A review of methods for burst/leakage detection and location in water distribution systems
Rui Li, Haidong Huang, Kunlun Xin and Tao Tao

ABSTRACT

The problem of bursts and leakages in water distribution systems has received significantly increased attention over the past two decades. As they represent both an environmental and an economical issue, how to reduce water loss through bursts and leakages is a challenging task for water utilities. Consequently, various techniques have been developed to detect the location and size of leakages. The methods for bursts (or leaks) detection and location can be broadly divided into two main categories, one based on hardware and the other based on software. Hardware-based methods include (i) acoustic detection methods such as listening rods, leak correlators, leak noise loggers and (ii) non-acoustic detection methods such as gas injection, ground penetrating radar technology and infrared photography. Software-based methods make use of the data collected by real-time pressure and/or flow sensors and several artificial intelligence techniques and statistical data analysis tools, including (i) methods based on numerical modeling methods, such as inverse transient analysis, time domain analysis and frequency domain analysis, and (ii) some non-numerical modeling methods, such as artificial neural networks, Bayesian inference systems, the Golden section method, and Kalman filtering. In this article, the authors describe the methods for pipe network burst location and detection, summarize the features of each method, and propose a suggestion for future work.

Key words | detection and location, leakage, pipe burst, water distribution system

INTRODUCTION

The problem of bursts and leakages in water distribution systems has received significantly increased attention over the past two decades. Bursts and leaks not only cause economic losses to the water industry but also represent an environmental issue and a potential risk to public health with regard to contaminated water (Puust et al. 2010). The amount of leaked water varies widely between different countries. In China, about 6 billion m$^3$ water are lost due to bursts and leaks each year.

To prevent water loss and improve water use efficiency, more effective methodologies of bursts/leaks control are required. Although there are a variety of methods to solve the problem of detecting and locating bursts/leaks, they can be broadly divided into two main categories (Sima et al. 2009), one based on hardware, and the other based on software.

There are a large group of methods using highly specialized hardware equipment, such as leak noise correlators, leak noise loggers, gas injection, ground penetrating radar and infrared photography. Despite the advantage of accuracy in bursts/leaks detection and location, they also have some drawbacks. For example, they are expensive, labor-intensive, slow to run, and may also require the cessation of pipeline operations for long periods of time (Romano et al. 2011). Therefore, researchers have been focusing more on finding faster techniques based on software that cost less to run.

Techniques based on fluid transients for burst/leak detection have gained popularity over the last decade, for example, inverse transient analysis, time domain analysis and frequency domain analysis (FDA). Using these techniques, a massive amount of data can be gathered in a very short period of time, therefore ensuring that the inverse problem will always...
be over-determined. However, they often require a significantly larger number of such sensors in the pipeline network that leads to high costs. In addition, methods based on transients are mainly used on single, above-ground pipelines, for it is hard to follow underground pipes of the system’s architecture.

With the latest developments of hydraulic sensor technology and on-line data acquisition systems, techniques that use artificial intelligence (AI) tools and statistical data analysis tools are emerging, including artificial neural networks, Bayesian inference systems, the Golden section method and adaptive Kalman filtering (Ye & Fenner 2011). They are different from transient analysis in that they only require pressure or flow data sampled at a much lower frequency. In addition, for the AI-based techniques, there is still room for improvement in terms of pinpointing bursts/leaks, as no information about its precise location is given when a burst/leak is discovered in a particular area.

In the rest of this paper, hardware-based and software-based methods are described, followed by the main conclusions and recommendations for future work.

**HARDWARE-BASED METHODS**

This type of approach for detecting the position of pipe bursts/leaks is usually associated with hardware devices. According to the theoretical principles that apply to the hardware device, these methods can be divided into acoustic and non-acoustic detection methods.

**Acoustic detection methods**

Specifically, the current broadly used acoustic methods include listening rods, leak correlators and leak noise loggers (Mutikanga et al. 2013). Such methods are mainly based on the features or principle of sound for detection.

**Listening rod**

The basic acoustic instrument is the listening rods, which is a cheap and useful tool. Its shape is like a probe, and the tail is equipped with a spherical object that can fit closely with the ears of metal rods; it can accurately determine problem areas by using the principle of conduction. By being in contact with the surface of the detection equipment, the listening rod can detect a variety of faint sounds which human ears cannot hear due to air isolation or outside interference when the equipment is in operation. It is like a doctor’s stethoscope, through contact with the human body, the doctor will be able to listen carefully to the sound of the heart beating, or the sound of breathing. The listening rod is simple, but to accurately determine where the problem lies will usually depend on the user’s experience and overall capability. Other available instruments, such as the electronic listening rod and listening devices, use the same working principle as the listening rod; however, due to great progress in the electronic zoom function, the detection accuracy of these devices is significantly improved.

**Leak correlator**

The leak correlator is a product of third-generation technology. It is also the world’s most widely used advanced technology to accurately determine the location of a leak (Thornton 2002), especially in noisy places, deeply buried pipelines or regions that are inappropriate for the ground listening method. With a leak-related instrument, we can quickly and accurately detect the exact location of underground pipe leakage. The method is different from the listening rod, because it is based on the noise velocity rather than the noise level caused by leakage. It calculates the leakage point by collecting data from both ends of the leaking pipeline, including the distance between the two sensors, the time difference between the two sensors when the sound reaches them, and the sound propagation velocity in the pipe, and performs relevant calculations with these data. The leak-related instrument is an effective detection method for long distance pipelines (Hunaidi et al. 2004), the sensitivity is slightly higher than the average, and the operator’s skill level requirements are relatively low. However, there are a number of difficulties in trying to determine the position of leaks in plastic pipes (Muggleton & Brennan 2004).

**Leak noise loggers**

Leak noise loggers (Shimanskiy et al. 2005; Muggleton et al. 2006) generally consist of several data loggers and a controller of all the acoustic receivers installed in the water
distribution system. When the computer equipped with special software for data loggers is programed, the recorder is put at different locations on the pipe network, such as hydrants, valves and other exposed piping. The recorder is then automatically turned on at the default time to record the acoustic signal throughout the leaking pipes. The signals are digitized and automatically stored in the logger, then processed through special software on the computer to quickly detect the existence of leakage. The basis on which leaks are distinguished is that each leakage point will produce a continuous leakage sound, which determines the presence of leaks near the recorder according to the degree of intensity and frequency the noise logger records. Computer software will identify this automatically and make a two-dimensional or three-dimensional map of leakage points. Such methods are typically used for non-district meter area (DMA) trunk pipe leaks. Compared with the listening rod, this method is generally done automatically by the computer system, with fewer requirements for professional experience.

In general, acoustic detection methods work well for medium and large metal pipe leakage detection. But tests showed that they cannot accurately detect small pipe leakage, especially in the case of large diameter, non-metallic trunk pipes. Because the leakage sound in large pipes is usually at a low frequency, the detection equipment cannot distinguish it. In addition, the success of acoustic detection methods for plastic pipe leakage is not significant, because non-metallic pipe leakage sound is also mostly at the low frequency that leak detectors or hydrophones cannot accurately identify.

### Non-acoustic detection methods

Being different from the acoustic detection method, the non-acoustic detection method is unaffected by those factors described above; therefore, the non-acoustic detection method has a wider application than the acoustic detection method. Specifically, the current non-acoustic detection methods include gas injection, ground penetrating radar detection technology, thermal infrared imaging, radioactive tracers leak detection, etc. Here the authors mainly discuss the gas injection method, ground penetrating radar detection technology and the thermal infrared imaging method.

### Gas injection

By injecting industrial hydrogen (95%N₂, 5% hydrogen) into the pipe and detecting the gas with a ground detector that is sensitive to industrial hydrogen, then the location of pipeline leakage can be determined according to the location of the gas detected (Figure 1). Hydrogen is the lightest gas and it has an important characteristic in that it can flow through very small surface cracks. As the gas detector is very sensitive to a very small amount of this gas, a very small leak can be detected using this method (Hunaidi et al. 2000). At present, such methods have been widely applied using machine detection; however, because of the high cost, this technique is generally used for large-scale low-pressure non-metallic pipe leakage detection. In addition, the technology has a major drawback in that only leakage above the pipeline can be detected using this method, for the gas cannot overflow from the bottom of the pipe.

### Ground penetrating radar

Ground penetrating radar (GPR) (Hunaidi 1998) inspection is a non-destructive and non-invasive geophysical method that produces a continuous cross-sectional profile or record of subsurface features. In recent years, it has been given a lot of attention. Using this technique, the equipment is not required to be inserted into the internal pipe. Ground penetrating radar technology works by transmitting high-frequency electromagnetic waves underground using...
transmitting antennae and receiving the electromagnetic wave reflected back to the surface, to infer the spatial location, structure, shape and burial depth of the subsurface according to the received electromagnetic wave, amplitude, and changes in intensity and time (Figure 2). Leakage water will make the relative dielectric constant of the medium increase at the leakage area or below the infiltration line, showing a significant difference to a site where there is no leakage. A characteristic image with lower frequency and larger amplitudes is produced on radar profiles to infer the spatial location, scope and burial depth of the leakage point. Compared to other methods, this method is fast, convenient, with high precision and resolution. It can be applied to leakage detection of large-scale low-pressure non-metallic pipes; however, it might not be applicable in cold climates or saturated soil.

**Thermal infrared imaging**

The principle of a thermal infrared (IR) camera (Mohamed & Osama 2010) is based on thermal infrared imaging. When it receives and displays the emitted IR radiation from an object, the infrared energy can be right on the focal plane of infrared detectors, then it can be converted into electricity through photoelectric conversion. Through a sequence of signal processing, the viewfinder of the thermal camera can get the thermal image of tested equipment and detect thermal contrasts, as is shown in Figure 3(a), and a case study is shown in Figure 3(b). A thermal infrared camera has many positive characteristics, such as high efficiency, accurate judgment, intuitive images, safe and reliable, detection without contact, immunity to electromagnetic interference, long detection distance and high speed, and is independent of pipe material type and size. However, it also has some drawbacks, for example, it is affected by many factors such as weather conditions, soil, and pavement surface conditions.

**Hardware-based methods – conclusions**

The various methods that are based on the hardware devices described above are currently used to detect leaks. With the
development of technology, the accuracy of such methods will be increasingly high. They are often accompanied by high costs, as relatively expensive equipment and a large number of leak detection staff are necessary for these methods. For a limited detection range and the required equipment installation, using such methods is generally more time-consuming, especially for large pipe networks. The effective range, advantages and disadvantages of the above methods are listed in Tables 1 and 2.

SOFTWARE-BASED METHODS

It can be seen from Tables 1 and 2 that many shortcomings exist in these methods based on hardware. The detection range is limited, and leaks cannot be detected in a timely fashion for large pipe networks, besides which the operating cost is usually high. Although the accuracy of hardware methods is high, the timeliness and sensitivity is low. Consequently, much research has been focused on finding faster techniques that cost less to run. Software-based methods typically rely on an algorithm or some kind of model for leakage detection. As such methods rely on additional information (like pipe network pressure, flow data) rather than on the leakage noise information, they run well on any type of pipes. Compared with hardware-based methods, software-based methods do not aim to accurately locate the definite leakage point, but to minimize possible leakage areas to the minimum level. Thus, the efficiency of the leakage detection is improved. Software-based methods can be roughly divided into

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**Table 1** | Effective scope of hardware-based methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Detection range</th>
<th>Degree of leakage detection</th>
<th>Accuracy</th>
<th>Applicable pipe material</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listening rod</td>
<td>200–500 m</td>
<td>About 0.003 l/s</td>
<td>30–75 m</td>
<td>Metal</td>
<td>Rajtar &amp; Muthiah (1997)</td>
</tr>
<tr>
<td>Leak correlator</td>
<td>15–2,000 m</td>
<td>About 0.03 l/s</td>
<td>&lt;0.6 m</td>
<td>Metal</td>
<td>Hunaidi et al. (2000)</td>
</tr>
<tr>
<td>Leak noise loggers</td>
<td>Related to accuracy demanded</td>
<td>Leaks above 10 dB</td>
<td>2.5 m</td>
<td>Metal</td>
<td></td>
</tr>
<tr>
<td>Gas injection</td>
<td>1 m</td>
<td>Unlimited</td>
<td>&lt;1 m</td>
<td>Unlimited</td>
<td>Hunaidi et al. (2000)</td>
</tr>
<tr>
<td>Ground penetrating radar</td>
<td>1 m</td>
<td>0.33 l/s</td>
<td>0.001 m</td>
<td>Unlimited</td>
<td>Hunaidi (1998)</td>
</tr>
<tr>
<td>Thermal infrared imaging</td>
<td>Related to temperature difference</td>
<td>Temperature difference 0.05–0.10°C</td>
<td>0.1 mrad</td>
<td>Unlimited</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2** | Advantages and disadvantages of hardware-based methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listening rod</td>
<td>Low cost and simple operation</td>
<td>Low accuracy, dependent on the experience of staff and less effective on non-metallic pipes</td>
</tr>
<tr>
<td>Leak correlator</td>
<td>Portable, high accuracy, FM and removing noise</td>
<td>Higher cost, accuracy susceptible from diameter, pipe material, pressure etc. and less effective on non-metallic pipes</td>
</tr>
<tr>
<td>Leak noise loggers</td>
<td>Automatic leak detection, does not rely on the staff's experience and easy installation</td>
<td>High cost, accuracy susceptible from the number and arrangement of loggers and less effective on non-metallic pipes</td>
</tr>
<tr>
<td>Gas injection</td>
<td>High precision, not susceptible to other factors</td>
<td>High cost, unable to detect the lower side of the pipe</td>
</tr>
<tr>
<td>Ground penetrating radar</td>
<td>High precision, not susceptible to other factors</td>
<td>High cost, expertise needed and unable to detect pipe leakage in a saturated soil</td>
</tr>
<tr>
<td>Thermal infrared imaging</td>
<td>Less time and less cost needed</td>
<td>Affected by many factors</td>
</tr>
</tbody>
</table>
Numerical modeling methods and non-numerical modeling methods. Numerical modeling methods identify possible leakage areas by establishing a relevant numerical model which is used to gain relevant data, and comparing simulation results with field data.

**Numerical model methods**

Currently, numerical model methods mainly include methods based on transient events and the traditional hydraulic model method. The traditional hydraulic model method detects leakage using data when the pipe network is under steady-state conditions. Compared with other hydraulic models, it is more convenient to build and solve the traditional hydraulic model. Thus, the traditional hydraulic model has been favored by many researchers.

**Kang & Lansey (2014)** proposed a novel pipe burst detection method combined with a limit analysis method. In this method, the pipe burst simulation is to add the node with a certain diffusion coefficient diffuser. The specific steps are divided into the following three parts. First, identify system pressure and flow uncertainty using the limit analysis method, then perform a pipe burst event simulation on each node, and finally obtain the pipe burst sensitivity matrix of each node according to the structure of the pipe burst simulation. Second, determine the possible location of a pressure and flow monitoring point based on the matrix of pipe burst sensitivity obtained above. Third, determine the possible pipe burst position according to the extent of the match between the specific burst sensitivity tables that are based on SCADA (Supervisory Control and Data Acquisition) monitoring data and the developed burst sensitivity matrix. A simple pipe network pipe explosion simulation shows that this method has some validity. However, this method needs further validation if it is applied to practical situations.

Based on similar principles, **Farley (2015)** proposed and demonstrated another pipe burst positioning method. This method obtains a Jacobian matrix by simulating a pipe burst, then selects monitoring sites according to the Jacobian matrix. Finally possible pipe burst locations are identified by comparing simulation results of the Jacobian matrix and the actual pipe burst Jacobian matrix. The author verified the method in several different DMA, and proved that it worked to some extent.

Leakage detection and location using fluid transients is given more and more attention by researchers. As large amounts of data can be obtained in a very short time when the fluid is under a transient state, it guarantees that a unique solution can be obtained when solving the inverse problem. Moreover, compared with steady-state fluid, hydraulic results are less susceptible to the pipe resistance coefficient under a fluid transient state. To sum up, current main methods based on transient events include inverse transient analysis, time domain analysis and FDA.

**Inverse transient analysis**

Inverse transient analysis (ITA) is a relatively new approach combining the inverse method with the transient analysis in networks (Covas & Ramos 2001). **Liggett & Chen (1994)** first introduced a transient model into water supply pipe network leakage detection. It is called ITA when pipe leakage is detected using simulation results of a transient model and transient measurement data. The ITA method generally involves researching and modeling the behavior of water supply systems under transient events. Transient events which can be artificially induced (e.g. closing the valve), or which occur through natural causes (such as pipe burst), tend to cause the pipe network pressure or flow to change significantly over a short time period. The pressure or flow change caused by transient events is big enough to characterize the information from water supply systems; however, how to effectively extract useful information like the pressure or flow data from transient events is still a problem, for such information is usually overshadowed by various noise sources. In the ITA method (Kapelan et al. 2003), leakage detection is described as an optimization problem and its objective function is shown in formula (1):

\[
\text{Min } \text{SSE} = \sum_{i=1}^{N_x} \sum_{j=1}^{N_t} (p_{ij}^* - p_{ij})^2
\]  \hspace{1cm} (1)

where: \(N_x\), the location number of the pressure monitoring point; \(N_t\), step interval numbering; \(\text{SSE}\), the summation of mean square error between field pressure data and simulated transient pressure data; \(p_{ij}^*\), pressure analog data at pressure monitoring point \(i\) with time step \(j\); \(p_{ij}\), pressure analog data at pressure monitoring point \(i\) with time step \(j\).
The actual pressure monitoring data is compared with the simulation pressure data obtained from the transient model, then the minimum mean square error between them is calculated, and lastly the location of the leakage point is determined. Leakage detection methods using an inverse transient model generally include the following main steps:

1. Pipe network transient events are artificially manufactured by opening or closing fire hydrants or pumping stations, thus the pressure or flow of the pipe network changes significantly. However, it must be noted that pressure and flow velocity caused by transient events need to be controlled within the permissible range.
2. The pressure at the selected monitoring points is measured with a high-resolution pressure sensor.
3. The model is corrected periodically until the end of the convergence condition by comparing the actual monitoring data and transient model simulation data.

The ITA method has been carefully researched since its introduction. However, the main effort has been focused on the development of the mathematical part of the technique rather than on experimental validation or field testing. Some limited experiences from laboratory and field tests can be found from Vitkovsky et al. (2001), Stephens et al. (2004), Covas et al. (2005b) and Saldarriaga et al. (2006). To test the effectiveness of the transient analysis method, Vitkovsky et al. (2007) verified this method in the laboratory. Experimental results show that the method has a certain rationality and feasibility. The main advantage of ITA lies in its simplicity and that it can be applied to any network topology in theory. However, it should be noted that there is some difficulty in making this type of approach practical. First, the ITA requires accurate transient model and pipe network boundary conditions, the model error is the main limiting factor applied to the actual pipe network. Second, the method often requires a large number of high-sensitivity sensors for high-frequency sampling. Third, no effective method has yet been found to accurately distinguish a signal response caused by leakage or by other similar noises. Similarly, Covas & Ramos (2010) collected data from two pipe systems (a laboratory facility at Imperial College London and a quasi-field system at Thames Water Utilities) to investigate to what extent transient pressure signals could be used for leak detection, location, and quantification by ITA. This transient-based technique has been shown to be successful in the detection and location of leaks of reasonable size, provided that physical and hydraulic characteristics of the system are known. However, it will be very difficult to apply to a buried leak in real systems considering that the signal will have multiple-random fluctuations, and the limited manpower resources a utility has to know the physical and hydraulic characteristics of the system. Thus, this method can only be successfully applied in single, well-known and controlled transmission systems for the moment.

**Time domain analysis and frequency domain analysis**

Similar to ITA methods, time domain analysis (TDA) and frequency domain analysis (FDA) also take advantage of the information generated by transient events. However, what is different is that TDA and FDA methods do not need to use the simulated data generated from a transient model, as there is often no available transient model, besides which, this kind of model is usually quite difficult to establish. In spite of this, these two methods also have to face another difficult problem, namely the problem of signal attenuation. The only difference between TDA and FDA lies in the different way of analyzing the pressure monitoring data. The TDA method generally does not involve any mathematical conversion. It analyzes the pressure monitoring data directly in the time domain, so it has the advantages of intuition and preciseness.

Jönsson & Larson (1992) first proposed the TDA method for the detection of leaks using the wave reflection method. Such a method first generates wave pressure by a transient event, then determines the position of the leakage point by detecting and measuring the arrival time and the velocity of the reflected pressure wave. The arrival time of the pressure wave consists of two parts: the arrival time from the transient event point to the leakage point, and the return time from the leakage point to measurement sites. Based on the same principle, Silva et al. (1996) proposed the sparse wavelet method, which is mainly used to detect negative pressure waves caused by pipe bursts. Compared to other methods, the main advantage of the method based on reflected waves is its simplicity. But how to
accurately monitor the weak pressure signal is still a problem to be solved, because the pressure signals are often subject to background noise, especially in the case of a small leak. Inspired by the research work of Liou (1994), Vitkovsky et al. (2003) proposed a new method for identifying pipeline leakage or blockage based on the principle of reflection. The location of the leak is determined according to the position of the spikes, and the size of the leak is estimated depending on the size of the spikes. Although the results show that the method has potential to become a tool for leakage detection, before this method can be applied to the actual pipe network, there are still some issues to be solved, for example, how to accurately measure the pulse, and how to determine the pulse which is caused by leakage in the presence of noise interference. Wang et al. (2006) proposed a new leak detection technique based on TDA, and the solution showed that the presence of a small leak reduces the amplitudes of the resonant frequencies while its influence on the non-resonant frequencies is negligible. Compared to the acoustic based leak detection methods, the proposed method may be applied with a much greater measurement interval and is less influenced by the background noise. However, as this method is also based on transient events, it can only be used on single pipelines.

Since the wavelet transform analysis can effectively extract information from the signal, it can carry multi-scale detailed analysis on function or signal through computing functions such as scaling and translation, so in recent years, some researchers have used wavelet analysis to treat pressure signals when performing leakage detection. Ferrante & Brunone (2005) tested the feasibility of such techniques, and the results indicated that the use of such technology could effectively identify pressure signal fluctuations caused by a small leakage. Taghvaei (2009) did a laboratory test, and the result showed that the combined wavelet transform and cepstrum method is possible for the detection and location of even small leaks in pipe networks. Wang et al. (2012) presented an improved cross-correlation algorithm for high-precision pipeline leak detection based on wavelet transform and energy feature extraction. To further verify the feasibility and superiority of the proposed method in practice, a set of field testing signals were analyzed with the improved algorithm, and the results showed that the improved method could achieve higher precision in the identification of signal similarity and time delay, especially when the continuous acoustic emission signals were affected by various disturbances and noise. However, it must be noted that such methods need detailed and specific authentication in the actual network.

In contrast to TDA, FDA can have a certain mathematical conversion of the pressure signal. Considering that the signal not only changes over time, but is also related to information such as the frequency and phase, the signal frequency structure requires further analysis, and the signal will be described in the frequency domain. Such methods also need to use the information generated by the transient event, but this time the transient event is usually induced by several cycle-driven devices, such as vibration valves, which are often installed at the downstream end of the pipe. Through analyzing the frequency response plot when leakage or no leakage exists in the pipe network, it can be determined whether leakage exists according to whether the formant is changed in the frequency response plot. Typically, when leakage occurs, the formant of the frequency response is lower than when there is no leakage. The use of frequency response methods for pipeline leakage detection was first suggested by Mplesha et al. (2001). Such a method converts the pressure signal from the time domain into the frequency domain using the Fast Fourier Transform, then determines leakage using the conversion matrix method for analysis. Experimental results show that a very small leak can be detected and located using this method. Inspired by cable fault locating methods, Covas et al. (2005a) put forward a standing wave difference method for leakage detection. The method takes advantage of the vibration flow and spectrum analysis principles. The authors performed related simulations using several different construction forms of pipe network, and the results showed that the method had some validity. However, such methods have not been validated by any experiments or field data.

From relevant research results, the method based on transient events has the potential to become a more effective tool for leakage detection. But it is undeniable that the method still has a long way to go before it becomes a practical technology. The main reason is that most tests of these methods are carried out in a simple pipe network under strictly controlled conditions of the experiment and so far these methods have not been verified in actual networks,
especially the more complex pipe network systems. The efficiency ranges of various leak detection methodologies using pressure transients is shown in Table 3.

Traditional hydraulic modeling techniques have improved over the last two decades due to technical improvements to modeling software and advances in SCADA systems. These techniques have been studied by many researchers (Rossman 2000; Todini 2006; Wu & Sage 2006; Giustolisi et al. 2007, and many others). In one of the most recent studies, Wu et al. (2011) developed a relatively new approach called pressure dependent leakage detection (PDLD) as a hydraulic model for identifying the leakage. Two case studies, one in Thailand and the other in the UK, have been undertaken by using the PDLD method together with step-testing and acoustic noise logging devices, respectively. The results obtained with PDLD were successful in predicting the leak while both hardware-based methods failed. The studies illustrated that the PDLD method was effective in identifying leakage hotspots regardless of pipe material, and proved to be practical and useful in assisting the engineer to quickly find leaks in large water distribution systems (Tables 4 and 5).

In summary, the numerical modeling methods are relatively low in cost and simple in application, as they solve complex problems of leakage detection and location by establishing a straightforward numerical model and with certain monitoring information. The methods dependent on the numerical model have some advantages; however, they may have some drawbacks, because there is a need for accurate pipe information and related parameters which cannot usually be obtained to create numerical models. In view of this, with the development of technology, another type of leakage detection method, namely non-numerical modeling methods, has gradually increased in recent years.

To sum up, categories and characteristics of leakage detection technology are shown in Table 5.

<table>
<thead>
<tr>
<th>Transient methodology</th>
<th>Case study</th>
<th>Inspection range (pipeline length) (m)</th>
<th>Detectable leak size (l/s)</th>
<th>Location precision (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITA</td>
<td>Real</td>
<td>5,936</td>
<td>3</td>
<td>50</td>
<td>Covas et al. (2005b)</td>
</tr>
<tr>
<td>ITA</td>
<td>Real</td>
<td>Network</td>
<td>1</td>
<td>–</td>
<td>Saldarriaga et al. (2006)a</td>
</tr>
<tr>
<td>ITA</td>
<td>Laboratory</td>
<td>272</td>
<td>0.12</td>
<td>5</td>
<td>Covas &amp; Ramos (2010)</td>
</tr>
<tr>
<td></td>
<td>Quasi-field system</td>
<td>1,280</td>
<td>0.35</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>TDA</td>
<td>Laboratory</td>
<td>37.2</td>
<td>0.01</td>
<td>0.38</td>
<td>Wang et al. (2002)</td>
</tr>
<tr>
<td>FDA</td>
<td>Numerical</td>
<td>2,000</td>
<td>4.73</td>
<td>&lt;500</td>
<td>Lee et al. (2005)</td>
</tr>
</tbody>
</table>

aThis case study did not mention the location precision but gave the accuracy of leakage discharge estimation.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Application</th>
<th>Results obtained</th>
<th>Benefits</th>
<th>Defects</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANN</td>
<td>DMA (UK)</td>
<td>Effective</td>
<td>Adaptive, effective and on time</td>
<td>Large amounts of data required for training and updating</td>
<td>Mounce et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>DMA (Tehran)</td>
<td>Effective</td>
<td></td>
<td></td>
<td>Nazif et al. (2010)</td>
</tr>
<tr>
<td>Kalman filtering</td>
<td>DMA (UK)</td>
<td>Effective</td>
<td>Faster speed and efficiency; does not require large amounts of data</td>
<td>Hard to detect stable leaks</td>
<td>Ye &amp; Fenner (2011)</td>
</tr>
<tr>
<td>BISs</td>
<td>DMA (UK)</td>
<td>Promising</td>
<td>Can be useful when data availability is limiting or when dealing with different kinds of errors that cannot be included in calculations</td>
<td>A great deal of data and computer power needed for training and prediction</td>
<td>Romano et al. (2009)</td>
</tr>
</tbody>
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Non-numerical model methods

Non-numerical models analyze monitoring data combined with tools such as data mining or artificial intelligence algorithms, and then identify possible leakage areas based on certain rules or principles, without resorting to simulation results of the model. Such methods can also be called data-driven approaches, because they need to analyze data, find their own rules from large amounts of data, and ultimately determine the possible leakage points. Compared with approaches based on transient events, the sampling frequency at the monitoring points of non-numerical modeling methods is much lower, although both methods need to use data from monitoring equipment. There is no need to establish a hydraulic model for non-numerical modeling methods, therefore detailed information and parameters of the pipeline and equipment are not required, this is a significant feature of such methods.

Mounce et al. (2013) proposed a method combining artificial neural networks with a fuzzy inference system to detect pipe bursts, and then to validate the method through field data of several DMA. First the probability density function is constructed to speculate the flow curve of the future by training artificial neural networks with adequate historical data, then the fuzzy inference system is used for classification. Considering the respective advantages of artificial neural networks and fuzzy inference systems, the results show that the method can effectively and timely conduct online pipe burst tests. Aksela et al. (2009) have also done some research work related to artificial neural networks. To obtain a reasonable prediction, it is not difficult to find that using artificial neural networks to detect leakage usually requires a lot of historical data (usually several months of data) to train the neural network, and the neural network needs updating every month. Therefore, the efficiency of these methods is usually lower. Also, the methods are not able to detect leakage quickly because the training time is usually relatively long, and that often leads to alarm delay.

Considering the problems a traditional artificial neural network has, Ye & Fenner (2011) proposed an adaptive Kalman filtering method to detect pipe bursts. Compared with the artificial neural network method, the adaptive Kalman filtering method has a higher speed and faster detection efficiency. More importantly, it does not require large amounts of training data, thus avoiding effects caused by data error or lack of data. In this method, the adaptive Kalman filtering works as a tool to build a normal water mode. It can determine whether the system downstream has anomalies (such as pipe bursts) by the residual of the filter which is the difference between the measurement and the filter estimation. To test and validate the adaptive

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Kalman filtering burst detection method, it has been applied to two kinds of UK DMA data. Tests showed that the test results of this method are in good agreement with the historical operating results of the pipe network. Compared with the pressure monitoring data, flow monitoring data are more sensitive to pipe bursts.

Other methods, such as the Bayesian inference system (Poulakis et al. 2005; Rougier 2005; Puust et al. 2006; Romano et al. 2009), and the Golden section method (Yamamoto et al. 2006) are all non-numerical modeling methods. With the rapid development of hydro-sensing technology and on-line monitoring technology, non-numerical modeling methods have achieved initial success and are expected to become effective tools for detection and identification of small and medium pipe bursts. Nevertheless, there is much room for improvement in terms of testing reliability and timeliness. Moreover, whether a pipe burst has occurred in a particular area network can be more accurately found (for example, DMA) with such methods, without giving any precise information about the location of the pipe burst.

CONCLUSIONS AND RECOMMENDATIONS

Burst/leakage detection and location methods have come a long way since the mid-1950s, and significant advances have been made in the past in both hardware-based and software-based techniques. According to the review presented here, conclusions and future work recommendations are made as follows.

The hardware-based methods are still superior in terms of detection accuracy; however, they also remain much more expensive to use than the software-based methods. With regard to timely detection and location, the software-based methods are much better.

To sum up, each method has its own advantages and drawbacks. In the hardware-based methods, both the leak correlator and the thermal infrared imaging method are most promising, because they have high accuracy and a wide detection range. While in the software-based methods, the AI methods are quite promising due to the development of hydro-sensor technology and real-time online data monitoring systems.

Finally, developing ways of combining hardware-based methods with software-based methods effectively is the trend for future pipe burst and leakage research, that is to say, developing a compound method (e.g. using software-based methods to minimize the possible leakage area first, and then using hardware to pinpoint the location of leakage) which enables the water company personnel to react more quickly with lower cost in the case of burst/leak events. Although not exhaustive, this review could be a valuable reference resource for practitioners and researchers dealing with water loss management in distribution systems.

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