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INVESTIGATION INTO AN ADAPTIVE LEAK DETECTION METHOD IN WATER DISTRIBUTION PIPES

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Pipeline leakage is a subject of increasing concern in China and across the world for transporting fluids and gases. Acoustic leak detection systems based on cross-correlation have been successfully applied to locate and detect leaks, in particular in water distribution pipes. Conventional methods for time delay estimation (TDE) involve some pre-filtering processes prior to performing the cross-correlation based on a priori knowledge of the leak signal and noise spectra to achieve the desired performance. Difficulties are often encountered in practical situations, since the leak signals in water pipes are narrow-band and of low frequency, which inevitably will be contaminated by noise. To overcome this, this paper presents an adaptive leak detection method based on an LMS algorithm for TDE between two acoustic/vibration signals measured using accelerometers/hydrophones bracketing a suspected leak. It builds on an analytical model of wave propagation in a fluid-filled pipe and combines the adaptive algorithm with the propagating characteristics of the leak signal in the pipe system. Compared to the basic cross-correlation method, the adaptive method shows some promise in the presence of ambient noise, which may offer improvement of TDE for locating a leak having a low signal-to-noise ratio. Experimental results confirm the improved performance of the LMS algorithm for TDE in water distribution pipes.
Keywords: adaptive filtering, cross-correlation, leak detection, LMS, TDE, water pipe

1. Introduction

Leakage from underground water supply pipelines may occur frequently because of natural pipeline corrosion and aging, loose soil, excessive traffic load, natural disasters and man-made damage. Water leakage is still high on the agenda across the globe, since it results in poor water quality and serious waste of water resource. Therefore, accurately locating the leakage in time is of great significance to improve the efficiency of water resource utilization and reduce the related cost. Currently used pipeline leakage detection methods mainly include the ground penetrating radar [1], infrared imaging [2], tracer gas detection [3], negative pressure wave method [4], and acoustic detection method [5-7], etc. Among them, the acoustic detection method based on the characteristics of leakage signals is most widely used for underground water supply pipeline.

Time delay estimation (TDE) plays a dominant role in the processing of acoustic leakage signals. Acoustic and/or vibration signals captured by sensors on both sides of the leak are used to estimate the time delay for the determination of the leak location. The commonly used techniques include the basic cross-correlation (BCC) [5-8], generalized cross-correlation (GCC) [9-11], bispectrum method [12], and adaptive algorithms [13-16]. For the BCC, the signals collected by two sensors are directly adopted to calculate the cross-correlation with the peak value corresponding to the time delay. In contrast, for the GCC correlation analysis is conducted on the pre-filtered sensor signals.

Commonly used GCC methods include the phase transform (PHAT), the smooth coherence transform (SCOT), the ROTH impulse response, and the maximum likelihood (ML), etc [9-11]. In the PHAT method, the time delay is directly derived from the phase information of the cross-spectrum between two sensor signals. The implementation of the other GCC methods often need the knowledge of the auto- and cross-spectra of received signals. The adaptive algorithm is a TDE method based on adaptive signal processing, from which the time delay is estimated by using the weighting function of an adaptive filter. Compared with the conventional cross-correlation methods (including the BCC and GCC), the adaptive algorithm does not require a prior statistical knowledge about the input and noise signals. Moreover, in different situations, the parameters of an adaptive filter can be adjusted according to the optimization criterion in the iterative process, thus suitable to track a dynamically varying input environment.

In the development of a model for the pipe leakage system, it was assumed in previous studies that the signals received by the two sensors only have time delay and amplitude attenuation, without considering the propagation characteristics of leak noise in the pipeline. However, the accuracy of the estimated location will be affected if the propagation characteristics are not included. To solve this problem, the propagation characteristics of a water leak along the pipeline are combined with the least mean square (LMS) adaptive algorithm in this paper. Experiments are conducted to validate the effectiveness of the proposed adaptive algorithm for water leak detection in a noisy environment.

2. Leakage localization using acoustic signals

When leakage occurs in a water supply pipeline, the water under certain pressure in the pipeline interacts with the leak location and then impacts upon the surrounding medium. As a result, acoustic signals generated at a leak source propagate upstream and downstream along the pipe wall and within the contained fluid. These signals are transmitted to the sensors installed at two access points of the pipeline. The generation and propagation of leak signals are shown in Fig. 1.

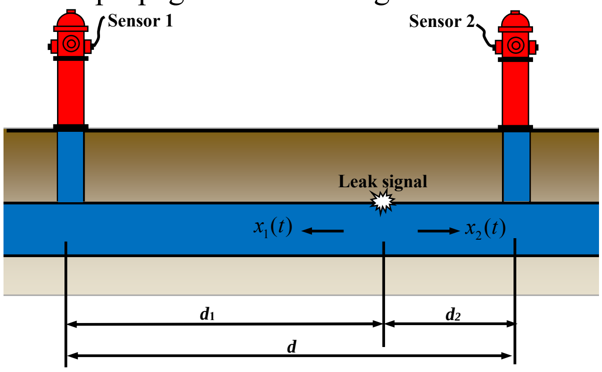

Figure 1: Schematic of a pipe with a leak bracketed by two sensors.

The distance between sensor 1 and the leak, d_1, is given by

$$d_1 = \frac{d + T_0 c}{2} \tag{1}$$

where d is the distance between the two sensors; T_0 is the time delay to be estimated; and c is the propagation speed of the leak in the pipeline, which can be determined by [17]

$$c = c_f \left(1 + \frac{2Ba}{Eh}\right)^{-1/2} \tag{2}$$

where c_f is the propagation speed of sound in the water; B is the bulk modulus of elasticity; E is the Young's modulus of pipe wall; a is the pipe radius; and h is the thickness of pipeline wall.

When leakage occurs, the leak noise generated at the source propagates along the pipeline. The frequency response function between the sensor location x and the leak location is [18]

$$H(\omega,x)=e^{-ikx}=e^{-i\omega x/c}e^{-\omega\beta x} \tag{3}$$

where k is the wavenumber, the real part of which represents the propagation speed of the leak, which is given by

$$\mathrm{Re}\{k\}=\frac{\omega}{c} \tag{4}$$

and the imaginary part of which represents the attenuation of the leak by

$$\mathrm{Im}\{k\}=-\beta\omega \tag{5}$$

where β is a measure of the loss within the pipe system. At low frequencies, both the speed and attenuation of the leak can be considered to be approximately constant. The received signals at locations 1 and 2, $x_1(t)$ and $x_2(t)$, are related to the leak signal $l(t)$ by

$$x_1(t)=l(t)\otimes h_1(t) \tag{6}$$

$$x_2(t)=l(t)\otimes h_2(t) \tag{7}$$

where $\otimes$ denotes convolution; $h_1(t)$ and $h_2(t)$ are the frequency response functions from the leak to sensors 1 and 2, respectively, which can expressed in the frequency domain by

$$X_1(\omega)=L(\omega)e^{-i\omega d_1/c}e^{-\omega\beta d_1} \tag{8}$$

$$X_2(\omega)=L(\omega)e^{-i\omega d_2/c}e^{-\omega\beta d_2} \tag{9}$$

where $L(\omega)$ is the auto-spectral density (ASD) of the leak signal. Combining the two equations above yields the transfer function between the two sensors by

$$H(\omega)=\frac{X_2(\omega)}{X_1(\omega)}=e^{-i\omega T_0}e^{-\omega\beta\Delta d} \tag{10}$$

where T_0 is the time delay and $\Delta d=d_2-d_1$.

3. Adaptive TDE algorithm

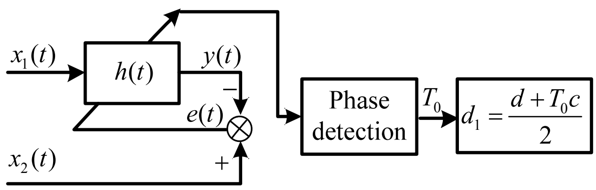

Figure 2: Diagrammatic representation of the LMS algorithm.

Consider the received signal $x_1(t)$ as the input signal to the adaptive filter, and $x_2(t)$ as the expected signal of the adaptive filter. A procedure for the determination of the leak location using the LMS adaptive filtering algorithm is shown in Fig. 2. The transfer function between the two sensors is theoretically infinite, which is truncated and adopted as a finite impulse response (FIR) filter $h(t)$. This transforms the time delay problem into an adaptive implementation of parameter estimation for the FIR filter. In the traditional adaptive model, it is assumed that the signals detected by the two sensors only have a time delay (without considering the propagation characteristics of a leak in the pipeline). Thus the input signal $x_1(t)$ passes through a filter with the transfer function of $H(\omega)=e^{-i\omega T_0}$, and thereby resulting in a delayed signal $x_1(t)$. The actual leak signals, however, attenuate as they propagate along the pipeline. When the influence of wave attenuation is neglected, only the maximum filter vector obtained by adaptive filtering are used to determine the time delay. Therefore this may lead to a large error for TDE. Nevertheless, as can be seen from Eq. (10), the imaginary part of the transfer function contains information about the time delay, suggesting the phase of the adaptive filter can be used as an alternative to calculate the time delay.

Assume that the transfer function at the *j*-th iteration is $\vec{h}(j)$, which is represented by

$$\vec{h}(j) = [h_1(j), h_2(j), \cdots, h_M(j)]^T \tag{11}$$

where the superscript T denotes transpose operation; and M is the order of the filter model. If the input signal vector at the *j*-th iteration is $\vec{X}(j)$ represented by

$$\vec{X}(j) = [x_1^j(t), x_1^{j-1}(t), \cdots, x_1^{j-M+1}(t)]^T \tag{12}$$

then the output of the adaptive filter is

$$y(j) = \vec{h}^T(j)\vec{X}(j) \tag{13}$$

The error adjustment signal is defined as

$$e(j) = x_2(j) - y(j) \tag{14}$$

In each sampling period, the parameters in the model can be adjusted by using the formula as

$$\vec{h}(j+1) = \vec{h}(j) + 2\mu \times e(j) \times \vec{X}(j) \tag{15}$$

where μ is the iterative step length controlling the convergence of the algorithm.

For the adaptive adjustment in the steady state, the mean square value of $e(j)$ approaches the minimum. Hence the corresponding phase information in the filter coefficients can be used to calculate the time delay T_0. The distance between the two sensors d is usually measured on-site or read off system maps and the propagation speed of the leak signal in the pipeline c can be calculated using Eq. (2). These parameters are further substituted into Eq. (1) for the determination of the relative distance from the sensor location to the leak.

4. Experimental validation

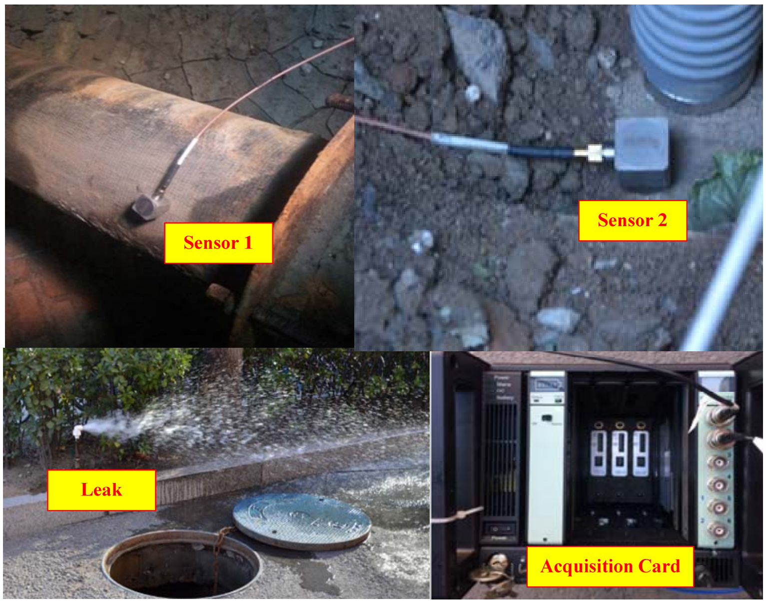

Figure 3: Test rig in the field.

In order to validate the proposed algorithm, tests were carried out at a leak detection facility connected to the mains located at the campus of the Institute of Acoustics, Chinese Academy of Sciences. The test rig comprised an 80 m length, 200 mm OD, cast iron pipe buried at a depth of approximately 2 m in clay soil. As illustrated in Fig 3, two accelerometers were mounted on the pipeline through the access manholes at each end of the pipe, and leak noise was generated by opening a valve fitted to the pipe section above the ground connected to the mains. Referring to Fig. 3, the leak signals were captured by using a B&K 3050-B-060 multi-channel noise analyzer.

Sensors 1 and 2 were located at the distance of 36.2 m and 43.8 m on either side of the leak. The 30 s signals were each captured at the sampling frequency of 8192 Hz. The parameters of the cast iron pipeline were c_f=1480 *m*/*s*,*B*=2.2 *Gpa*, *E*=140 *GPa*. Substituting these parameters of the pipe system into Eq. (2), the propagation speed of the leak signal was calculated as *c*=1291 *m*/*s*. From Eq. (1), a time delay T_0=5.8915 ms was subsequently obtained.

The signals were then processed via a 1024-point FFT using a Hanning window. The frequency results including the ASDs, coherence and phase spectrum, are shown in Fig. 4 (a-c). It can be seen from these figures that the signals measured by the accelerometers are concentrated below 3000 Hz. They are largely attenuated above 3000 Hz while below 700Hz the background noise dominates. Several peaks are observed in the ASDs at different frequencies, which are mostly likely due to pipeline resonances. It can be seen from Fig. 4(c) that the two signals have good coherence below 3000 Hz despite some dips at 1300 Hz and 1700 Hz. It is evident from Fig. 4(d), phase shifts occur at these two frequencies. The mechanism governing this is unclear at this moment. Nonetheless, a straight line can be fitted to the phase in the range of 700 Hz to 3000 Hz, indicating that the signal is predominantly non-dispersive in this frequency band.

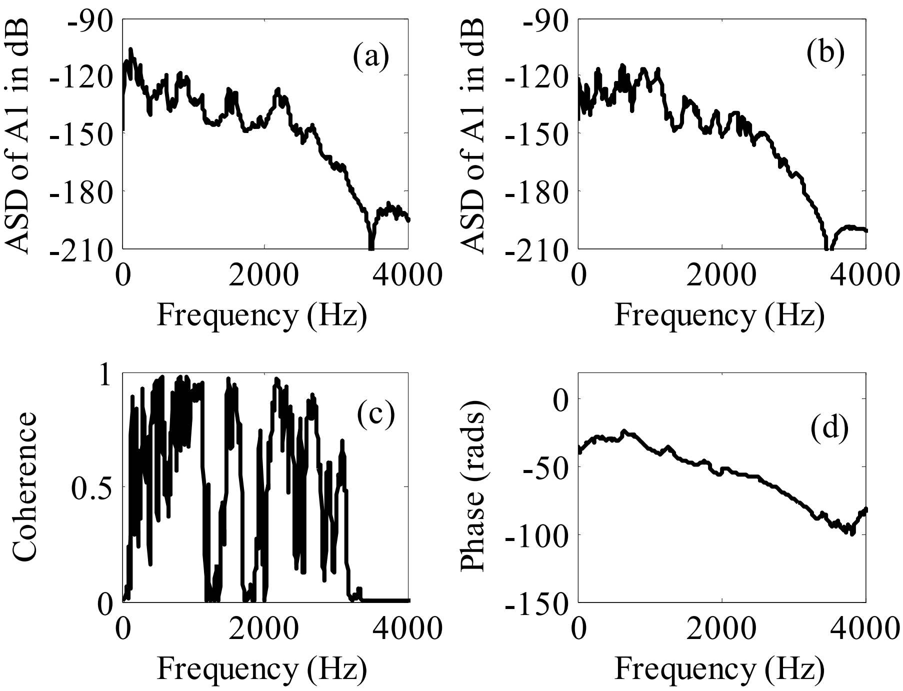

Figure 4: The ASD, coherence and unwrapped phase for accelerator-measured signals: (a) ASD of A1; (b) ASD of A2; (c) Coherence function; (d) Phase.

In the cross-correlation analysis, the original sensor signals were first filtered, and then passed through a 4th order Butterworth bandpass filter with the cut-off frequencies set as 700 Hz and 3000 Hz. The BCC result is normalised to the peak correlation value and plotted in Fig. 5. The time delay between the two signals is found to be 6.120*ms*, at which the maximum cross-correlation occurs.

In the adaptive filtering algorithm for TDE, the length of the weighting vector was set to be M=500, and the step size in each iteration was μ=1e-5. Fig. 6 shows the relationship between the iteration number and the estimated time delay. As can be seen from the figure, when the number of iterations is greater than 1.8e5, the estimated time delay converges to a steady value of about 5.249 *ms*. Fig. 7 shows the filter coefficients in the steady state adopted in the adaptive LMS algorithm. Compared with the conventional BCC as shown in Fig. 5, the time delay estimator given by the adaptive algorithm is less accurate than that provided by the BCC, since the wave attenuation in the pipeline is neglected in the analysis. As suggested in Section 3, in order to improve the accuracy for TDE, the propagation characteristics of the leak noise need to be accounted for in the analysis of the proposed algorithm. Fig. 8 plots the phase of the filter coefficients in the steady state. The slope of the phase plotted in Fig. 8 is calculated to be k=-0.2571, which can be converted into the estimated time delay 5.926 *ms*. Table 1 lists the results obtained by the three TDE algorithms. By comparison, it can be seen that the time delay estimated based on the phase information of the filter coefficients has the minimum error.

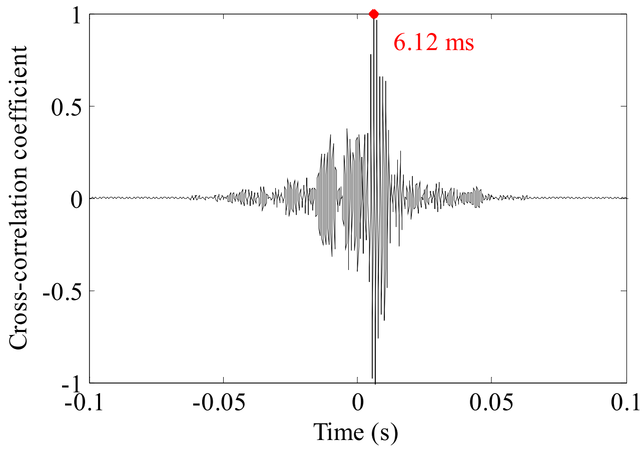

Figure 5: Normalized cross-correlation of two signals by using BCC.

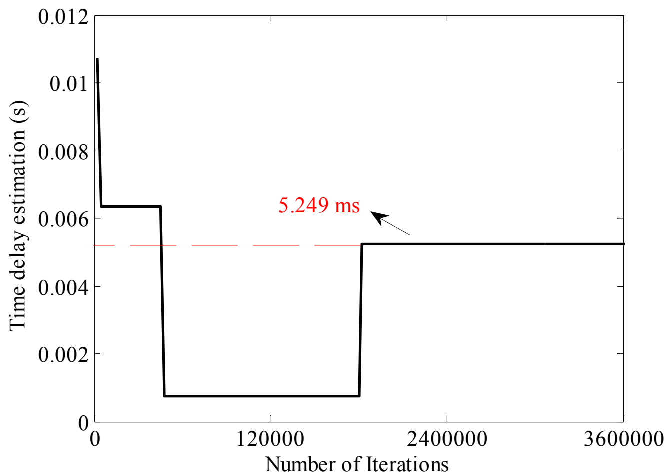

Figure 6: The number of iterations by LMS algorithm.

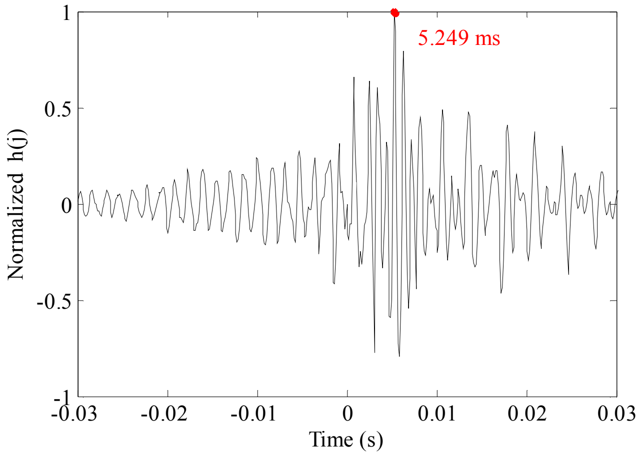

Figure 7: Transfer function in time domain.

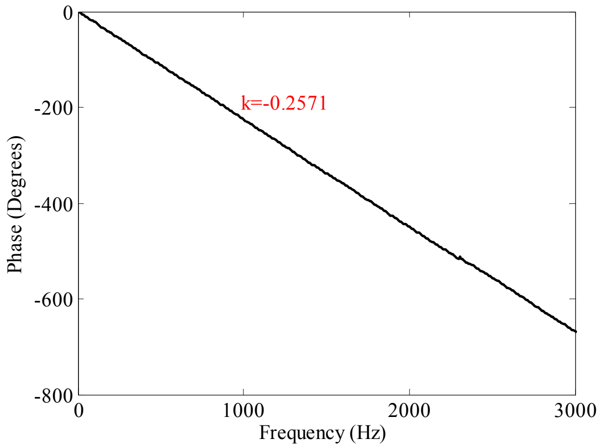

Figure 8: Phase of transfer function in frequency domain.

Table 1: Comparison of three TDE algorithms

	BCC	LMS	LMS_Phase
Estimate value of T_0 (ms)	6.120	5.249	5.926
Relative Error (%)	3.8785	10.906	0.5856

5. Conclusion

In this paper, an LMS adaptive method is presented for the detection and location of a leak in water distribution pipes. Based on the propagation characteristics of pipeline leakage, a new approach for TDE has been developed by using the phase information of the filter coefficients in the steady state. The main advantage of the adaptive method over the conventional cross-correlation methods is the possibility of locating a water leak without any concern with the spectral information about the leak and ambient noise. To evaluate the effectiveness of the proposed algorithm, analysis has been carried out on test data from a leak detection facility connected to the mains. Test results have confirmed the improved performance of the LMS algorithm for TDE in water distribution pipes.

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