Improving the shape of the cross-correlation function for leak detection in a plastic water distribution pipe using acoustic signals

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A B S T R A C T
This paper is concerned with time delay estimation for the detection of leaks in buried plastic water pipes using the cross-correlation of leak noise signals. In some circumstances the bandwidth of over which the signal analysis can be conducted is severely restricted because of resonances in the pipe system, which manifest themselves as peaks in the modulus of the power spectral and cross spectral densities, and deviations from straight-line behaviour in the phase of the cross spectral density. The result can be a cross-correlation function in which it is difficult to estimate the time delay accurately. This paper describes a procedure in which the shape of the cross-correlation function can be significantly improved, resulting in an unambiguous and clear estimate of the time delay. The frequency response function(s) of the resonator(s) responsible for the resonance effects are first determined and then the data is processed using the model(s) of the resonators to remove these effects. This enables more signal processing to be conducted, potentially over a much wider bandwidth, further improving the shape of the cross-correlation function. The process is illustrated in this paper using hydrophone measured data at a leak detection facility. The current limitation in the process is that it is carried out manually, which could potentially restrict its application in practical acoustic correlators. The challenge now is to develop an algorithm to carry out the procedure automatically.

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1. Introduction

Water distribution networks are of paramount importance for maintaining a substantive modern life and economic growth. Underground pipes are susceptible to leakage, due to excavation damage, sabotage, deterioration and aging. Water leakage is a subject of increasing concern across the world because of the potential danger to public health, economic constraints, environmental damage and wastage of energy. Acoustic based leak detection techniques have been developed over the past 30 years, and are in common use in water distribution networks [1,2]. One such technique uses cross-correlation of measured leak noise signals to determine the difference in arrival times (time delay) between acoustic/vibration signals measured either side of a water leak. Together with the knowledge of the speed of noise propagation, this is then used to determine the location of the leak.

Time delay estimation (TDE) is of great interest in many engineering fields, such as direction finding, source localization, and velocity tracking [3]. It can be carried out in the time and/or frequency domains [4,5]. Most commercial leak noise correlators utilize the basic cross-correlation (BCC) function via the Fast Fourier transform for TDE. In plastic pipes, measured water leak noise mostly occurs at low frequencies, below about 200 Hz, although this can be higher for leaks close to a measurement point. The reason for this predominantly low frequency content, is that a plastic pipe essentially acts as an acoustic low-pass filter, which degrades the TDE procedure using the conventional BCC, in particular in the case of a poor signal-to-noise ratio [6,7]. To overcome this problem, Gao et al. [4] applied a pre-whitening process, using appropriate frequency weighting functions to improve the resolution of the time delay estimate. One particularly effective correlator uses only the phase spectrum, setting the modulus of the cross-spectrum to unity over the frequency range of analysis. This is the so-called

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phase transform (PHAT) correlator [4], which gives equal weighting to all frequencies, effectively increasing the bandwidth over which the time delay is estimated, compensating to some extent for the low-pass filtering properties of the pipe [7]. The pre-whitening approach can, however, cause errors in the time delay estimate if there are additional phase shifts in the measurements caused by the dynamic behaviour of the pipe system [4,9]). Such phase shifts have been observed by Gao et al. [6] in hydrophone measured data. The associated increase in the modulus of the cross-spectrum at the frequencies where there is an additional 90° phase shift suggest that the dynamics is due to resonance behaviour. The resonance behaviour is highly undesirable from the perspective of leak detection, as it can significantly reduce the bandwidth over which the BCC extracts time delay information.

The aim of this paper is to describe a method to remove the additional phase shifts due to the resonances in the system, so that a much wider bandwidth can be utilized, thus improving the shape of the cross-correlation function, making it easier to determine the time delay estimate. To achieve this, the ROTH correlator is used (as this is based on the frequency response function (FRF) of the pipe system [4,9]), which facilitates the visualization of the resonance effects. Using a model of a resonator capable of capturing the additional phase shift behaviour observed in measured data, these phase shifts are subsequently removed leaving only the phase spectrum due to time delay. This process is illustrated using some experimental data measured on an actual PVC water pipe.

2. Problem statement

Fig. 1 depicts a typical arrangement for water leak detection based on cross-correlation. Pipe fittings such as meters, valves and fire hydrants are used as access points for the installation of the acoustic/vibration sensors such as hydrophones and accelerometers. The leak generates broadband noise, which propagates along the pipe, and the difference in the arrival times of the noise at the sensors (time delay) is used to determine the position of the leak. This is given by Ref. [6],

\[ d_1 = d - cT_0 \]

where \( c \) is the propagation speed of the leak noise (wave speed); \( d \) is the distance between the sensors; and \( T_0 \) is the time delay estimate.

In many cases the wave speed is estimated from tables, but it can also be measured in-situ [10]. The time delay \( T_0 \) is estimated from the peak in the cross-correlation function between the two measured signals \( x_1(t) \) and \( x_2(t) \), which is given by Ref. [4]

\[ R_{x_1x_2}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} W(\omega) e^{i\omega\tau} d\omega, \tag{2} \]

where \( W(\omega) = \Psi(\omega)S_{x_1x_2}(\omega), \) in which \( \Psi(\omega) \) is given in Table 1 for the three correlators considered in this paper; \( j = \sqrt{-1}; \) \( S_{x_1x_2}(\omega) = |S_{x_1x_2}(\omega)| e^{i\phi_{x_1x_2}(\omega)} \) is the cross spectral density (CSD) function, in which \( |S_{x_1x_2}(\omega)| \) and \( \phi_{x_1x_2}(\omega) \) are the modulus and phase spectra between the signals \( x_1(t) \) and \( x_2(t) \) respectively; and \( \omega \) is circular frequency. The time delay estimate can also be determined from the frequency domain data by Ref. [5]

\[ T_0 = -\frac{\sum_{i=1}^{N/2} W_i|\phi_i(\omega)|}{\sum_{i=1}^{N/2} W_i|\omega_i|^2}. \tag{3} \]

where the subscript \( i \) denotes the variable at the \( i \)-th frequency. Thus, the peak in the correlation function corresponds to the gradient of a straight line which is fitted to the measured phase in a weighted least squares sense.

Measured signals from a pipe rig, specially constructed for water leak detection at the National Research Council campus in Canada, are used to illustrate some issues. The description of the test site and measurement procedures are given in [2,11], and a plan of the site is shown in Fig. 2. Noise from a leak, an illustration of which is shown in Fig. 3(a), was measured using hydrophones, one of which is shown in Fig. 3(b). The distance between the measurement points was 102.6 m, and the distance of the upstream measurement point from the leak was 73.5 m. The signals of 66 s duration were each passed through an anti-aliasing filter with the cut-off frequency set at 200 Hz and then digitized at a sampling frequency of 500 Hz.

Some processed data from the two leak noise signals are shown in Fig. 4. These were determined using a 1024-point FFT, a Hanning window (with 50% overlap) and spectral averaging. Fig. 4(a) shows the power spectral densities (PSDs) of the two measured signals. Apparently, the PSD plots show that the signals attenuate with frequency and distance from the leak. It is also clear that there is resonance behaviour, which is evident in each measurement. The PSD plots also show that the signals are at times delayed due to the dynamic behaviour of the pipe system. Such phase shifts are subsequently removed leaving only the phase spectrum due to time delay. This process is illustrated using some experimental data measured on an actual PVC water pipe.
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