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A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes

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Abstract

The position of a leak in buried water distribution pipes, may be determined by accurate estimation of the time delay between two measured acoustic signals. By using a model for the wave propagation along plastic pipes, various time delay estimators using cross-correlation are compared in this paper for their ability to locate a leak in plastic pipes. The estimators of interest are the ROTH impulse response, the smoothed coherence transform (SCOT), the WIENER, the phase transform (PHAT) and the maximum likelihood (ML) estimators. For leak detection in buried plastic water pipes it is found that the SCOT estimator is particularly suited to this purpose. The accuracy of the estimators is also discussed. It is found that random errors introduced by random noise on the signal measurements are insignificant compared with the resolution of the time delay estimators imposed by the low-pass filtering characteristics of the pipe. Limited experimental results are presented to support the findings.

1. Introduction

A leak from a water supply pipe system generates noise, which can be used for leak detection and location. The correlation technique [1–3], which is used to estimate the time delay between two measured acoustic/vibration signals, is central to this process. Important factors in the detectability of the leak are the signal-to-noise ratio (SNR) and the amount of a priori knowledge, principally, the sound propagation wavespeed c in the pipe. A sensor is placed either side of the leak, and the distance between the two sensors is usually measured on-site or read off system maps, whereas the propagation wavespeed is normally estimated using pipe data [4,5] or measured on-site using a simulated leak [6].

Various time delay estimation techniques have been proposed and implemented over the years. Some of the most important are summarised in Refs. [7–9]. These techniques are based on the cross-correlation of two measured signals and include the basic cross-correlation (BCC) and generalised cross-correlation (GCC) methods, of which the BCC method is a trivial example. The essential difference between the BCC and the GCC methods, is that with the latter, the signals are passed though filters (pre-filtering) prior to performing the cross-correlation. The advantages of pre-filtering are two-fold: (i) to enhance the signals in the frequency

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Nomenclature

$\tau, \tau_{peak}, \hat{\tau}_{peak}$ lag of time; time delay at the peak value and its estimate
$x_1(t), x_2(t)$ acoustic/vibration signals
$n_1(t), n_2(t)$ background noise
$X_1(f), X_2(f)$ Fourier transforms of $x_1(t)$ and $x_2(t)$, respectively
d distance between two sensor signals
d_1, d_2 relative distance between the leak and signals $x_1(t)$ and $x_2(t)$
c propagation wavespeed
$R_{x_1x_2}(\tau), \hat{R}_{x_1x_2}(\tau)$ cross-correlation function between signals $x_1(t)$ and $x_2(t)$ and its estimate
$R^g_{x_1x_2}(\tau), \hat{R}^g_{x_1x_2}(\tau)$ GCC function between signals $x_1(t)$ and $x_2(t)$ and its estimator
$R^P_{x_1x_2}(\tau), R^R_{x_1x_2}(\tau), R^W_{x_1x_2}(\tau), R^S_{x_1x_2}(\tau), R^M_{x_1x_2}(\tau)$ the PHAT, ROTH, WIENER, SCOT, ML estimators
$R_{s_1s_2}(\tau)$ cross-correlation function between signals $s_1(t)$ and $s_2(t)$
$S_{x_1x_2}(\omega), \hat{S}_{x_1x_2}(\omega)$ CSD between signals $x_1(t)$ and $x_2(t)$ and its estimate
$\Psi_{2n}(\omega)$ frequency characteristics due to propagation effects along the pipe, which is a function of wave attenuation and the type of sensor
$S_{s_1s_2}(\omega)$ CSD between signals $s_1(t)$ and $s_2(t)$
$S_{ll}(\omega), S_{n_1n_1}(\omega), S_{n_2n_2}(\omega)$ ASD of the leak signal $l(t)$, and noise signals $n_1(t)$ and $n_2(t)$
$\Phi_{x_1x_2}(\omega)$ phase spectrum between signals $x_1(t)$ and $x_2(t)$
$\gamma^2_{x_1x_2}(\omega)$ ordinary coherence function between $x_1(t)$ and $x_2(t)$
$\Psi_g(\omega)$ frequency weighting function of the GCC function
$\Psi_P(\omega), \Psi_R(\omega), \Psi_W(\omega), \Psi_S(\omega), \Psi_M(\omega)$ frequency weighting functions of the PHAT, ROTH, WIENER, SCOT, ML estimators
$H(\omega, x)$ frequency response function between the signal measured at the sensor location and the pressure at the leak location
$\delta(\tau)$ Dirac delta function
$\sigma^2_{\hat{\tau}_{peak}}, \sigma_{\hat{\tau}_{peak}}$ variance and standard derivation of $\hat{\tau}_{peak}$
σ_z standard deviation of the first derivative of the cross-correlation function
$\left|\frac{\partial E[z]}{\partial \tau}\right|_{\tau=\tau_{peak}}$ slope of the cross-correlation function at $\tau = \tau_{peak}$
$G(\omega)$ band-pass filter
$\Delta\omega, \omega_0, \omega_1$ frequency bandwidth of band-pass filter; lower and upper cut-off frequencies of band-pass filter
ω_c centre frequency of a band-pass filter
$\Delta\tau$ temporal bandwidth, i.e., resolution of the time delay estimator

bands where the SNR is high, thereby suppressing the signals outside these bands, and (ii) to pre-whiten the signals in order to sharpen the peak in the cross-correlation function. Knapp and Carter discussed the characteristics of five GCC methods and compared them with the BCC method [7]. In this paper, we compare the same GCC methods with the BCC method for the purpose of leak detection in buried plastic water pipes to determine which method is best suited to this particular application.

The five GCC methods considered are the ROTH impulse response (proposed by Peter Roth), the smoothed coherence transform (SCOT), the WIENER (after its inventor Norbert Wiener), the phase transform (PHAT) and the maximum likelihood (ML) estimators.

In the ROTH estimator [10], rather than determining the cross-correlation between two signals, the signals are used to deduce the impulse response of the system. This is achieved by normalising the cross-spectrum by the auto-spectrum of one of the signals (the input), prior to transforming back to the time domain. The rationale for this procedure is that it removes the effects of the input, thus deducing the system delay more accurately. However, because the input (leak) spectrum cannot be measured directly it is difficult to see how this method could be beneficial for leak detection, but it is included in this paper for completeness.

The SCOT estimator favours neither sensor signal and was developed by Carter et al. [11] to suppress the undesirable effects of strong tonal signals in weak broad-band signals. In the SCOT estimator the cross-spectrum is normalised by the square-root of the product of the auto-spectra of the two signals. For leak detection in pipes we show this to be a worthwhile procedure; the reasons why this is so, and an alternative interpretation of this processor, is given in Section 3.