers are shown in figures 5 (ai), 5(aii) and 5(aiii), respectively. The blue-dashed line shown in figure 5(aii) is a straight line plotted to highlight the linear behaviour of the phase. It can be seen that there is quite a broad bandwidth over which the unwrapped phase has linear behaviour. This region, where the phase can be unwrapped, contains information about the difference in the arrival times of the leak noise at the two sensors (time delay). Although the coherence is very low when the CSD of the modified time series is calculated, the modulus and phase are similar to that calculated using the actual time series. Note that the coherence is low because the signum function is a nonlinear operator.

In some cases, the dynamics of the pipe system such as resonances add additional components to the time delay information in the data [7]. Moreover, in practice the signals are passed through band-pass filters to attenuate the signals outside the frequency range of interest [8], suppressing undesirable noise effects. Here a band-pass filter with lower and upper limits of 15 Hz and 150 Hz, respectively, is used. Figures 5(bi), 5(bii) and 5(biii) depict the measured modulus and phase of the CSD, and the coherence calculated using two leak signals (black-solid line), and their modified version using the signum function (red-dotted line), measured at Positions 1 and 2. As observed in Fig. 5b(ii), there is a phase shift at about 88 Hz in addition to the phase shift associated with the time delay (the straight-line behaviour). This additional phase shift is related to a resonance in the pipe system. Hence, as this feature affects the phase spectrum then the time delay can also be jeopardised. Moreover, as observed in Fig. 5(bii) the phase calculated using the modified times histories cannot be unwrapped properly above the resonance frequency of 88 Hz.

Figure 6(ai) and 6(aii) show the BCC and PHAT calculated using the actual leak data (black-solid line) and the modified time histories (red-dotted line), respectively, for the cases shown in figure 5(ai), 5(aii) and 5(aiii). It can be seen that the BCC calculated using the modified time series is similar to that calculated using the actual leak data. The PHAT calculated using the modified time series, however, is noisier than that calculated using the actual leak data. This is because the phase calculated using the modified time histories also has some additional noise compared to the phase calculated using the actual leak data. Moreover, both BCC and PHAT give the same time delay, no matter which time histories (modified or not) are used to calculate them.

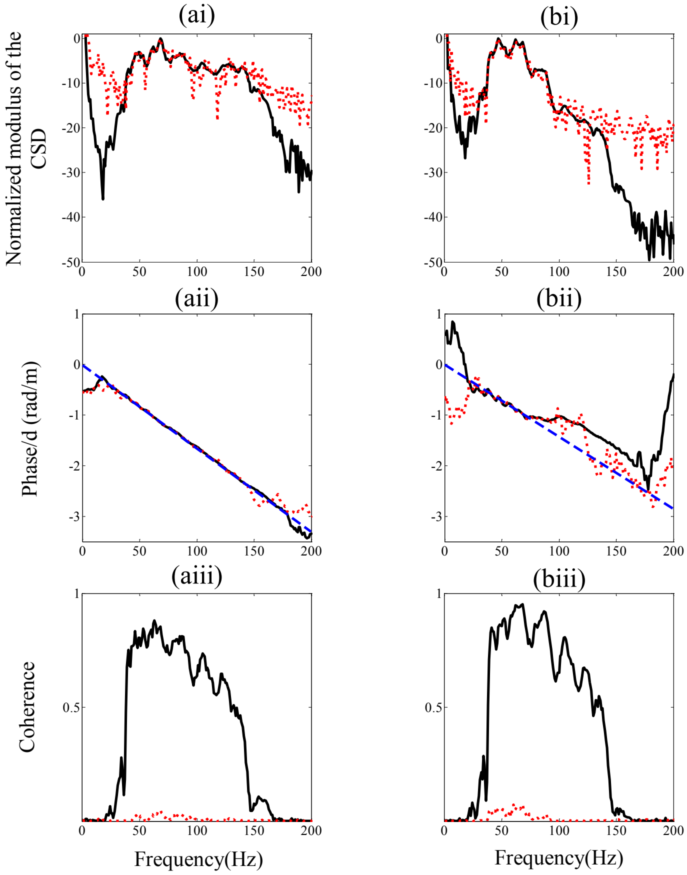

Fig. 5. Typical strong leak noise signals from the pipe rig measured using accelerometers. The labels ‘a’ and ‘b’ mean that the measurements were made between the leak position and position 1 and between positions 1 and 2, respectively. (ai) and (bi): The modulus of the CSD. (aii) and (bii): Phase spectrum. (aiii) and (biii): Coherence. Typical strong leak noise-signals (black-solid line), calculated from the modified time histories (red-dotted line).

Figure 6(bi) and 6(bii) show the BCC and PHAT calculated using the actual leak time histories (black-solid line) and the modified time histories (red-dotted line), respectively, for the case shown in Fig.5(bi), (bii) and (biii). As shown in the previous case, the BCC is marginally affected when the leak time histories are processed using the signum function. However, the PHAT calculated using the modified time histories is also noisier than the PHAT calculated using the actual leak data, but the time delay estimate given by its peak is the same as the BCC calculated using the actual and modified time series. This is not the case for the PHAT calculated using the actual time histories because the PHAT is sensitive to the additional phase shift caused by the resonance [8]. The PHAT calculated using the modified time series is not heavily affected because the phase cannot be unwrapped above the resonance, reducing its effect on the time delay estimate.

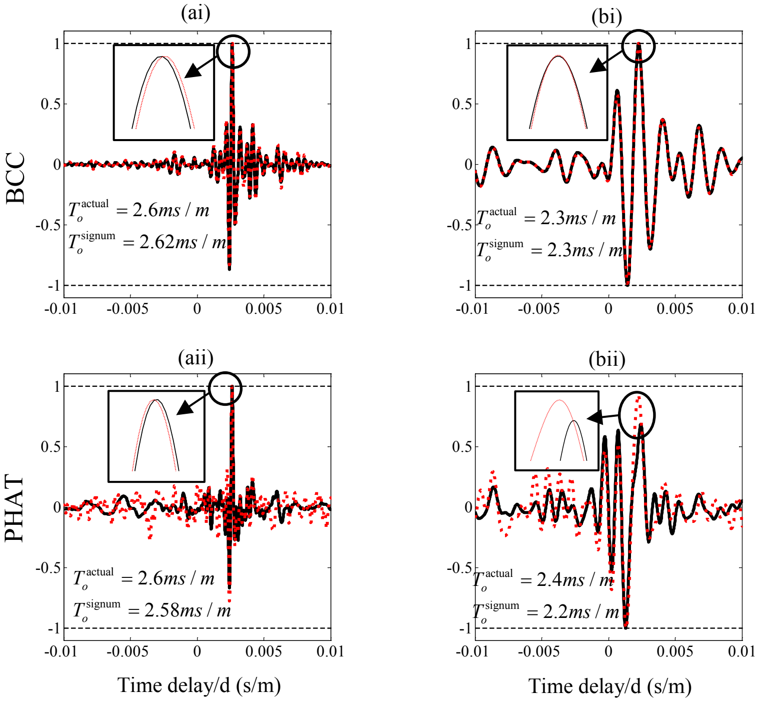

Fig. 6. BCC and PHAT of the cases shown in Fig.5. The labels "a" and "b" stands for measurements made at the leak position and Position 1, and between Position 1 and Position 2, respectively. (ai) and (bi): BCC. (aii) and (bii): PHAT. — Actual data. ---- Signum function.

5. Conclusion

This paper has investigated the effects of severe clipping of leak noise signals on time delay estimation and hence leak detection and location in buried plastic water distribution pipes. This has been achieved by applying the signum function to time histories removing all amplitude information. Using leak noise data from a bespoke test rig in the UK, it has been shown that the signum function does not have a substantial effect on the BCC correlator, even when distortions in the phase spectrum related to the dynamics of the pipe system are present in the data. For the PHAT correlator, the use of the signum function makes this correlator noisier than if using actual leak time series. However, the time delay given by its peak is not heavily affected by the dynamics of the pipe system.

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