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

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ABSTRACT

In the use of 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 information with the speed at which the leak noise propagates along the pipe, gives an estimate for 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 phenomenon, 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 or the Phase Transform (PHAT), is more robust to the undesirable structural dynamics of the pipe system. It is found that time delay estimation is highly sensitive to the frequency 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.

1. Introduction

Buried water pipelines are susceptible to leakage. To repair these pipe-systems, the ground is generally 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), and 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 comprehensive reviews on the classical techniques used to locate and detect leaks, and have outlined the main advantages and disadvantages of each method. 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]. Acoustic Emission (AE) is also used successfully to detect leaks [7,8], whereby AE sensors are placed on the pipe or on the ground (buried pipes) around where the suspected leak is located. More recently, algorithms have been developed to detect leaks automatically, based on the spectral characteristics of the leak noise [9,10]. Leak noise correlators are portable devices that 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. The peak in the cross-correlation function is then used to locate the leak. Although correlators are effective for metallic pipes [3,11], the range over which they can detect leaks is significantly less for plastic pipes [3,11,12]. This is because of the relatively high level of 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 [12,13]. 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 function may be computed 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 available in some types of commercial correlators [14,15]. One of them uses the phase transform (PHAT) as discussed by Gao et al. [16]. 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. In a study related to the one reported here, some of the authors of this paper have determined a way to compensate for time delay errors due to resonance behaviour [17], and to compare its performance with the correlator that uses the BCC function. It is shown that measurements made on water distribution pipes can include the effects of resonances. Another objective of this paper is to propose possible reasons for the occurrence of these resonances based on experimental data from two test-rigs. Examination of these data shows 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 or acoustic signals as a tool for leak location in water distribution pipes, further details of which can be found in [11] and [18] 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 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,
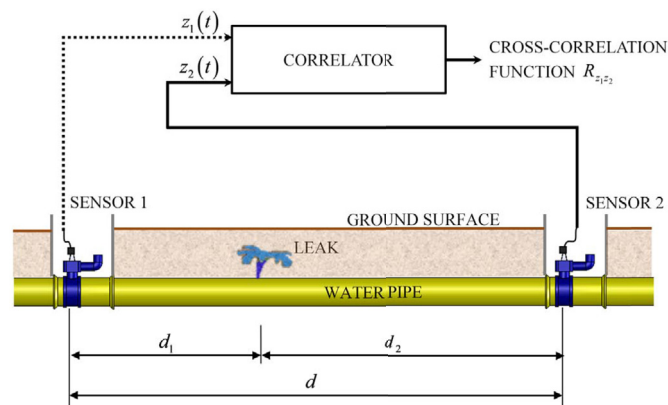

Fig. 1. Schematic of leak detection in a buried water pipe using acoustic/vibration signals with a leak bracketed by two sensors.