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A selective literature review of transient-based leak detection methods

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Abstract

This paper offers a selective literature review of transient-based leak detection methods with the goal of offering a summary of current and past work, describing the state-of-the-art in the area, providing a degree of historic perspective and categorizing the major themes in this line of research. While not exhaustive, numerous publications are cited in an attempt to provide a reasonable cross-section of research activity and of the various methodologies. Unfortunately, field work and verification of these techniques, while not entirely absent, are shown to be still generally lacking.

Keywords: Leak detection; Transients; Inverse methods; Literature review

1. Introduction

The problem of leaks in water distribution systems has generated significant interest due to the financial cost borne by utilities, potential risks to public health and environmental burden associated with wasted energy. In recent years, such concerns have led to the introduction of stricter penalties against water authorities for ignoring leakage and have provided the necessary incentives for the investment in better leak detection technology and enhanced leak reduction strategies.

Preoccupation with water loss is nothing new and is perhaps the most obvious cost of leakage since there is a clear relationship between a utility's income and water that fails to reach customers. Numerous studies have attempted to estimate typical water loss figures. Lai (1991) conducted one of the first 'global' surveys that reported water loss (then referred to as "unaccounted-for-water") figures from several different countries and cities and discovered that these varied widely, from a low of 9% in Germany to a high of 43% in Malaysia, with most countries falling into the range of 20–30%. Brothers (2001) estimated average water loss in North American networks to be about 20%, most of this being leakage. Growing concern over resource scarcity and water loss, partly confirmed by studies such as these, induced the International Water Association (IWA) to devise clear and unequivocal water audit procedures in order to facilitate system comparison and benchmarking (Alegre et al., 2000; Farley and Trow, 2003), a move also embraced by the American Water Works Association (AWWA, 2003).

In addition to water loss, leaks are costly in terms of energy consumption. Colombo and Karney (2002) raised this issue as part of a preliminary evaluation of the relative importance of energy waste via leakage. Further recognition of the energy cost of leaks was made in the AWWA Water Loss Control Committee's 2003 report which acknowledged that "the additional energy needed to supply leakage unnecessarily taxes energy generating capabilities" (AWWA, 2003, p. 75). In fact, the committee estimates that 5–10 billion kWh of power generated each year in the United States is wasted on water that is either lost via leaks or not paid for by customers.

The potential for leaks to admit contaminated water during hydraulic transients is yet another cost of leakage which has also been a key subject of inquiry. Funk et al. (1999) assessed the intrusion risk by evaluating the possible volume of intruding groundwater given transient duration and severity

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(minimum waterhammer pressure). As part of the AWWARF study *Pathogen Intrusion into the Distribution System* (Kirmeyer et al., 2001), Karim et al. (2003) collected and tested soil and water samples in the immediate vicinity of water mains at eight locations in six US states and found that often these soils contain potentially harmful bacteria and pathogens such as coliforms (detected in 58% and 70% of water and soil samples, respectively) and fecal coliform bacteria (detected in 43% of the water and 50% of the soil samples).

2. Common leak detection techniques

There is currently a variety of available commercial leak detection techniques ranging from simple physical inspection to acoustic methods. These largely depend on a leak's local properties, which entail interruption to pipe material integrity, water release and the emission of a characteristic noise or the manifestation of some other signal. Perhaps the oldest, albeit largely unsystematic, leak detection approach is visual observation. Ponding at the ground surface and anomalous vegetation growth can be indications of a compromised water main. Among current methods that depend on a devised procedure, acoustic techniques are the most widely used since fluid exiting from a leak generates high frequency oscillations in the pipe wall and transducers can be used to trace the vibration data to its source (AWWA, 1987). Even early acoustic techniques incorporated many variations, such as the use of metal rods equipped with earphones that are sunk to pipe level and transmit vibrations to the listener or stethoscope-like apparatus used in conjunction with leak position interpolation devices (Babbitt, 1920). Most of these techniques have not completely disappeared and some continue to enjoy relatively widespread use. Other methods include ground penetrating radar—which detects points of low electric impedance along the pipe, indicative of ponding (Eiswirth and Burn, 2001)—or electromagnetic techniques that find breaks in metallic pipes (Atherton et al., 2000). These all rely on the detection of certain *local* characteristics of the leak and thus suffer from a restricted operational range. Typically, leaks can only be detected if measurements are within 2 m of the breech, for electromagnetic techniques, and up to 250 m for acoustic methods, impeding their application to long transmission mains. Other commercial techniques, such as tracer gas injection, (Furness and van Reet, 1998; Black, 1992; Hargesheimer, 1985) and liquid sensing cables (ADEC, 2000) also pose range issues that may require numerous repeated tests or a string of sensors closely spaced along the pipe. Furthermore, many acoustic techniques are insensitive to large leaks as they do not generate vibrations in the characteristic high frequencies.

3. Transient leak detection

3.1. The principle of transient leak detection

An alternative to the above approaches is to exploit the hydraulic behaviour of the pipe system for determining leak position. Because a leak is first of all a hydraulic phenomena, and since it is located at a specific place, it is not surprising that its presence can be detected hydraulically, and that a transient pressure wave is an ideal vehicle with which to probe its presence and character.

In fact, any change in the physical (or propagation) structure of the pipe or system, such as a junction, constriction, expansion, blockage, roughness transition or leak imposes a wave reflection to an incoming transient signal, thus altering in some way a system's flow and pressure response. These modifications are in theory apparent or discernable at other locations in the network and their identification and characterization have the potential to reveal useful information about the nature of the originating singularity as well as the system as a whole. If a singularity establishes a clear and unique signature, it should be theoretically possible to locate it, typically via comparison of the pressure signal registered by monitoring devices relative to the signal that would be observed if the system did not contain the leak or singularity. The second way in which a leak can be identified is through its role in pressure relief. As a high pressure wave passes, the leak causes some attenuation in the primary transient signal by permitting escape of some pressurized fluid. (Note an important implication of this: leaks do in fact provide a degree of transient protection and fixing them removes some of this benefit. Thus, a well-thought program to fix leaks should explicitly address transient phenomena.) Two numerical examples illustrate these basic premises of transient-based leak detection.

In the first example, the effect of a leak on a transient signal measured at the valve boundary of a reservoir-pipe-valve system is shown in Fig. 1 for both mechanisms: singularity signature and attenuation. The transient is generated by closure of a downstream in-line valve from an initially opened state and the transient is measured at the upstream face of this valve. The figure compares the transient signal when the system is intact and when a leak exists. The transient signal from the leaking pipeline exhibits a distinct singularity not present in the intact system and this singularity is related to the arrival of a leak-reflected signal at the measurement station. The transient signal in the leaking system also decays more rapidly. The properties of the reflected signal and the increased

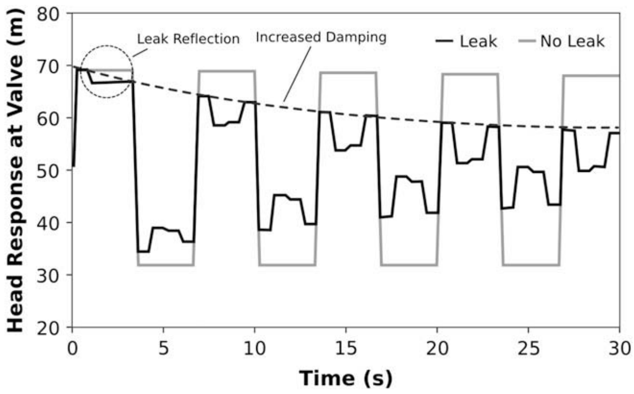

Fig. 1. Comparison of transients in intact and leaking pipelines.

transient damping can be exploited to achieve detection and is the key premise of transient-based leak detection.

The second example consists of the 2000 m long pipeline depicted in Fig. 2 for which a transient was generated by the sudden closure of an initially open side-discharge valve located 500 m from the upstream boundary. The wavespeed for this system is 1200 m s^{-1}. The unsteady traces measured at the transient source for the intact system, and when a leak was located 1500 m from the upstream boundary, are shown in Fig. 3. The figure indicates that a leak causes additional reflections, circled in the figure, in the transient trace. These reflections are leak-induced and the sequence of events leading up to the occurrence of the reflections in the signal is considered below (an approach that goes by the technical name of time-domain reflectometry).

Fig. 4 shows the propagation of the transient wave away from the source at $t = 0$ after generation of the transient event corresponding to the time labelled (A) in Fig. 3. Closure of the side-discharge valve induced a rise in the hydraulic grade line at the transient source that is detected immediately by the pressure transducer located in the same position. Note that two distinct wave fronts were generated from the transient event, one propagating upstream of the source and the other downstream.

Fig. 5 summarizes wave activity in the pipeline 0.833 s [$L/(2a)$] after transient generation. The upstream propagating wavefront has been reflected from the upstream reservoir and has returned to the measurement station, illustrated in Fig. 3 as the time labelled (B). The downstream propagating wave front is at the leak and is partially reflected. This leak-reflected signal begins to propagate upstream while the original transmitted signal continues to move downstream. Fig. 6 shows the pipeline at 1.667 s [$L/(a)$] when the leak-reflected wave has returned to the measuring point, giving the leak-reflected signal at the time labelled as (C) in Fig. 3.

In this example, the disturbance in the trace is generated by the arrival of the leak-reflected signal at the measuring transducer. The position of this disturbance in the trace indicates the arrival time of the leak-reflected signals and signifies the time needed for the transient signal to migrate from its source, reflect off the leak and return to the measurement transducer.

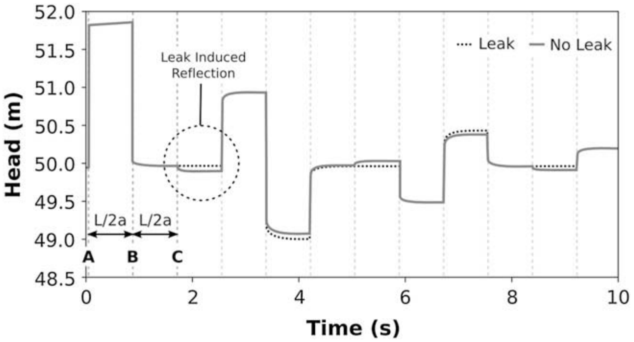

Fig. 3. Numerical comparison of transient traces from leaking and intact pipes.

While altered wave patterns and energy attenuation are properties of leaks under all flow regimes, analysis of the transient behaviour of networks for the purpose of leak detection may prove more fruitful owing to the vast amount of data that can be produced in a single test; in essence, the hydraulic transient puts the system through a succession of different states in a compressed time frame and can, thus, offer more information than simply registering system performance only at steady state. One of the other real challenges is of course the issue of system noise which, in a complex system, can arise from many sources, all of which complicate the separation of the leak signal from a vast range of other disturbances and events.

It needs to be emphasized that due to space constraints, this overview of the literature cannot be exhaustive. Currently, there are slightly more than a handful of research groups around the world who are dedicating significant resources to advancing the state of knowledge in this area. Yet, despite this, transient-based leak detection is still not widely known or applied in practice. This is not altogether surprising considering the novelty of the techniques, the many challenges still impeding their implementation, and engineering inertia to new methodologies. Nonetheless, transient-based leak detection is gaining interest as an economical and unobtrusive way to evaluate and diagnose network condition. The coming years are likely to be pivotal in their development and refinement.

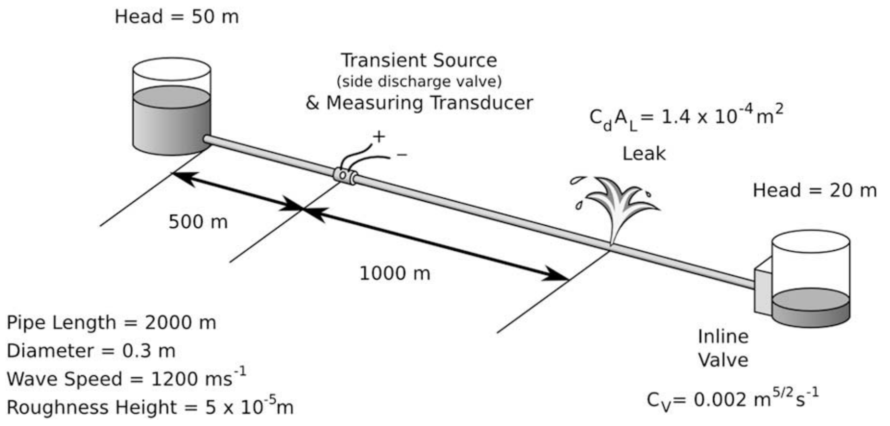

Fig. 2. Schematic of pipeline for illustrating the generation of leak-reflected signals in a transient trace.

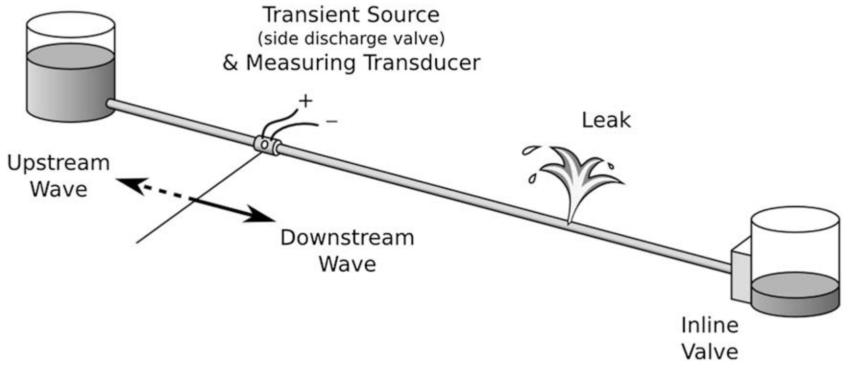

Fig. 4. Transient propagation at $t = 0$ s.

3.2. Overview of transient leak detection approaches

A perusal of the recent literature on inverse-transient analysis might suggest that transient-based leak detection is a recent development. However, almost a century ago, Babbitt (1920) surveyed the then existing leak detection approaches, describing techniques ranging from simple observation of flooded streets and anomalous vegetation growth to chemical tracer injections and acoustic methods employing a gamut of devices from iron bars to stethoscope-like apparatus. Among the strategies recounted, he mentions leak detection via attenuated transient pressure waves, exploiting the pressure-relief action that leaks provide during surges. The same property of leaks is the basis of the method proposed by Wang et al. (2002) over eighty years later. Moreover, the idea of scrutinizing pressure traces is a common feature of many of the variations of transient leak detection methods currently espoused by researchers.

One promising early technique using transients for leak detection is known as the rarefaction wave method which seeks to detect the low-pressure surge generated by pipe rupture (Silva et al., 1996; ADEC, 2000; Misiunas et al., 2003, 2004, 2005). The arrival time of this negative wave at each measurement transducer, and knowledge of the wavespeed, reveals leak location. This approach can be easily incorporated into a real-time fault monitoring system. However, it requires accurate detection of a small pressure signal of unknown shape which may be masked by background noise if the leak is small.

Another approach calls for customized pressure signals which are *injected* into a pipeline and the subsequent behaviour of the transient analysed. During its travel, a transient signal acquires properties that relate to the configuration and integrity of the system. Analysis of this signal can expose and locate leaks. These injected transients are designed to be small and can be used on a regular basis for system monitoring. Employing this method, operators are concerned solely with the behaviour of the injected signal, which is distinct from background noise and pressure fluctuations.

As mentioned, a leak affects the transient signal by:

- increasing its damping rate (Wang et al., 2002) or by
- creating reflected signals in the resultant pressure trace (Jönsson and Larson, 1992; Jönsson, 1995; Covas and Ramos, 1999; Jönsson, 2001).

Identification and quantification of these effects is at the heart of all transient leak detection techniques. There are essentially three schools of thought regarding how these effects can be exploited. The first involves inverse calibration of an accurate numerical system model to the observed transient data—known as the inverse-transient method—which utilizes the transient signal in the time domain in its analysis. Alternatively, the presence of the leak also changes the frequency response of the system, and thus the associated variation in system response can possibly be detected and decoded. The third class of techniques attempts to isolate the leak-induced effects in the pressure trace, seeking to directly

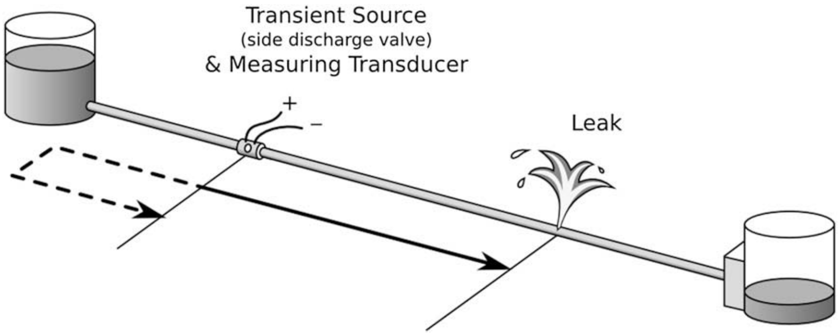

Fig. 5. Transient propagation at $t = L/(2a)$ s.

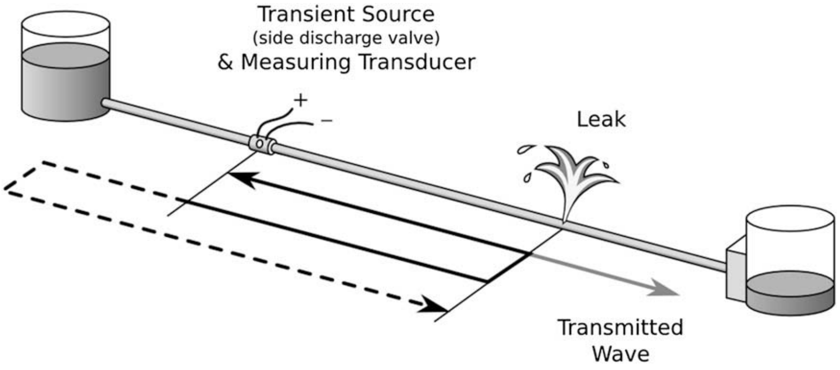

Fig. 6. Transient propagation at $t = L/a$ s.

expose particulars in the signal induced by the leak. A number of varied techniques fall under this latter category and, for the purpose of nomenclature, these techniques are referred to as direct transient methods because they exploit special features in the unsteady signal rather then infer leak location by reproducing the trace in a simulator in the time or frequency domain. All these methods are described in the following sections.

4. Inverse-transient analysis

The article by Pudar and Liggett (1992) is a milestone of leak detection research for two reasons: first, it was one of the first papers to advocate a leak detection procedure based on the measurement of pressures and, second, it explicitly called for the solution of the *inverse problem*. Usually, network analysis proceeds with the *forward problem* in which the demands and system characteristics (i.e., pipe roughness) are assumed known and what is sought are the resulting pressures and flows. In an *inverse problem*, the system state is known/measured (pressures, some demands, flows, etc.) but some parameters (pipe roughness, other demands, leaks, etc.) are unknown. Typically, the system's state variables are recorded during a transient event and compared with measurements corresponding to the same system free of leaks. Potential singularities (leaks) are then tested in a numerical-hydraulic simulator until the pressure traces of the system with and without leaks are satisfactorily matched. Then, the inverse problem is solved for the system parameters like pipe roughness and leak size and position.

In Pudar and Liggett (1992), the objective was to minimize the sum of the squared differences between measured and calculated pressure heads under steady state conditions, a result achieved through the derivative-based Levenberg–Marquardt (LM) method. When the procedure was applied to both over-determined and even-determined examples, the solutions were exact. For under-determined problems, useful information could still be discerned, but exact answers were no longer possible. In fact, error analysis performed even on a small system revealed that variation in leak areas due to errors in friction factor estimates were significantly greater than the variation due to errors in head measurement, indicating that accurate pipe friction values were needed in the inverse calculation. This did not bode well for most calibration exercises since leak size/location and pipe roughness coefficients are usually sought simultaneously. Results for the larger network were even more discouraging as they were overwhelmed by numerical error. Overall, the authors concluded that "in the case of leak detection by static methods, an inverse program is unlikely to provide the definitive results that would supplant more conventional methods. It could, however, serve as a supplement to leak surveys."

Liggett and Chen (1994) substantially broadened the scope of inverse calibration by coupling it to unsteady analysis. In contrast to the steady state approaches, transient conditions potentially offer a wealth of information from even a few measurement points, thus transforming an under-determined problem into an over-determined one. Since each measurement station can now provide an essentially unlimited number of data points in time, the goal of calibrating a system for leaks and pipes simultaneously comes within reach. Practically, inverse-transient analysis (ITA) is facilitated by economical high speed pressure transducers and faster computers for both data logging and problem solving. Real time monitoring merely further facilitates data acquisition for ITA.

As in Pudar and Liggett (1992), Liggett and Chen (1994) define the objective function of the inverse problem as the sum of squared differences between measured and simulated pressure heads. An accurate transient solver, usually MOC based, is required in conjunction with an optimization algorithm to minimize the model error. The procedure was numerically tested with the hypothetical 5-loop network described in Pudar and Liggett (1992). As it was not a laboratory or field test, the "measured" pressure heads at the four data extraction points were obtained by first solving the forward problem in a transient simulator (implying zero error in a perfectly contrived system). Initial guesses for pipe friction factors estimated them all at twice their true value. The procedure exhibited rapid convergence to the correct friction factors for all pipes and leak areas. The authors also described issues of error analysis, calculation and interpretation of the sensitivity matrix and some aspects of sampling design. A similar comparison between measured and predicted transient behaviour for the purpose of leak detection was also carried out by Liou and Tian (1995). The methodology proposed in Liggett and Chen (1994) has been refined by numerous researchers over the years with particular attention focused on methods for optimizing the objective function, the deployment of measurement devices and the hydraulic transient model.

4.1. Optimization algorithms

There are essentially two approaches to minimizing the sum of the squared differences between observed and simulated pressure sequences, a prerequisite to solving the inverse problem and presumably pinpointing leaks. These are nonlinear derivative-based optimization (e.g., Levenberg–Marquardt or LM) or targeted enumeration by means of some sort of sampling and search algorithm (e.g., genetic algorithms GA). The decision to go with either one or the other is largely influenced by the inherent trade-off that arises between these fundamentally different approaches; that is, convergence versus speed. On the one hand, derivative-based techniques run the risk of becoming trapped in local minima or inflection points. On the other, GAs and other evolutionary schemes are less susceptible to the quagmire of sub-optimal ‘‘entrapment’’, but may involve longer computation times as the algorithm is probabilistically based and multiple runs must be tested in succession. Often a statistical analysis of the solution is required to determine whether it is meaningful. The increased power of microprocessors in recent years has, however, rendered the use of GAs increasingly popular and practicable. Despite this, optimization for large water distribution systems can still consume many hours, or even days, of computer time. Thus, effort is being invested in ways to circumvent the trade-off altogether and realize the so-called best of both worlds. Various authors (Vitkovský et al., 2002; Kapelan et al., 2003a, 2002) have sought to realize this goal and develop hybrid approaches. Overall, a significant portion of the ITA literature is preoccupied with ways in which to improve or accelerate solution of the inverse problem (Kapelan et al., 2004, 2003a,b, 2002; Nash and Karney, 1999; Vitkovský et al., 2006, 2003a,b 2002, 2000) and a selection of contributions in this area is described in detail below.

Vitkovský et al. (2002) demonstrated in simple laboratory tests the lacklustre performance of the LM minimization scheme, exposing its failure in a number of global minimum tests. The authors compared the LM's performance with the shuffled complex evolution (SCE) algorithm and showed that the SCE was more accurate in identifying the correct simulated leak locations in the laboratory system. SCE was originally found to be 30 times slower than its gradient-based counterpart. In order to improve LM convergence, and yet avoid the lengthy SCE simulation process, the authors proposed a modified LM form based on improving the initial guess of leak locations and thus reducing the chance of ‘‘barking up the wrong tree’’. They named the technique of using a smaller number of better leak candidates the Systematic Levenberg–Marquardt (SLM) algorithm. Essentially the inverse-transient problem is solved for the trial leak at all locations and that which yields the best objective function value determines the leak position. The leak is set at this position and a new trial leak, which is tested for all locations, is now introduced. The process is carried out until no further improvements are evident. In laboratory tests, the authors found that SLM outperformed traditional LM in terms of leak identification accuracy (which was comparable with SCE) and that it improved on SCE in terms of execution time.

Kapelan et al. (2003a, 2002) developed a hybrid optimization scheme derived by combining the LM and GA approaches. This hybridization resulted in a two-stage model whereby a GA search is first conducted until a candidate global optimum is found. The LM method is then run within the limited search space around the best GA solution. In this way, the component schemes (that is, GA and LM) are employed exactly where they perform best: GA for an effective global search and LM for an efficient local search, thereby avoiding both GA's slow convergence and the tendency for LM to become trapped in a local optimum. The approach was applied to the hypothetical looped network presented in Pudar and Liggett (1992) and was found to outperform both LM and GA applied individually.

Inspired by the work of Greco and Del Giudice (1999), Kapelan et al. (2004) introduced modifications to the inverse-transient solver objective function that allowed for the incorporation of prior information. Essentially, they retained the classic least squares objective function but added a term to account for prior information, obtaining a weighted objective function which could be adjusted to reflect the desired influence of such data. Prior information includes i) data from field tests, ii) data from specific analyses (such as prior estimates of demand from a demand allocation analysis), iii) information form the engineering literature (e.g., hydraulic roughness tables) and iv) expert knowledge and experience. Types of prior estimate parameters are divided into implicit and explicit estimates. Implicit (indirect) estimates are any non-linear function of calibration parameters such as head/flow measurements obtained in the past. Explicit (direct) estimates include pipe roughness coefficients (based on material properties, diameter, adjacent soil type and age) or nodal demand as obtained from a demand allocation analysis. Either LM or GA can be used to solve the expanded objective function, although the authors chose to use LM in their numerical case studies since it was expected to benefit most from the incorporation of prior information.

4.2. Measurement strategy and sampling design

When conducting inverse-transient analysis, the questions of where to place measurement devices (transducers), for how long to measure system response, and how many devices should be deployed, are key considerations. The answers constitute sampling design and are vital for ensuring that tests are productive, efficient and economical.

Liggett and Chen (1994) suggested pressure transducers should be deployed according to two sensitivity measures related to the mathematics of the objective function and system hydraulics. The first is the partial derivative of the objective function (the sum of squared differences between measured and simulated pressure heads) with respect to model parameters (e.g., friction factors, leak orifice coefficients, etc.).

This measure is basically the convergence rate toward the inverse-transient solution related to the particular model parameter. The second measure is the partial derivative of pressure head at each sampling point with respect to model parameters, such as friction factors, etc. These can be evaluated for all candidate measurement sites or other nodes in the system. In general, measurement devices should be situated at nodes where these derivative values are larger so that a wider response range can be sampled.

Kapelan et al. (2003b) address the issue of optimal sampling design, considering specifically the number and location of measurement points. They cast the problem as a dual objective optimization formulation in which the goals are: i) to minimize the error in the final prediction and ii) to minimize the number of pressure transducers employed. Essentially, these objectives represent the trade-off between accuracy and cost as more transducers would presumably permit greater data collection, but at higher cost. Since these goals are non-commensurate, the problem is resolved according to Pareto domination rules, with a Pareto front of non-inferior solutions delineating the various options. Illustrating with a case study, the authors detected the Pareto front by means of multi-objective genetic algorithms (MOGA). The MOGA approach circumvents the need for separate optimization runs to find the Pareto front, as would be the case if single objective GA were used.

Vitkovský et al. (2003a) examined the question of optimal measurement site configuration and data length acquisition by introducing three performance indicators: i) the sum (over the total number of parameters, measurement length and number of measurement sites) of partial derivatives of pressure head with respect to a given parameter; that is, head sensitivity, ii) the sum of the variance of parameter errors and iii) the determinant of the normalized curvature matrix of the objective function (the half Hessian). The search for the optimal placement of measurement sites calls for an objective function to distinguish among possible configurations and, in the case of the above indicators, the objective function actually becomes three, in which the first and third indicators are to be maximized and the second minimized. They also demonstrated that, with a good transient model, ITA produced better results than steady state analysis (ISA). The related case studies showed that the performance indicators did not always agree on the optimal configuration but, taken as an ensemble, they provided guidance. In general, results indicated that more measurement sites led to better solutions, but that diminishing returns often occurred beyond a certain number. Not surprisingly, longer runs led to more accurate results, although this relationship became asymptotic as the transient died out. General conclusions regarding the spatial disposition of measurement devices are more difficult but are closely linked with the sensitivities inherent to the three indicators.

4.3. Further improvements to transient modelling

Kim (2005) employed the IMPREM method presented by Suo and Wylie (1989) to predict a system's transient response, circumventing the Method of Characteristics (MOC) as used in ITA. This requires determination of the system's impulse response function which relates the movement of the transient generating valve to the observed signal. Once identified, this function can be used to predict other transient responses through a time convolution process—without a forward transient model. The impulse response function was derived using the 1-D unsteady flow equations assuming an impulse discharge at the downstream end of a simple reservoir-pipe-valve (RPV) system.

The method was tested by attempting to recreate the time series of pressure head and discharge as reported for experimental data in Bergant et al. (2001). It was found to compare well with the MOC (incorporating unsteady friction) in reproducing the damping behaviour of the experimental data published by Bergant et al. (2001). A hypothetical RPV system was used to test leak detection capability. An impulse response method incorporating frequency-dependent friction for laminar flow, and an extended version incorporating unsteady friction for turbulent flow, were applied to several leak calibration exercises on the hypothetical system and found to yield accurate results with good representation of system damping.

The approach is billed as possessing several advantages over other techniques. Firstly, it provides a transient solution in the frequency domain, avoiding MOC-dependent simulation in the time domain and thus not being constrained by the Courant number for numerical dissipation control. Disadvantages associated with system discretization are also avoided, presumably allowing for a more accurate representation of system topography and properties.

Vítkovský et al. (2007) outlined the various sources of error that can creep into ITA, classifying them into three categories: i) data errors (noise in measured variables and calibration accuracy), ii) model input errors (parameter values and boundary conditions) and iii) model structure errors (incorrectly represented, or unaccounted for, model processes; numerical algorithm mistakes). They concluded that model structure error is the most probable limiting factor for the successful field application of ITA, despite application of model error compensation techniques, because "there are often unknown local defects like air pockets, blockages, vibration, or construction changes that are not recorded" and it is "unrealistic to model the pipeline system down to the smallest components, such as water connections to individual homes".

The role of unsteady friction has also come under scrutiny in transient modelling generally, and ITA specifically. Nixon and Ghidaoui (2007) attempt to clarify when inclusion of unsteady friction is important, concluding that the significance of unsteady friction effects decreases as the flow rate of the side flux increases. Thus, with the exception of very large leaks (that may be evident without sophisticated detection techniques), accounting for unsteady friction is an important modelling component that ought not to be ignored.

4.4. Validation of ITA

Much work to test and validate inverse-transient calibration and leak detection has taken place in experimental and, to a much smaller extent, field facilities. The contribution by Tang et al. (1999) is perhaps one of the earliest to report field applications of ITA for parameter estimation and system condition assessment, in this case the focus being on pipe friction factors. Test results suggested promise for ITA but, as the authors readily admit, ‘‘clearly the inverse process is not magic’’. The model calibrated with ITA using field test data was subsequently used and compared with field measurements during induced transients, along with an uncalibrated system model (based on either past calibrations of friction factors, installation and/or surrogate data). For the cases described, the model calibrated with ITA performed better than its uncalibrated counterpart, exhibiting pressure traces closer to those measured in the actual system.

Covas et al. (2001) conducted a series of laboratory trials at Imperial College, London in order to evaluate ITA for leak detection. In general, ITA located leaks at a variety of positions along a well-characterized test pipe, but there was some discrepancy between the known leak size and positions and those determined by the inverse-transient solvers. Moreover, false leaks were sometimes detected, a problem attributed to shortcomings in the transient model. Additionally, complications related to experimental set up and procedure were also discovered (pump vibrations, pipe elbow effects, etc.). It was also believed that the transient solver failed to capture the system’s response with an appropriate level of accuracy, thus leading the inverse solver somewhat astray. For example, it was thought that the formulation of unsteady friction was unable to reproduce the observed damping, causing the inverse solver to incorrectly place leaks as it attempted to compensate for the disagreement between measured and simulated results. The authors suggest improvement to the transient solver by: i) enhancing the 1-D model to include viscous and mechanical damping, ii) implementation of the 1-D model coupled with an axi-symmetric motion equation and iii) development of a complete 2-D model. In general, Covas et al. (2001) illustrates that successful ITA depends on: i) the accuracy of the transient simulator, ii) accuracy of the data, iii) correct synchronization of the data measurements from different loggers and iv) accuracy of the estimated system parameters (i.e., wavespeed, valve manoeuvre, etc.). Overall, the study points to the potential future application of ITA for leak detection, but also highlights that, even in carefully controlled laboratory settings, excellent results are not always easy to come by and that the road from laboratory to the field can indeed be long.

Together with other contributions (Reis et al., 1997; Vitkovský and Simpson, 1997; Vitkovský et al., 1999), Tang et al. (2001) raised the idea of using GA as the primary optimization vehicle for the inverse solver. The article combines numerical case studies with a laboratory based ‘‘blind test’’ in order to evaluate the potential of ITA. The synthetic case studies were computer models of four ‘‘ideal’’ systems of differing complexity, including a homogeneous system (single pipe of consistent diameter), a non-homogeneous system (one line composed of two pipes of different diameter), a Y-branch line and a small network (topology not specified). The systems are termed ideal because complete knowledge regarding topology and conditions were known. The goal was to first see how well the ITA procedure could detect leaks in straightforward and thoroughly characterized systems. Overall, leaks were found using a small number of generations and limited population sizes, indicating methodological effectiveness and comfortable run times in well-characterized and small scale configurations. Leak size estimates did exhibit small errors which the authors suggested can be rectified by increasing population sizes in the GA pool. Such errors may also have arisen from the discrete nature of the GA encoding (Vitkovský and Simpson, 1997).

The tests in Tang et al. (2001) revealed that GA, as part of the ITA procedure, could be successful in locating and sizing leaks under favourable conditions. This article is particularly interesting in that a series of blind tests were conducted with the involvement of two research groups. Laboratory tests were carried out at the University of Perugia for well-characterized (and straightforward) system configurations in which a simulated leak of known size and location was applied. The first configuration was a single pipe while the second involved a Y-junction with one branch terminating in a dead-end. The systems’ responses to induced transients were measured and the time-pressure data was sent to the University of Toronto for subsequent analysis. In order to simulate more realistic testing conditions, only the system topology and the transient responses were provided to the analysts in Toronto who succeeded in determining, within about 2 m, the actual leak location in both configurations. Other noteworthy studies published during the same period include Vitkovský et al. (2001) and Wang et al. (2002).

In applying ITA to field systems for general fault detection, Stephens et al. (2004a,b) were among the first to employ transients for the identification of leaks, air pockets and blockages in the field (the water distribution network of Adelaide, Australia). Of particular note is the innovative use of transients for the determination of valve status (Stephens et al., 2004a). As an ensemble, these publications underscore the seemingly forbidding complexities that can arise in a real system and serve as a renewed impetus for testing ITA under more realistic conditions.

Covas et al. (2006) juxtaposed several laboratory tests of the inverse-transient procedure alongside one field test in an ambitious study documenting the use of ITA in order to characterize a number of singularities including leaks, bursts, diameter changes, air pockets and pipe branches. The laboratory tests were conducted at three institutions: Imperial College (London), the Istituto Superior Tecnico (Lisbon) and the 1.3 km long Thames Water pilot testing pipeline at Kempton Park, UK (perhaps the world’s longest experimental one-pass PE pipe system; 125 mm nominal diameter). In general, ITA pinpointed leaks for these carefully controlled laboratory settings in which the attenuation of the pressure signal attributable to the pressure-relief action of the simulated leaks was clearly observed and the signal complexity resulting from multiple leaks and their associated reflected waves was evident.

Broadening their investigation to burst discovery in real water distribution networks, the authors carried out a field data collection program on the 5.9 km ductile iron Balmashanner branch main in Scotland. ITA also exhibited good performance here, identifying simulated bursts with an accuracy of approximately 50 m (about 1% of the pipe length). While the simulated pressure traces fitted the measured data well, agreement was best for the first half of the pressure wave (i.e., $t < 2L/a$), after which discrepancies in pressure amplitude became obvious. This was largely attributed to the treatment of the upstream boundary as a constant level reservoir when in fact it was a 700 mm diameter trunk main, altering the reflection properties at the end of the conduit. Scrutiny of numerical results also revealed other discrepancies in pressure wave morphology that grew with time, suggesting that there was some combination of reflected waves arriving from various and unknown boundary conditions. As in the laboratory tests, dividing the pipe into more reaches tended to numerically disperse leakage in the vicinity of the leak. Thus, while the results were encouraging for ITA's application to burst localization in large conduits, there still remain practical, theoretical and computational issues to resolve before reliable field applications can be assured. This is not surprising given that every feature in a system reflects incident transient pressure waves and many such features can coexist in even a relatively uncomplicated system.

Saldarriaga et al. (2006) have recently exploited ITA for leak identification in a real distribution system in the town of Chia near Bogota, Colombia. The network consists of 248 nodes, 253 pipes and a reservoir and was chosen because of its small size (about 5 km) and the homogeneity of pipe material (95.6% PVC, 4.4% asbestos–cement). The GA inverse solver was used to match simulated results to measured tests carried out at about 11 a.m., representing average flow conditions for the network. Imposed leakage (via control valves) was about 12% of the average supply flow. The authors followed a "two-tier" procedure where eighteen groups of five adjacent nodes were lumped together into a modelling area node (one node was used to represent the group). When such a "group" node was identified as a leak candidate during the inverse process the inverse problem objective function was re-calculated for each of the five nodes in the flagged group to determine the true leak location. Leakage was found successfully using this approach, but it was noted that within the flagged group, it was distributed between two adjacent nodes (one of which being the actual node); however, the sum of the leakage magnitudes at each node was roughly equal to the actual leak size. This observation is supported by the finding previously discussed in Covas et al. (2001).

5. Frequency domain techniques

Instead of monitoring transient response from a variety of locations throughout a system, as in standard ITA, frequency domain techniques usually call for measurement of the pressure history at only one measurement section. In addition, they involve a periodically actuated device, usually a control valve, for transient generation and analysis of the system's frequency response during the resulting steady-oscillatory flow. Once such flow is established in a system, pressure measurements are undertaken and maximum amplitudes are determined for each frequency, giving rise to a frequency response diagram from which comparisons can be made between intact systems and those with singularities such as leaks and breaks.

In fact, steady-oscillatory flow can be analysed in either the time or frequency domain. However, because the frequency response is determined directly, it requires less computational time. Moreover, the governing head/flow equations can be solved in the frequency domain by assuming that both head and flow are composed of steady state average and oscillatory components. These sinusoidal components are functions of space and time and, for each position, have a sinusoidal variation that either dampens or amplifies. Merging the governing head/flow equations with those that resolve these variables as average and oscillating components, and solving the resulting expressions, leads to the system's so-called transfer functions. These can then be solved by either the impedance or transfer matrix methods. In Mpesha et al. (2001) this analysis is facilitated by the transfer matrix method to relate the magnitude and phase of system output to its input for different frequencies.

In practice, the method involves the following procedure: A valve at the downstream end of a pipeline is periodically operated according to a set pattern, producing steady-oscillatory flow in the system. The start-up time of the test should allow for wave propagation throughout the system a large number of times before measurements are taken in order to ensure the system's response has become steady oscillatory. At the valve location, the amplitudes of pressure head and discharge are recorded. These actions are then repeated for a range of frequencies by adjusting the period of the valve oscillations, giving rise to an experimentally obtained frequency response diagram for the system. This frequency response pattern can then be compared to that for a "no-leak" system which is itself obtained by numerically modelling the system from known geometry and parameters (for proposed systems) or from experimental/field measurements conducted at installation (for existing systems).

Similar to Jönsson and Larson (1992) and Covas and Ramos (1999), Mpesha et al. (2001) proposed that the presence of leaks, and other singularities, is revealed by the appearance of additional resonant pressure amplitude peaks in the experimental frequency response diagram (FRD). These peaks are asserted to be lower than the resonant pressure amplitude peaks for the frequency response of the leak-free system. Various cases were considered, including a single pipe with one and two leaks as well as series and branched pipe systems with one leak each. The numerical data presented in Mpesha et al. (2001) appears to confirm the idea that leak-induced peaks in the system frequency response exist. Detailed investigation of the data in the paper (Lee et al., 2003), however, reveals possible discrepancies with results in other publications such as Wylie and Streeter (1993) and Chaudhry (1987).

The frequency response of a single pipeline typically contains peaks at odd multiples of the fundamental frequency (Chaudhry, 1987; Wylie and Streeter, 1993) whereas the results in Mpesha et al. (2001) have peaks at the 1st, 7th, and 13th harmonics. In the leaking case, an additional frequency spike is present in the Mpesha et al. (2001) results and the position and size of this spike were used as the basis for their leak detection procedure. It appears that it is located at the fifth system harmonic and the reason as to why it was missing in the no-leak case, and yet reappears for the leak case, is unclear.

Ferrante and Brunone (2004) presented further results that refute the existence of leak-induced frequencies. They varied leak size from small flows up to 80% of the pipe's base flow and noted that, while modifying leak size results in a shift in the pipe's fundamental frequency, no additional harmonic peaks were apparent. The presence of the "leak-induced frequencies" in previous publications appears to result from confusion with existing pipe harmonics. It should be noted, however, that Jönsson and Larson (1992) was one of the first articles to propose the idea that leak properties can be determined via the Fourier spectrum of the measured pressure trace, and that Mpesha et al. (2001) were the first to clearly identify the potential for detecting leaks in the frequency domain. These early papers have inspired other researchers to consider the possibilities offered by frequency domain analysis.

Lee et al. (2005a) introduced two transient leak detection techniques based on the frequency domain analysis of a system's response to an induced transient: the inverse resonant and peak-sequencing methods. They are based on the fact that a leak imposes a sinusoidal pattern upon the peaks of the frequency response function and that the characteristics of this pattern can provide useful information regarding leak size and location. The first technique, like standard ITA, entails inverse fitting; that is, it seeks to minimize the sum of squared differences between measured and modelled frequency response functions (the FRDs) by adjusting leak size and position within the transfer matrix model. One purported advantage of this approach over ITA (in the time domain) is that the model is not spatially discretized and a leak can be located at any point along the pipe.

The resonance peak-sequencing method is also based on the uneven damping of the harmonic peaks across the frequency axis of the FRD caused by the presence of a leak. This frequency-dependent behaviour is also at the root of the transient damping method advanced by Wang et al. (2002). The leak-induced damping pattern of the FRD reveals useful information concerning the leak and offers a method based on the rank sequencing of resonant peaks by means of matching observed FRDs with those archived for an identical system in a lookup table. In this way, both procedures eschew the matching of system responses (and associated optimization routines) that are part and parcel of the inverse resonance method and standard ITA.

Four cases were examined numerically for a simple reservoir-pipe-valve system: A leak-free situation, two scenarios in which the same size leak was positioned at two different places, and the leak at one of those positions doubled in size. The FRDs for all scenarios were extracted at the downstream valve and compared. Numerical analysis showed that the location of the leak changes the shape of the pattern on the resonant peaks, and the size of the leak changes the magnitude of this pattern. The authors note that the peak-sequencing method does not lend itself to network-wide analysis since the FRD of a network will be unclear and network specific, but recommend that the system can still be subjected to such analysis by subdividing it into individual pipe segments and determining the FRD for each segment. The impact of unsteady friction of the FRD was also considered and assessed. Although unsteady friction is known to cause peak attenuation in the FRD, it does so more for higher frequencies and exhibits a smooth trend that can readily be distinguished from more complex leak-induced patterns within the FRD.

The standing wave difference method (SWDM) proposed by Covas et al. (2005), as with Lee et al. (2005a,b) and Mpesha et al. (2001), makes use of steady-oscillatory flow and spectral analysis. The method is inspired by an analogous approach in electrical fault detection in which discontinuities in cables are found by subjecting the cable to sinusoidal excitation and measuring voltage and current in order to produce a frequency response signature from the standing waves produced, in part, by reflected incident waves at discontinuities. A hypothetical infinite pipeline with both one and two leaks was first studied. The assumption of infinite length was intended to ensure that reflections from the extremity of the system did not return to the source of disturbance, thus clarifying leak resonance signatures and verifying the technique, at least conceptually. For an undamaged pipe, no resonance condition was observed. In the pipe with one leak, however, maxima of the hydraulic impedance amplitude were evident, with the resonance condition directly related to leak position. In the case of the pipe with two leaks, a more complex resonance condition, requiring spectral analysis via a fast Fourier transform of the pressure response diagram for locating the leaks, was obtained.

A reservoir-pipe-valve (RPV) system was then considered for leak and no-leak scenarios. For an undamaged pipe, the frequency response for the pipe was observed and was shown to contain a series of even spaced and equal magnitude peaks. With the addition of a leak, the system's frequency response continued to exhibit equidistant resonance peaks but also revealed a pattern that correlated with the leak's position—corroborating observations in Lee et al. (2005a,b). A sensitivity analysis was performed for assessing the impact of various leak positions on the system's frequency response. Although amplitude peaks associated with the reservoir's position maintained the same frequencies, the shape of the leak-induced pattern shifted depending on leak location. Leaks were located using spectral analysis of the frequency response which permitted exposure of the maximum resonant frequencies embedded in the response. Analysis was also extended to a conceptual reservoir-loop-pipe-valve system. Here too, spectral analysis of the frequency response had potential to indicate leak positions. Note that Covas et al.

(2005) performed a Fourier transform on the pipe's frequency response in order to ascertain leak location. However, by doing so, the frequency response of the pipeline reverts to a time-domain representation—which corresponds to a cross-correlation of the transient signal in time. The relationship between the Fourier spectrum of the frequency response and the cross-correlation function is derived by Vítkovský and Lee (2008). This finding directly connects the frequency domain leak detection techniques in Covas et al. (2005) with the time-domain cross-correlation approach presented by Beck et al. (2005) (discussed later in the review).

Lee et al. (2005b) derived an analytical expression for the leak-induced pattern on the FRD for a single pipeline using the transfer matrix equations. It was found that the frequency and phase of the leak-induced pattern on the resonance peaks are directly related to the position of the leak and the magnitude of the leak-induced pattern is directly related to the size of the leak. This analytical result validates empirical observations presented in Covas et al. (2005), Ferrante and Brunone (2004) and Lee et al. (2005a,b). Using this analytical expression, a simple procedure was developed for the determination of the leak from the FRD. The procedures involved in extracting the magnitude of the peaks from the FRD and through spectral analysis, determine the properties of the leak-induced pattern—leading to the location and size of the leak. A series of numerical tests were conducted which show that this technique can be used to detect both single and multiple leaks in a numerical system. The approach is an improvement to those presented in Lee et al. (2005a) as it does not rely on a comparison with known system behaviour.

A little later, the same authors presented the first experimental validation of a leak detection technique in the frequency domain (Lee et al., 2006). They also propose an alternative to the creation of steady-oscillatory flow typically used to analyse system behaviour in the frequency domain (Mpesha et al., 2001; Covas et al., 2005; Kim, 2005; Wang et al., 2002) since it can be time-consuming, require specialised valve driving equipment and exciting the system at harmonic frequencies is potentially dangerous. Although examining resonant frequencies, Lee et al. (2006) relied on an induced transient of sufficient input bandwidth in order to produce a comprehensive frequency response, circumventing the need for a steady-oscillatory signal. Instead, any transient generated by a valve operation can be used for generating a frequency response, simplifying the practical implementation of frequency domain leak detection methods.

This paper also raised a number of issues with regard to the practical implementation of a transient-based leak detection procedure—for example, the concept of "signal bandwidth". It was observed that each transient signal contains a limited range of frequencies—the bandwidth. A signal with a greater range of frequencies can excite a higher number of modes in the system, represented by a higher number of observable peaks in the frequency response. The number of peaks observed is directly related to the amount of information contained in the transient signal and hence the ability to detect leaks. A time-domain analogy of this observation is that faster valve manoeuvres appear to outperform slow pump trips in other leak detection methods because they create a transient trace that contains sharp, clearly identifiable leak reflections. From this, Lee et al. (2006) suggested that only sharp transient signals (containing a large range of frequencies) should be used for transient-based fault detection in order to maximise the amount of information that can be extracted from the system.

The results in this paper provide the first experimental confirmation for the effect a leak has on the frequency response of a system and are consistent with the numerical findings in Covas et al. (2005), Ferrante and Brunone (2004) and Lee et al. (2005a,b). The technique was shown to be able to detect a single leak under controlled experimental conditions and provided a validation for the leak detection approach. However, several limitations of frequency domain techniques were noted. For example, in a short pipe, the number of observable peaks t may be low, making it difficult to accurately pinpoint the leak. In addition, the approach is unable to detect leaks situated at the quarter-points of a conduit. The recent development of frequency domain methods stems from a need to accurately detect leak reflections in the transient signal.

6. Direct transient analysis

The inverse-transient method can offer effective leak detection provided that, among other considerations, an accurate transient model of the system exists (Covas et al., 2001). Connected with this requirement is that system parameters (i.e., inputs to the transient model) should also be representative of true conditions. At times, a detailed inspection of pipeline components is needed in order to implement ITA. While the greatest advantage of ITA is its attention to detail, the number of unknown physical complexities in a system can be overwhelming. Thus, alternative approaches that do not require accurate predictions of the full pressure trace, or complete frequency response, may be attractive. In fact, the varieties of detection approaches that are beginning to be available are likely to be complementary in practice, particularly since field conditions present a host of measurement and specification challenges.

6.1. Time-domain reflectometry

When a propagating transient signal arrives at a leak, part of the energy of the principal wave is diverted to form a new reflected signal. Detection of this reflected signal, and measurement of its arrival time, can be harnessed to expose the leak. The arrival time of the reflected signal at the transducers is the time needed for the main signal to travel from the transient source to the leak and for the reflected wave to travel to the measurement station. Given a known wavespeed, the location of the fault can be determined from this arrival time.

Numerous publications have described such use of leak-reflected signals in the pressure trace. Brunone (1999) proposed a simple and cost-effective technique for exposing leakage in outfall pipes. The study considers a single pipe subjected to a transient initiated at the upstream end (such as a tank truck discharging to the pipe). Starting with key attributes of pressure wave transmission, several relationships pertaining to primary and reflected wave arrival times to and from the leak, downstream end and measurement sections were derived to permit calculation of leak position and size. Manipulation and solution of these equations provided the desired information and obviated the use of least squares minimization or GA enumeration. Simulations of an experimental configuration mimicking an outfall configuration were conducted for both an intact pipe (leak valves shut) and a damaged conduit (leaks active). In general, the procedure yielded acceptable values of leak location and size in simulation studies. This procedure assists in the periodic inspection of outfall pipes by comparing transient signals with those recorded immediately following a conduit's installation.

Other articles, for example Jönsson and Larson (1992), Covas and Ramos (1999), Jönsson (2001) and Brunone and Ferrante (2001), also make use of this approach which hinges on the detection and location of leak-reflected disturbances in the transient signal. In Brunone (1999), these signals were detected by means of a visual comparison between the leak-free transient response and the observed trace. While simple to apply, considerable experience is required because pipeline vibrations, background transients and instrument noise can obfuscate the leak reflection signals.

6.2. Advanced reflection techniques

As with Brunone (1999), Beck et al. (2005) exploited the interpretation of pressure signals, specifically the discernment of waves reflected from singularities. The authors present a refinement of a technique they had already developed for interpreting such signals by applying an extension of cross-correlation analysis and testing the method with laboratory experiments on simple systems. Essentially, the approach calls for plotting the second derivative of the cross-correlations in order to uncover the signatures of reflected waves that are buried in more complex patterns of superimposed transient waves arising from various system features and representing an array of travel paths. The first derivative of the cross-correlation function indicates the magnitude of the gradients while the second exhibits peaks at the points where the gradient changes; that is, the various reflected waves.

The technique was applied to a straightforward and more complex system. For the larger network, the plots of the pressure trace and cross-correlations pertaining to the leak and no-leak cases revealed little difference; however, the plot of twice differentiated cross-correlations evinced a clear peak corresponding to the leak, permitting evaluation of its actual location. Challenges to the approach are several. Firstly, even in rudimentary systems there are a large number of paths that reflected transient waves can follow. Given that some of these waves overlap, their individual discernment is hindered or at least complicated. As the number of system features increases, the number of peaks in the cross-correlation plots does too. This renders use of a single pressure transducer (a stated goal of the authors) difficult. Alterations in conduit properties and geometry, such as large changes in diameter or the presence of different pipe materials, could sufficiently alter wave speeds and introduce complex reflection patterns that inhibit application of the method to larger systems. Changes in demand also introduce transients that are superimposed on existing wave patterns, possibly confusing interpretation of reflected waves. Some way to eliminate such complexities from the analysis appears necessary in such cases.

Current transient-based leak detection methods often rely on a solid understanding of leak-free system behaviour. This benchmark is generated using a particular transient signal and assumes that future tests will be conducted using the same transient event. In cases where the induced transient signal is not perfectly reproducible, it is difficult or impossible to determine changes in system integrity from the benchmark transient.

Vitkovský et al. (2003b) described a method for identifying leak reflections in the transient signal via determination of the system's impulse response function (IRF), a unique relationship between the injected transient event and measured pressure response. This relationship is based only on the system's physical characteristics and, for a given system, transient responses of completely different shapes produce an identical impulse response function. The use of the function for leak detection was first suggested in Liou (1996, 1998); however, it was strictly used as a way to determine a change in the slope of the hydraulic grade line, essentially resembling steady state methods of leak detection.

Vitkovský et al. (2003b) show that the IRF can refine all system reflections to sharp pulses, suggesting that leaks can be located with a greater accuracy as a result. Numerical data illustrating the technique's operation revealed that it could detect and locate a leak under such conditions.

There are also studies by Stoianov et al. (2002), Ivetić and Savic (2002), Ferrante and Brunone (2003) that use discrete wavelet transforms to detect leak reflections in the transient signal. The wavelet transform involves a time convolution of the data trace with localised mathematical functions and is designed to highlight discontinuities (i.e., sharp edges). These localised mathematical functions can be dilated or contracted in time to produce the time convolution result at different scales. It was suggested that the decomposition of the trace in this way could allow for the detection of a leak-reflected signal in the data. The wavelet transform is best suited for detecting discontinuities in a data trace and is therefore affected by the shape of the injected transient and the sampling rate (Young, 1995). Detection of a leak reflection is difficult when the injected transient signal deviates from a perfect step/impulse.

6.3. Transient damping methods

As mentioned earlier, the pressure attenuating property of leaks can be exploited for their discovery (Babbitt, 1920). Wang et al. (2002) articulated a methodology based on such

Table 1
Summary of the key attributes of the major articles comprising the inverse-transient analysis literature.

Work	Theory	Case study	Lab	Field tests	Minimization scheme			Lit. review
					LM	GA	Other	
Al-Omari and Chaudhry (2001) [a]	■	■					Lagrange	
Beck et al. (2005)								
Brunone (1999)		■	■	■				
Covas et al. (2006)			■	■	■	■		
Covas et al. (2005)	■	■						
Covas et al. (2001)	■		■		■	■		
Kapelan et al. (2004)	■	■					Prior info.	
Kapelan et al. (2003a)	■	■					Hybrid	
Kapelan et al. (2003b)	■	■				■	Multiobjective	
Kapelan et al. (2002)	■	■					Hybrid	
Kim (2005)	■		■					
Lee et al. (2005a)	■	■					SCE	
Liggett and Chen (1994)	■	■			■			
Misiunas et al. (2006)				■				
Misiunas et al. (2005)	■		■	■				
Mpesha et al. (2001)	■	■						
Nash and Karney (1999)	■				■			
Pudar and Liggett (1992) [b]	■	■			■			
Saldarriaga et al. (2006)	■			■		■		
Stephens et al. (2004a)	■	■		■		■		
Stephens et al. (2004b)	■	■		■		■		
Tang et al. (2001)			■			■		
Tang et al. (1999)	■			■		■		
Vítkovský et al. (2007)			■				Shuffled complex	
Vitkovský et al. (2006)	■							
Vitkovský et al. (2003a,b)		■				■		
Vitkovský et al. (2002)	■		■		■	SCE	Modified LM	■
Vitkovský (2001)	■	■	■		■	■		
Vitkovský et al. (2000)	■	■				■		
Wang et al. (2002)	■	■	■					

(LM = Levenberg–Marquardt, GA = Genetic algorithms, Lagrange = Lagrange multipliers, SCE = Shuffled Complex Evolution).
The literature review column (with the exception of Vitkovský, 2001) refers to articles that provide an interesting and informative, though necessarily short, survey of past work authors on a particular subfield of ITA. To qualify, the review must be more substantial than the typical listing of past works found in most articles.
Note: Not all, papers listed in this table have been given equal coverage in this review.

[a] Unlike most articles that focus on network calibration and/or leak detection, this paper examines the use of ITA for assessing chlorine decay parameters.

[b] Pudar and Liggett (1992) did not conduct a transient analysis for leak detection, but introduced the notion of solving the inverse problem for leak detection during steady state.

a premise which depends on inference from the harmonic analysis of a system's transient response. Leak size and location are determined analytically with Fourier analysis applied directly to modified versions of the governing equations to determine the relationship among the damping rates of different harmonics. It was found that the damping rate of each harmonic frequency within a transient signal is different for a leaking pipeline. This finding is directly linked to the leak-induced pattern on the frequency response function observed in the works of Covas et al. (2005), Ferrante and Brunone (2004) and Lee et al. (2005a,b). It is claimed (and demonstrated for rudimentary systems), that the procedure can find leaks as small as 0.1% of a pipeline's cross-sectional area. The approach was verified with numerical simulations and laboratory experiments. While the authors demonstrated the method's efficacy for simple configurations, they noted that accuracy depends on several factors, including the appropriate incorporation of unsteady friction terms (which are component dependant) and the validity of linearizing head and flow into steady and transient components.

A detailed study of the transient damping technique was carried out in Nixon and Ghidaoui (2006) and the effects of the linearity approximation were found to pose only minor restrictions. However, it was found that the method lacks the generality of some techniques (such as ITA), and further research is required before applying this technique to real systems where numerous branches, loops, demands and intricate geometry produce complex wave forms not amenable to straightforward scrutiny.

7. Concluding thoughts

The basic premise of transient-based leak detection is both appealing and attractive. It is attractive for its operational range, and its appeal is magnified by the promise of a network condition assessment strategy that is inexpensive and non-invasive. Traditional calibration and leak detection methods, while enjoying their successes, are often found wanting. The same can be said for transient-based leak detection. While it holds out promise, it is in yet no position to supplant existing techniques. Granted, there have been many valuable improvements in optimization algorithms and, coupled with advances in computer power, these have permitted the development of efficient and effective calculation procedures (such as GA and hybrid schemes) for conducting ITA and also other direct transient analyses for leak detection. Greater theoretical understanding, the reward of intense research efforts, has also given researchers and practitioners deeper insight into the process and has clarified some aspects of water distribution system physics.

Attempts to validate transient-based leak detection have entailed numerical case studies, laboratory experiments and limited field testing. While all have bestowed upon the technique some measure of approval, carefully contrived hypothetical examples and heavily controlled laboratory trials with the most rudimentary systems do not yet achieve the level of validation required for a strategy that must work in complex systems under a wide range of conditions. Even in these simple networks, interpretation of measured data is not trivial. Unequivocal validation of the technique will eventually have to come from the field. Testing real systems in typical operating conditions is, in essence, the ultimate laboratory. Hitherto, little field testing has been reported in the literature. Table 1 lists the types of validation conducted in a selection of transient-based leak detection studies and it is clear that many have not yet involved field testing. As researches forge new bonds with municipalities and private engineering consultants, access to networks and opportunities for field investigations should increase. Documentation of these future tests will be a welcome addition to the literature. It is only with time and continued effort that a more complete picture of transient methods' promise and capabilities will be better understood.

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