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Application of the differentiation process into the correlation-based leak detection in urban pipeline networks

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ABSTRACT

One major challenge currently facing pipeline networks across the world is the improvement of leak detection technologies in urban environments. There is an imperative to locate accurately leaks in buried water pipes to avoid serious environmental, social and economic consequences. Much attention has been paid to time delay estimation (TDE) in determining the position of a leak by utilising cross-correlation, which has been proven to be effective with varying degrees of success over the past half century. Previous research in published literature has demonstrated the effectiveness of the pre-whitening process for accentuating the peak in the cross-correlation associated with the time delay.

This paper is concerned with the implementation of the differentiation process for TDE, with particular focus on the problem of determining a leak in pipelines by means of pipe pressure measurements. Rather than the pre-whitening operation, the proposed cross-correlation via the differentiation process, termed here DIF, changes the characteristics of the pipe system so that the pipe effectively acts as a band-pass filter. This method has the potential to eliminate some ambiguity caused by the interference at low frequencies and to allow more high frequency information to pass. Given an appropriate differentiation order, a more pronounced and reliable peak is obtained in the cross-correlation result. The use of differentiation process may provide a viable cross-correlation method suited to water leak detection. Its performance in relation to leak detection is further compared to the basic cross-correlation and pre-whitening methods for TDE in detecting a leak from actual PVC water pipes. Experimental results are presented to show an additional property of the DIF compensating for the resonance effects that may exist in cross-spectral density measurements, and hence better performance for TDE.

1. Introduction

Water stress has been increasing in recent decades due to high water demand following rapid urbanization and lack of access to reliable water supply. Leakage is usually the largest component of distribution loss (sometimes accounting for more than 70% of the total water losses), and indeed a major challenge facing urban pipeline networks. Water leakage is still high on the agenda across the globe, since it results in wasting the energy and material resources used in abstraction, trans-

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portation and treatment, additional damage to the pipe network and public health concerns. Common causes of water leakage include pipe aging and deterioration, poor network design and construction, inadequate corrosion protection, and mechanical damage. Much of our water distribution pipes installed decades ago are nearing the end of the useful life and approaching the age at which they need to be replaced. As documented in the American Water Works Association report [1], the replacement or rehabilitation of water distribution and transmission systems poses a new challenge emerging in the United States. Leakage rates of 10–20% are considered normal, but in some areas the aging infrastructure is losing more than 50% of water distributed [2]. According to the No. 1 document issued in 2011 [3], with the rapid economic and social development, China's water resource situation is undergoing profound changes. As such, in the years ahead, there will be a renewed focus on the reliability and integrity of underground pipeline networks. Water industries face growing challenges in their attempts to improve the performance of leak detection techniques, in particular in difficult conditions such as plastic pipes, pipes with large diameters, low pressure situations and deeper buried pipelines. Reflecting the mood of water industry across the world, there is an urgent demand on innovation and new leak detection technology for improving the sustainability of urban pipeline networks.

Pipeline leak detection methodologies have been the focus of numerous studies [4–21]. Methods such as visual observation and sounding with a steel rod were reported in early research. In addition, water-hammer techniques and acoustic measurements were also examined nearly one hundred years ago. Until recently, more advanced techniques have been developed and validated to some extent under laboratory and/or field conditions, including acoustic methods, infrared thermography, ground penetration radar, flow and pressure modelling, and transient-based methods, etc. It has been shown in published literature that pressure waves propagate downstream and upstream along the pipe as a result of water leakage. The position of a leak can be deduced from pressure measurements in that these waves carry the information or features of the leak source. In recent years, significant efforts have been made to investigate the transient leak detection methods [14–18]. The basic idea of these methods is that a pressure wave is generated by any sudden changes of flow such as rapid closing or opening a value; these propagating waves are partially reflected as they encounter a leak, and subsequently measured by pressure sensors for extracting the information of the leak source. Although they show some promise, it has been found that the effectiveness for determining the leak position depends largely on the properties of pressure transients. Moreover, the transient-based leak detection methods have safety issues that may have an influence on pipe integrity. Consequently, they are less attractive when undertaking leak detection surveys.

Acoustic methods using vibro-acoustic sensors are commonly adopted for the detection and location of water leaks, including simple listening sticks, ground microphones, acoustic loggers, and leak noise correlators. These methods have proven to be effective in locating a leak based on the knowledge of low-frequency propagation characteristics of the fluid-borne wave that is responsible for the structural and fluid motions in water distribution pipes [22–28]. When a leak occurs in a pressurised water pipe, the water as it flows out will cause these waves to transmit along the pipe and through the surrounding soil. The corresponding fluid motion can be measured by the employed pressure sensors at two access positions on pipe fittings or hydrants. Rather than transient pressure waves, continuous leak signals are used in the correlation analysis to calculate the time difference in arrival leak signals. As a result, currently available leak detection correlators operate by passive means. They have been developed over the past half century, and continue to provide a powerful solution for identifying precisely the location of the leak once it has been localised to a particular area of the pipe network.

The correlation-based leak detection methods involve the classical problem of time delay estimation (TDE) of sensor signals in the presence of background noise. A variety of cross-correlation algorithms have been developed, including the basic cross-correlation (BCC) and generalised cross-correlation (GCC), with the latter performing an additional weighting on the cross-spectral density (CSD) measurements, i.e., a pre-filtering operation in the time domain. Examples of the well-known GCC methods were presented by Knapp and Carter [29], including the ROTH impulse response, the WIENER, the phase transform (PHAT), the smoothed coherence transform (SCOT), and the maximum likelihood (ML). Their performance was further discussed by Gao et al. [30] for the application of water leak detection. It was shown that the GCC via a pre-whitening process has a desirable feature of accentuating the peak in the cross-correlation function.

This paper presents a new cross-correlation method, termed here the DIF method, which involves the implementation of the differentiation process before performing cross-correlation. Based on the analytical model of wave propagation established in earlier work by Gao et al. [10], this paper aims to study the performance of the DIF for leak detection in water distribution pipes. Theoretical analysis demonstrates that in the DIF method, the pre-filtering operation changes the characteristics of the pipe system in order that the pipe effectively acts as a band-pass filter, and thus leads to potentially more accurate TDE. Test data from actual PVC water pipes are used to validate the proposed method in comparison with the BCC and the pre-whitening GCC methods.

2. Correlation-based leak detection methods

2.1. Leak detection system

Correlation-based leak detection methods have been studied in previous work by Gao et al. [10,12,30,31] with the application for plastic water distribution pipes. In this section only a brief review is provided to assist readers to gain the basic knowledge of acoustic methods for water leak detection. As stated earlier, waves travel away from the leak source along the