Transient frequency response based leak detection in water supply pipeline systems with branched and looped junctions

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ABSTRACT

The transient frequency response (TFR) method has been widely developed and applied in the literature to identify and detect potential defects such as leakage and blockage in water supply pipe systems. This type of method was found to be efficient, economic and non-intrusive for pipeline condition assessment and diagnosis, but its applications so far are mainly limited to single and simple pipeline systems. This paper aims to extend the TFR-based leak detection method to relatively more complex pipeline connection situations. The branched and looped pipe junctions are firstly investigated for their influences to the system TFR, so that their effects can be characterized and separated from the effect of other components and potential leakage defects in the system. The leak-induced patterns of transient responses are derived analytically using the transfer matrix method for systems with different pipe junctions, which thereafter are used for the analysis of pipe leakage conditions in the system. The developed method is validated through different numerical experiments in this study. Based on the analytical analysis and numerical results, the applicability and accuracy as well as the limitations of the developed TFR-based leak detection method are discussed for practical applications in the paper.

Key words | leak detection, pipe junction, transfer matrix, transient frequency response, transient tests, water pipeline system

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INTRODUCTION

The problem of potential leaks in water supply pipelines has raised great interest for a long time to both academic researchers and practical engineers in this field. Pipe leakage may cause waste for water and energy resources and can also provide entry points for contaminants in urban water supply systems (Lee *et al.* 2013). Various leak detection methods have been developed in the past decades and widely used in urban water pipeline systems. The most common leak location technique is acoustic analysis. This method involves the use of a special listening device (i.e. geophone) to listen to the sounds emanating from a pipeline. Acoustic analysis relies on the fact that sound emanating from a leak has well-defined characteristics, which enables leak-induced noise to be distinguished from the noise of the mean pipe flows. Infrared thermography technique is another common method and involves the use of infrared imaging to analyze the ground temperature characteristics surrounding water pipes. Other common methods include fluoride testing and tracer gas analysis. While useful, these methods are limited to large leaks and can only work when the operator happens to be in the vicinity of the leak (Wang 2002; Lee 2005). Particularly, the fact that over 30% of portable water is lost from pipes around the world is a clear testimony that current methods are far from satisfactory (Duan *et al.* 2011).

Recent research activities have intensified the transient-based leak detection methods that utilize the hydraulics of the transient flows to detect leaks in the pipeline (e.g. Liggett

doi: 10.2166/hydro.2016.008

& Chen 1994; Brunone 1999; Vítkovský *et al.* 2000; Mpesha *et al.* 2001; Wang *et al.* 2002; Lee *et al.* 2005, 2006; Duan *et al.* 2010, 2011, 2012). The tenet of this kind of method is that a pressure wave with appropriate bandwidth and amplitude is intentionally injected into the pipeline (Lee *et al.* 2015). The system response (e.g. pressure head) is then measured at specified location(s) in the pipeline and analyzed for leak detection (Duan *et al.* 2010). Such transient-based methods have become popular for the advantages of their fast speed, ability to work online and large operational range (Colombo *et al.* 2009).

A leak in a pipeline system results in an increased transient damping rate and the creation of new leak reflected signals within the time traces (Tang *et al.* 2000; Duan *et al.* 2010). Many different transient-based leak detection methods have been developed by researchers and applied to water piping systems relying on these two effects. The developed leak detection methods vary greatly in their modes of operation, but may be divided into four main categories according to their utilized transient information (Duan *et al.* 2010), namely: (1) transient wave reflection (TWR) based method, such as Brunone (1999), Brunone & Ferrante (2001), Meniconi *et al.* (2011, 2015) and Covas *et al.* (2004); (2) transient wave damping (TWD) based method by Wang *et al.* (2002) and Nixon *et al.* (2006); (3) transient frequency response (TFR) based method by Mpesha *et al.* (2001), Ferrante & Brunone (2003), Covas *et al.* (2005), Lee *et al.* (2006), Sattar & Chaudhry (2008), Duan *et al.* (2011, 2012) and Ghazali *et al.* (2012); and (4) inverse transient analysis (ITA) based method studied in Liggett & Chen (1994), Vítkovský *et al.* (2000), Stephens (2008), Covas & Ramos (2010) and Soares *et al.* (2011).

While these different types of transient leak detection methods have been proposed and applied to many simple pipe systems in the literature, it was found from many field studies that these methods encountered difficulties in dealing with systems with complex configurations as commonly seen in practical water pipeline systems (Stephens *et al.* 2011). Currently, the transient-based methods have been largely applied to simple pipelines that could be isolated by valves from the rest of the network (Stephens *et al.* 2004; Lee 2005; Stephens 2008). Even then, the solution would probably fail if this pipeline happens to have continuous changes in diameters (non-uniform). In addition, the effort in going around and isolating pipes is bewildering given that the total length of water supply lines in a modern city attains to an order of 1,000 km or more (e.g. about 8,000 km in Hong Kong). Therefore, an extension of such transient-based methods to more realistic and complex pipelines is urgently required and practically significant to reduce leakage in urban water supply systems.

Recently, few researchers in this field have attempted to extend the transient-based method to relatively more complex pipeline systems. Particularly, the TWR method based on wavelet analysis has been applied to simple branched pipeline systems (e.g. Ferrante *et al.* 2009; Meniconi *et al.* 2015). The ITA method has been applied to small-scale real-life pipe networks (e.g. Soares *et al.* 2011). For the TFR method, Duan *et al.* (2011) recently studied the possibility of leak detection in relatively complex pipeline systems which consist of multiple pipes in series. Both the leak-induced and series-pipe-junctions induced transient effects were investigated analytically and numerically in that study. Using the TFR-based method, an analytical expression was derived for the single leak-induced transient 'pattern' in series-pipeline systems. The results confirmed that the leak-induced transient behaviors could be separated from those by the connecting junctions of series pipes as long as the original intact (leak-free) pipe system is well-defined for its configuration and boundaries and the change extent of pipe diameters at junctions is not too large to violate the linear assumptions made in the analytical derivation. In addition, the analysis indicated that the pipe connecting junctions with different diameters can cause the shifting of the system resonant frequencies but leaks do not, which gives the possibility of separating the leak-induced effect from the junctions. This result was consistent with many experimental observations in previous works such as Ferrante & Brunone (2003), Lee (2005) and Brunone *et al.* (2008), and thereafter confirmed in relevant studies by the author and his partners (e.g. Duan *et al.* 2011; Lee *et al.* 2013).

Compared with other methods, the TFR method has the additional advantage of increased tolerance to system noises and flow instabilities (Lee *et al.* 2006, 2013; Duan *et al.* 2011). However, only the cases of single and simple series pipelines are considered for the TFR-based method in previous studies; and for the cases of branched and looped pipelines that commonly exist in practical systems, an extension of this method is highly required in both method and application, which is the scope of this study. In this paper, the influences of typical pipe branched and looped junctions to the transient responses are firstly examined by numerical applications. The method and principles for TFR-based leak detection in branched and simple looped pipeline systems are then derived and developed, which are thereafter applied for different numerical cases. In the end, the results and findings of this study are analyzed and the limitations and future improvements of the developed method are discussed for practical applications in this field.

MODELS AND METHODS

The one-dimensional (1D) waterhammer model and its equivalent form in the frequency domain based on the transfer matrix are used in this study, which are described in this section. The classic 1D waterhammer model is expressed as follows (Chaudhry 1987; Wylie *et al.* 1993):

$$\frac{gA}{a^2}\frac{\partial H}{\partial t}+\frac{\partial Q}{\partial x}=0, \tag{1}$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{f}{2DA}Q|Q|=0, \tag{2}$$

where H = pressure head, Q = pipe discharge, A = pipe cross-sectional area, D = pipe diameter, a = acoustic wave speed, t = time, x = spatial coordinate along pipeline, g = gravitational acceleration, ρ = fluid density and f = pipe friction factor. The method of characteristics is applied to solve the waterhammer model (Chaudhry 1987). Note that only steady friction effect is considered in the analytical derivation and the unsteady friction effect will be included and validated in the numerical simulations.

The frequency domain equivalents of the 1D mass and momentum equations in Equations (1) and (2) above can be obtained by applying the linear transfer matrix method for describing the transient system behaviors in the frequency domain (Chaudhry 1987; Lee *et al.* 2006; Duan *et al.* 2010). After linearization and transformation, the result in the frequency domain becomes:

$$\begin{Bmatrix} q \\ h \end{Bmatrix}^2=\begin{bmatrix} \cosh(\mu l) & \frac{1}{Y}\sinh(\mu l) \\ Y\sinh(\mu l) & \cosh(\mu l) \end{bmatrix}\begin{Bmatrix} q \\ h \end{Bmatrix}^1, \tag{3}$$

or in a matrix form:

$$\boldsymbol{O}=\boldsymbol{U}\boldsymbol{I}, \tag{4}$$

where $\boldsymbol{I}$, $\boldsymbol{O}$, $\boldsymbol{U}$ = input of transient information (e.g. the upstream end), output of transient information (e.g. the downstream end), and the transfer matrix; q, h = transient discharge and pressure head in the frequency domain; l = length of pipe section; the superscripts '1' and '2' represent quantities at the two ends/sides of the pipe section or system element under investigation respectively; μ and Y = propagation factor and impedance coefficient, and:

$$\mu=\frac{\omega}{a}\sqrt{1-i\frac{gAR}{\omega}};\quad Y=-\frac{a}{gA}\sqrt{1+\frac{gAR}{i\omega}}, \tag{5}$$

in which ω = frequency, i = imaginary unit, R = friction related coefficient and $R=fQ_s/gDA^2$ with Q_s being steady (pre-transient) state discharge. Equations (3) or (4) are called the transfer matrix equation that represent the modification effect of the given element (e.g. pipeline, junction, and valve) on hydraulic responses from one end/side to the other. With this result, the frequency response of a whole transient pipe system can then be obtained by multiplying the relevant transfer matrices of all the system elements in the order of connections (Lee 2005; Duan *et al.* 2011). This method is used later in this study for deriving the TFR results of the branched and looped pipe systems.

TRANSIENT INFLUENCES OF PIPE JUNCTIONS

Prior to developing the detection methods for relatively complex pipeline systems, it is necessary to understand and investigate the impacts of different pipe connecting junctions on the transient responses. For illustration, three test cases of systems with single and uniform pipeline (without junction) and multiple pipes with simple branched and looped junctions shown in Figure 1(a)–1(c) respectively are used herein for comparative study in both the time and frequency domains (denoted as systems no. 1, no. 2, no. 3 in this study). Specifically, the main pipelines for these three systems (i.e. from node *a* to node *b*) are assumed to be the same so as to fairly analyze the impacts of junctions on the system transient responses through result comparisons. The details of system settings and parameters are provided in Figure 1.

In each test system in Figure 1, the side-discharge valve at the downstream (V_2 in the figure) is used for generating transients and the inline valve (V_1 in the figure) is used for controlling the initial steady state discharge (Q_s) in the system. For simplicity of analysis and to highlight the transient behaviors (separated from steady state), initially both valves (V_1 and V_2) are fully closed (i.e. $Q_s = 0$). That is, the transient flows are generated on the basis of initial static flow condition. The effect of initial non-static flow conditions will be included in the analytical and numerical analyses later in this study. In order to provide a preferably large bandwidth of wave injection for transient system analysis (e.g. defect detection), the transients in all test cases are generated by the side-discharge valve with operations of fast closure-open-closure as given in previous studies (e.g. Duan *et al.* 2010, 2011, 2012; Lee *et al.* 2015). The numerical results of transient pressure traces collected at the just upstream of the inline valve are used for analysis.

Time domain transient responses

The obtained transient pressure head responses in the time domain are shown in Figure 2(a) for the three systems. For comparison, the axial coordinate of the figure is dimensionless time with regard to wave period of single pipeline case (i.e. $4L_0/a_0$), and the vertical coordinate is normalized by the first peak amplitude of transient head at side-discharge valve (i.e. *Joukowsky* head, $a_0\Delta V_d/g$ with ΔV_d being the velocity change through the valve operation).

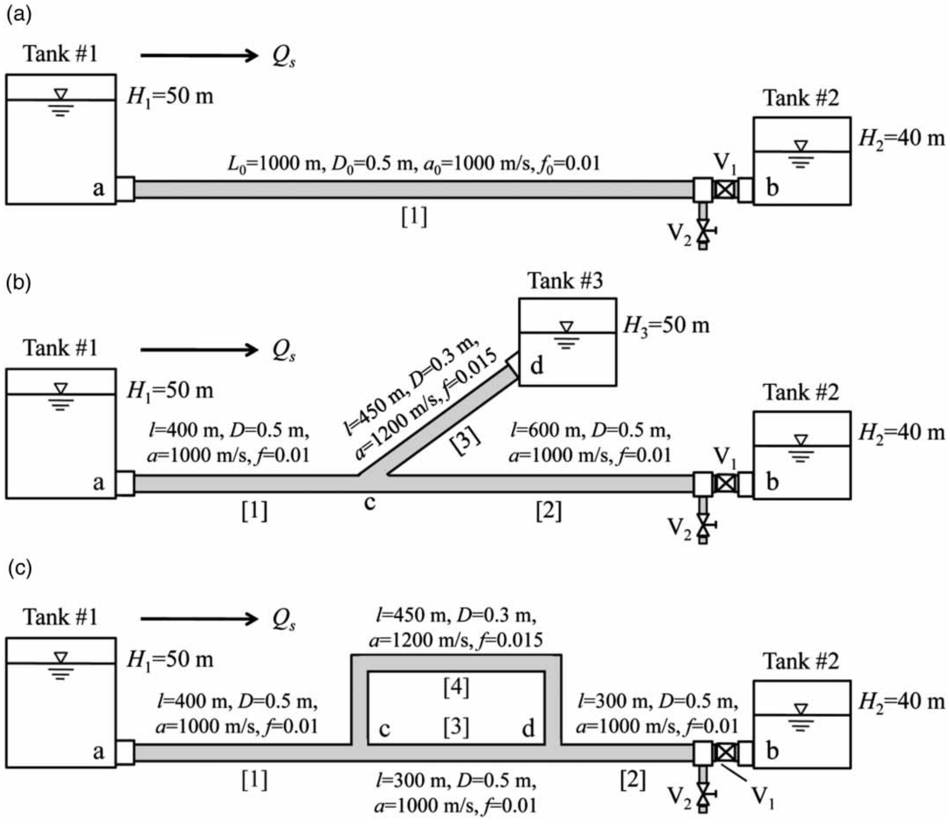

Figure 1 | Sketch for test pipeline systems: (a) no. 1: single and uniform pipeline system; (b) no. 2: branched pipeline system; (c) no. 3: looped pipeline system.

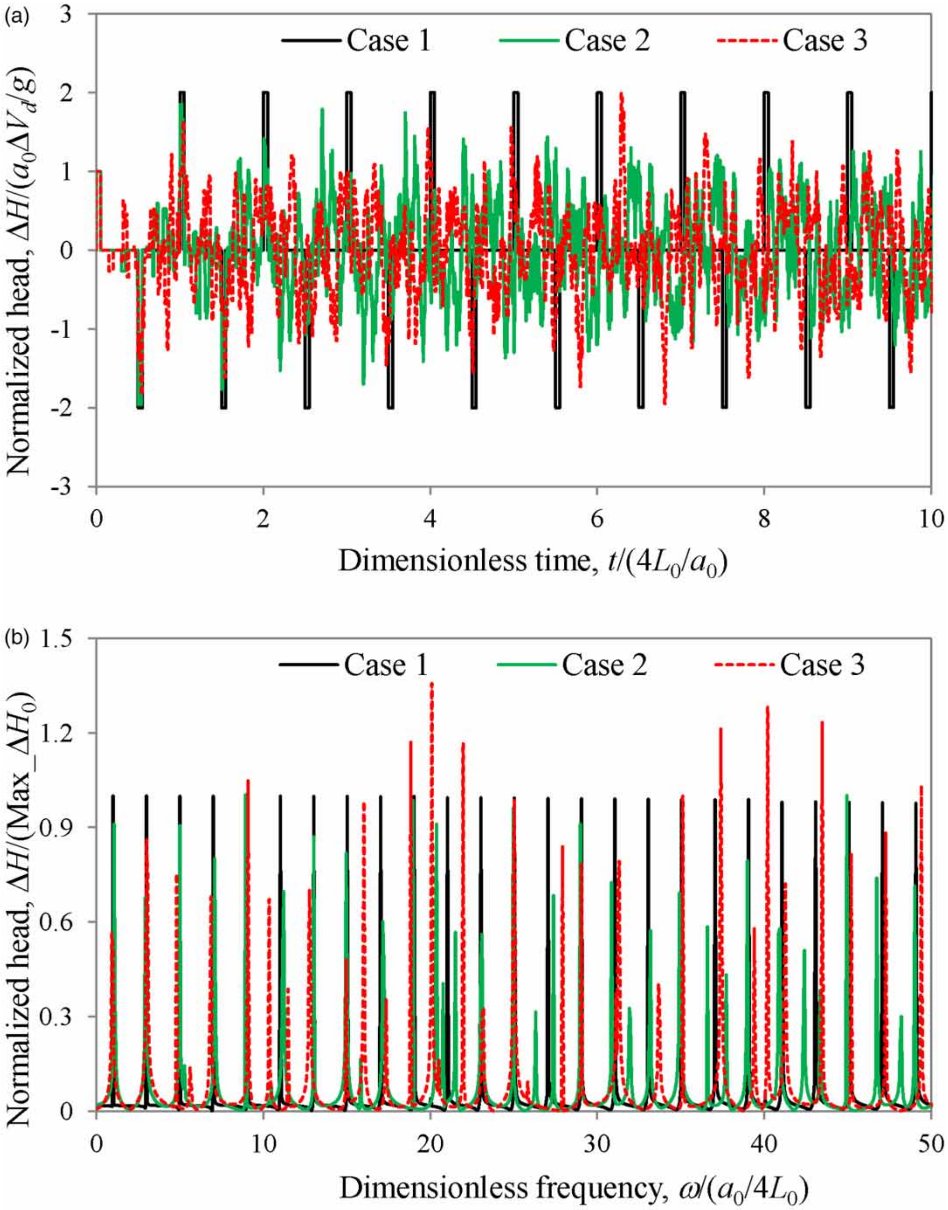

Figure 2 | Results of test pipeline systems with/without pipe junctions in: (a) the time domain results; (b) the frequency domain.

The results in Figure 2(a) clearly show the differences of the transient wave traces for the pipeline systems with/without pipe junctions. Particularly, more frequent reflections are caused by the junctions, which results in complex (e.g. non-monotonic) wave amplitude envelope attenuations with time. Moreover, different pipe junctions (e.g. the simple branched and looped junctions here) may induce different extent and frequency of wave reflections from the result comparison of systems no. 2 and no. 3 in Figure 2(a). In this regard, it is very difficult to clearly characterize the transient wave behaviors in the time domain for such relatively complex pipeline systems. Meanwhile, it has been demonstrated that this selected type of injected signal with relatively large bandwidth (high frequencies) could provide more accurate results of leak detection in the pipeline (Lee *et al.* 2015). Therefore, current transient-based time domain methods (i.e. TWR and TWD), which depend mainly on the wave reflection and damping information, may become inapplicable or inaccurate for using this preferable signal injection with relatively large bandwidth for the leak detection in complex pipeline systems. This result has also been confirmed in the previous study for series-pipeline systems in Duan *et al.* (2011). Based on these findings here and from previous studies, the frequency domain transient response is examined in the following study, with its features used for characterizing and diagnosing relatively complex pipe systems.

Frequency domain transient responses

The TFRs can be obtained from the Fourier transform of the time domain traces in Figure 2(a), and the results of the three systems are shown in Figure 2(b) for analysis. As expressed in Figure 2(a), the axial and vertical coordinates of Figure 2(b) are non-dimensionalized by the fundamental frequency ($a_0/4L_0$) and the first peak amplitude (Max_ΔH_0) of single pipeline case respectively.

As indicated similarly from the time domain results in Figure 2(a), obvious differences between the results of pipe systems with and without pipe junctions are observed in the frequency domain. With the existence of different pipe junctions, both the resonant frequency shifts and amplitude changes of the TFRs are caused with different extents by these two junctions. This result is consistent with various numerical and experimental observations in the previous studies (e.g. Brunone *et al.* 2008; Duan *et al.* 2012, 2014; Duan & Lee 2016). However, compared to time domain results, the influences of pipe junctions to the TFRs become relatively simple and independent for different resonant peaks, which have similar impact complexities that are not superimposed or accumulated with frequency. From this perspective, it might be easier to use the frequency domain results for characterizing the influences of pipe junctions to the transient system responses than the time domain results. Consequently, the TFR-based method is adopted as the investigation tool for the development of leak detection method in the typical branched and simple looped pipeline systems in this study.

TFR RESULTS FOR DIFFERENT PIPE JUNCTIONS

To develop the leak detection method, it is necessary to understand and characterize the difference of the system TFRs under intact (leak-free) and leakage conditions. That is, the leak-induced patterns are required to be explored and derived for the TFRs of pipeline systems with different pipe connecting junctions (Duan *et al.* 2010). Two typical junctions of three-pipe branch and simple two-pipe loop shown in Figure 1(b) and 1(c) are considered in this study. For simplicity and illustration, only the single leakage situation is considered in this study, and for multiple leaks, the similar derivation and analysis procedure can be extended and applied. The main results of TFR for these two cases of branched and looped pipe systems are summarized in this section, with the derivation details presented in the appendix (available with the online version of this paper).

For the intact case of branched pipeline system shown in Figure 1(b), the following resonant condition is obtained by the transfer matrix method as given in Equation (A10) in the appendix:

$$\begin{bmatrix} Y_3Y_2\sin(\mu_3l_3)\cos(\mu_2l_2)\cos(\mu_1l_1) \\ -Y_3Y_1\sin(\mu_3l_3)\sin(\mu_2l_2)\sin(\mu_1l_1) \\ +Y_2Y_1\cos(\mu_3l_3)\cos(\mu_2l_2)\sin(\mu_1l_1) \end{bmatrix} = 0, \tag{6}$$

where subscript numbers are pipe numbers described in Figure 1(b). This result has been validated and used in previous studies by the author for dead-end side branch detection (e.g. Duan & Lee 2016). Under single pipe leakage condition, after mathematical manipulations and essential simplifications, a general form of the converted transient pressure response in the frequency domain can be obtained as (see Equations (A14)–(A16) in the appendix):

$$\hat{h}^B_{Ln} = \frac{K_L}{C^B_n}\left[1 - \cos\left(2\mu_n x_{Ln} + \varphi^B_n\right)\right], \tag{7}$$

where $\hat{h}_{Ln}$ is the converted TFR based on the difference between the intact and leakage situations; n is the number of pipe that the potential leakage is located ($n = 1, 2, 3$ in this study); x_{Ln} is the distance of leakage location from the upstream end of the pipeline n; K_L is the impendence factor for describing the leakage size; the subscript L is used for quantity for leaking pipe system; the superscript B indicates the quantity for branched pipeline system, and C, ϕ are intact system based known coefficients with their expressions provided in the appendix. The result of

Equation (7) indicates that the leak-induced pattern for TFRs is dependent on the system configuration as well as the location of the leaking pipe section in the system. Moreover, for given branched pipeline system, the leak-induced pattern relies only on the potential leak information (location and size), which therefore can be used inversely to identify and detect pipe leakage in the system.

Similarly, for the simple looped pipeline system in Figure 1(c), the leak-induced patterns for different leaking conditions can be derived and expressed as follows (see Equations (B11) and (B12) in the appendix):

$$\hat{h}_{Ln}^{O} = \frac{K_L}{C_n^O}\left[R_n^O + \sqrt{\left(S_n^O\right)^2 + \left(T_n^O\right)^2}\sin\left(\mu_n l_n - 2\mu_n x_{Ln} + \varphi_n^O\right)\right], \tag{8}$$

where the superscript O indicates the quantities obtained for the looped pipeline system; the expressions of known coefficients C, R, S, T, ϕ are given in the appendix. Therefore, there are four possible leak-induced patterns in the system of Figure 1(c) for analyzing the leak information by using Equation (8). Again, these leak-induced patterns are only dependent on the leak information for the specified looped pipeline system. The detailed principle and procedures of applying Equations (7) and (8) for leak detection are stated in the following section.

TFR-BASED LEAK DETECTION

It is known from Equation (7) or (8) that the leak-induced pattern is dependent on the potential leaking pipe location (pipe number) in the above-mentioned branched or looped pipeline system, which is different from the result of single or simple series-pipeline system (e.g. Duan *et al.* 2011). Therefore, a traversal calculation and comparison of all the possible leak-induced patterns and leak detection processes is required for evaluating such relatively complex pipe systems to find out the most likely or optimal results of the pipe leakage information in the system. For the simple branched and looped pipeline systems focused in this study (e.g. the total number of pipes is less than 6), an enumeration method is used for such calculation and comparison. To obtain accurate and globally optimal results for each leak-induced pattern analysis, the GA-based optimization procedure developed in Duan & Lee (2016) is used here for the inverse analysis of Equation (7) or (8). The detailed formulation and steps for applying this GA-based method in water pipeline systems refer to Duan & Lee (2016). Figure 3 shows the main application principle and procedure of the proposed TFR-based leak detection method in this study.

It is also noted that, in this proposed method and procedure, the potential leakage information is identified

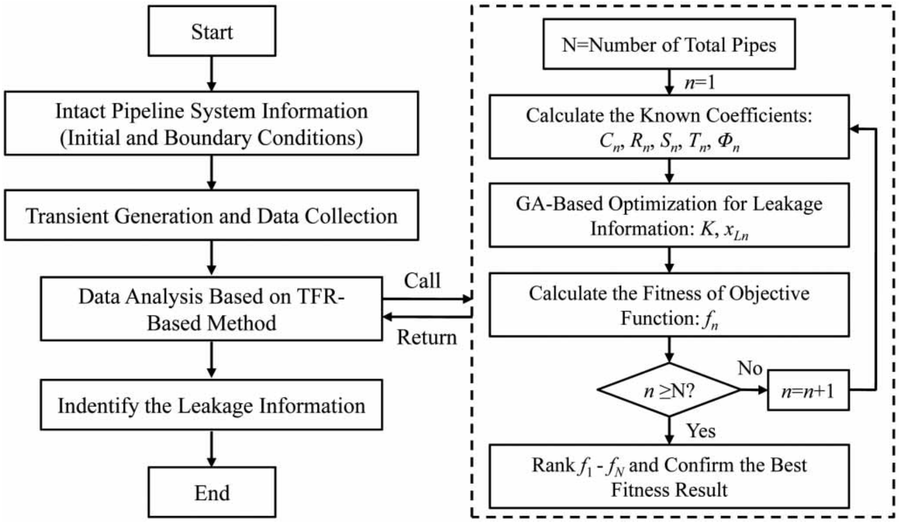

Figure 3 | Flowchart of TFR-based leak detection.

through the fitness comparison of different leak-induced patterns in the given pipeline system. Therefore, as in other transient-based method for pipe defects detection (e.g. Duan *et al.* 2011, 2012, 2014; Lee *et al.* 2013, 2015), the applicability and accuracy of this method may be affected by the model bias/errors (e.g. linear approximation and turbulence) and system uncertainties (e.g. input and output measurements). The accuracy and limitations of this method are discussed through the applications later in the paper.

NUMERICAL VALIDATIONS AND RESULTS ANALYSIS

The system configurations in Figure 1(b) and 1(c) are firstly used for numerical validations of the proposed TFR-based leak detection method, with the system parameter settings and information given in Table 1. Different leakage cases (location and size) are considered for each test system and shown in Table 2, with tests no. 1 to no. 3 for the branched pipe system and tests no. 4 to no. 7 for the simple looped pipe system. For clarity, the relative leak effective area, $A_L{}^* = C_d A_L / A_p$ with $C_d A_L$ being leaking area and A_p the cross-sectional area of leaking pipe, for each test case is also listed in the table for reference. The system transient responses are obtained by the 1D numerical simulations in the time domain (i.e. Equations (1) and (2)). The transient pressure head at the just upstream of the inline valve are collected and then converted by Fourier transform into the frequency domain for the analysis. The results of leakage detection based on the proposed method and procedure in this study are obtained and listed in Table 2. The accuracy of the method is evaluated by the difference between the real and predicted values of the leakage information, which is defined as the relative error (ε) by:

$$\varepsilon(\%) = \frac{\text{predictedvalue} - \text{realvalue}}{\text{realvalue}} \times 100. \tag{9}$$

Based on Equation (9), the prediction errors for the test cases are also given in Table 2. The results demonstrate the validity and accuracy of the proposed method for the leak detection (location and size) in the simple branched and looped pipeline systems considered in this study. Specifically, the maximum relative errors of the prediction are 13 and 28% respectively for locating and sizing the leakage. That is, this proposed method is more accurate to locate the pipe leakage than to size the leakage, which is similar with the results applied for single and series pipeline systems

Table 1 | Settings and information of test pipeline systems

System	Pipe length (m)	Pipe size (mm)	Wave speed (m/s)	Pipe friction
No. 2 (branched)	$l_1 = 500, l_2 = 240; l_3 = 200$	$D_1 = 500, D_2 = 300; D_3 = 60$	$a_1 = 1{,}000, a_2 = 1{,}100; a_3 = 1{,}200$	$f_1 = f_2 = f_3 = 0.01$
No. 3 (looped)	$l_1 = 500, l_2 = 300; l_3 = 200; l_4 = 350$	$D_1 = 500, D_2 = 400; D_3 = 500; D_4 = 200$	$a_1 = 1{,}000, a_2 = 1{,}100; a_3 = 1{,}000; a_4 = 1{,}200$	$f_1 = f_2 = f_3 = f_4 = 0.01$

Table 2 | Leakage detection results for branched and looped systems

		Real leakage information			Results of leakage detection			
System	Test no.	x_{Ln} (m)	K_L (10^{-4} m^2/s)	A_L* (10^{-3})	x_{Ln}^P (m)	ϵ (%)	K_L^P (10^{-4} m^2/s)	ϵ (%)
Branched pipeline system	1	150 ($n = 1$)	1.0	1.6	146	–2.7	0.83	–17
	2	100 ($n = 2$)	3.0	13.6	101	1.0	2.84	–5.3
	3	160 ($n = 3$)	0.2	22.6	167	4.4	0.19	–5.0
Looped pipeline system	4	300 ($n = 1$)	3.0	4.9	281	–6.3	2.68	–10.7
	5	120 ($n = 2$)	1.0	2.5	124	3.3	0.97	–3
	6	150 ($n = 3$)	4.0	6.5	169	12.7	3.69	–7.8
	7	100 ($n = 4$)	0.8	8.1	113	13	0.58	27.5

(Lee *et al.* 2006; Duan *et al.* 2011). This is mainly because of the linear approximations made for the derivations, which is discussed later in this study.

To further demonstrate the detection process and results, the leak-induced patterns of tests no. 1 and no. 4 from the numerical simulations by 1D models and theoretical prediction by Equation (7) or (8) are plotted in Figure 4 for comparison. Both the results in Table 2 and Figure 4 indicate the good agreements of the phase changes between the leak-induced patterns by numerical simulations and analytical analysis, which results in the relatively small errors in the prediction of the leak locations in Table 2. However, the results also reveal overall that the analytical result of Equation (7) or (8) has underestimated the amplitudes of the leak-induced patterns due to the simplifications of the nonlinear effects of friction term during the derivations, which also results in the relatively large and negative errors of the leak size prediction in Table 2. In this regard, the inclusion of nonlinearities of transient effects in the system (e.g. friction or turbulence or wave-structure interactions) is required to improve the accuracy of the leak detection results for the proposed method. This aspect may become the next-step work in

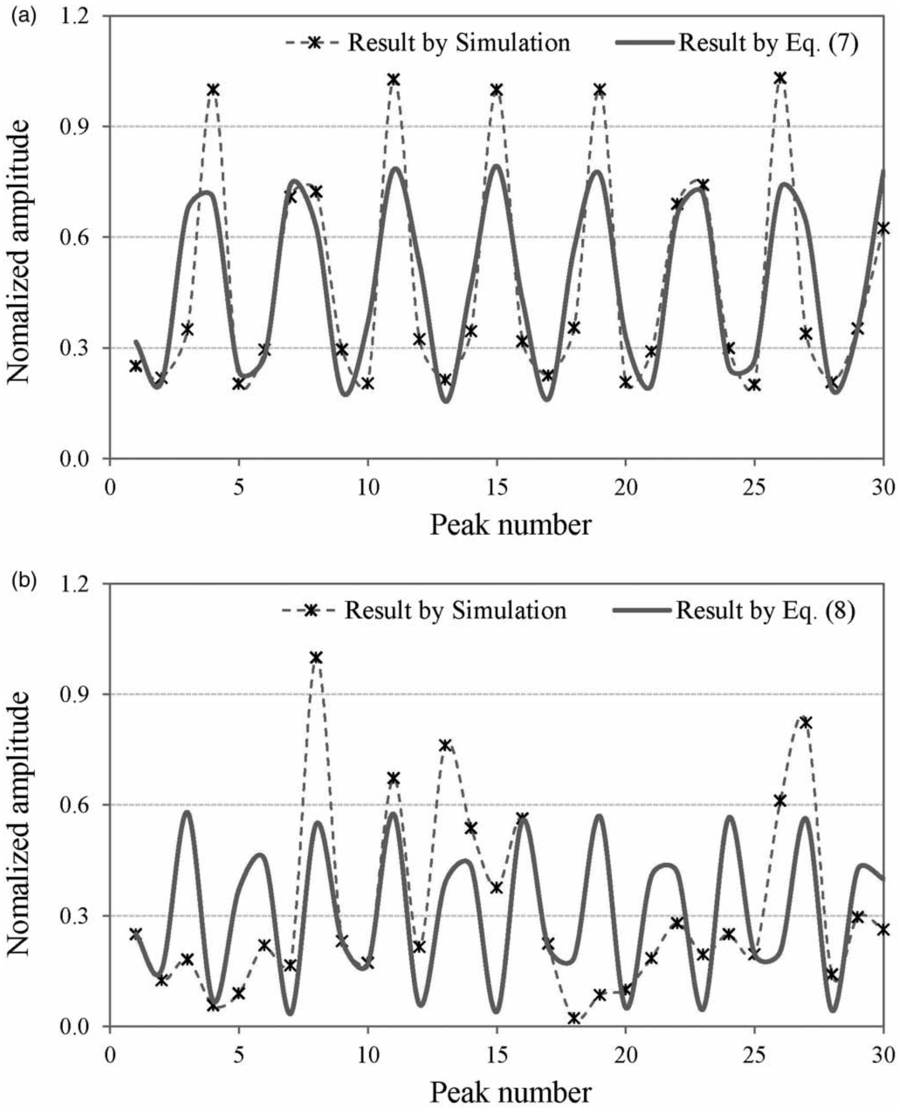

Figure 4 | Leak-induced patterns of system TFR results for: (a) test no. 1; (b) test no. 4.

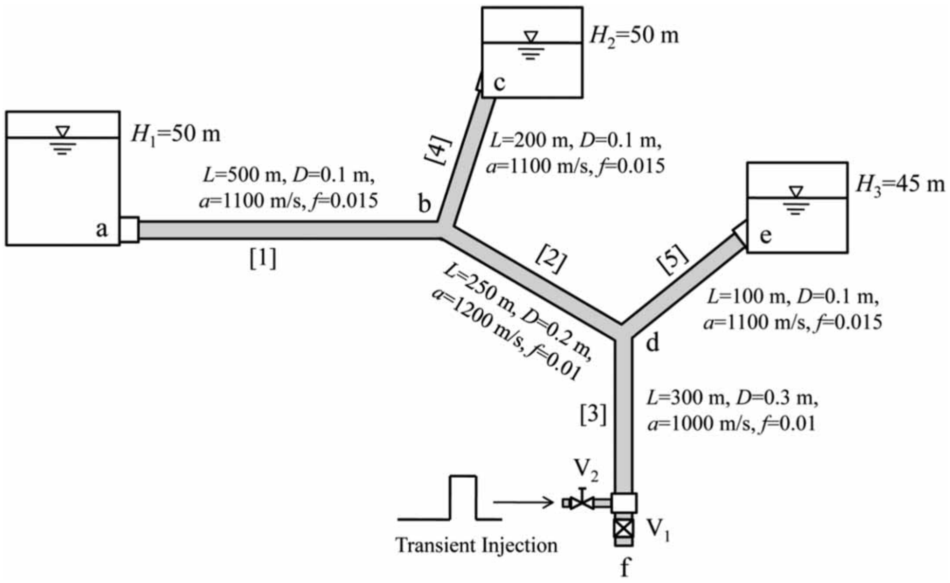

Figure 5 | Test pipeline system with two branched junctions.

the future for the improvement of the TFR-based defect detection method.

FURTHER APPLICATION AND DISCUSSION

The application results and analysis above have validated and confirmed the applicability and accuracy of the proposed method and application procedure for pipe leak detection in the single branched and simple looped pipeline systems considered in this study. These successful validations provide the possibility of the extension of the TFR-based method for leak detection to relatively more complex pipe systems consisting of multiple branched and looped junctions. From this perspective, and based on the similar procedures of this study, the TFR results can also be derived and applied for such pipeline systems with multiple junctions (branched and looped), which actually results in a similar form of leak-induced patterns given in this study, but with different expressions of the known-system based coefficients (e.g. C, R, S, T, and ϕ). For demonstration in this study, a typical pipeline system with two branched pipe junctions shown in Figure 5 is adopted for investigation. The information of system configurations and parameters are plotted in Figure 5, with different leakage test cases (no. 8 to no. 12) listed in Table 3.

Table 3 | Leakage detection results for the system with two branched pipe junctions

	Real leakage information			Results of leakage detection			
Test no.	x_{Ln} (m)	K_L (10^{-5} m^2/s)	A_L* (10^{-3})	x^P_{Ln} (m)	ϵ (%)	K^P_L (10^{-5} m^2/s)	ϵ (%)
8	300 ($n = 1$)	2.0	8.13	346	15.3	1.36	–32.0
9	150 ($n = 2$)	1.2	1.22	141	–6.0	0.78	–35.0
10	210 ($n = 3$)	0.5	2.26	216	2.9	0.43	–14.0
11	140 ($n = 4$)	5.0	12.20	157	12.1	4.65	–7.0
12	80 ($n = 5$)	3.0	2.03	84	5.0	2.49	–17.0

The TFR-based leak detection results by the proposed method and procedure in this study are shown in Table 3 and the obtained leak-induced patterns for tests no. 8 and no. 10 are plotted in Figure 6, which demonstrate again the applicability and accuracy of the TFR-based method for identifying and detecting pipe leakage in relatively more complex pipe systems with multiple pipe branches. Compared to the single branched pipe system in Figure 1(b), the detection accuracy of the TFR-based method becomes decreased with the increase of the connection complexities of the system. However, the relative errors are still within 16 and 35% for leakage location and size respectively, which may also provide useful information and significant implications for the pipe leakage detection and diagnosis in practice. From this point of view, the TFR-based leak detection method is extendable and applicable to relatively more complex pipeline systems with multiple branches and simple loops, as long as the pipe system under investigation has been pre-defined for the topological configurations and the system properties and operation parameters are well known for the analysts under the original and intact conditions (before the occurrence of leakage).

While the successful applications of the developed TFR-based method for leakage detection in pipeline systems with single and multiple branched junctions and simple looped junctions respectively, the application results also reveal the obvious increase of the detection errors with system complexities (e.g. number of junctions), especially for predicting the leakage size. This result and trend may be attributed to the assumptions and simplifications made for the method development as follows:

1. Linearization of steady friction term, which requires the relatively small transient flow perturbation to the steady state discharge (Duan *et al.* 2011; Lee *et al.* 2013).
2. Neglect of unsteady friction effect, which is frequency dependent and could be included in the developed

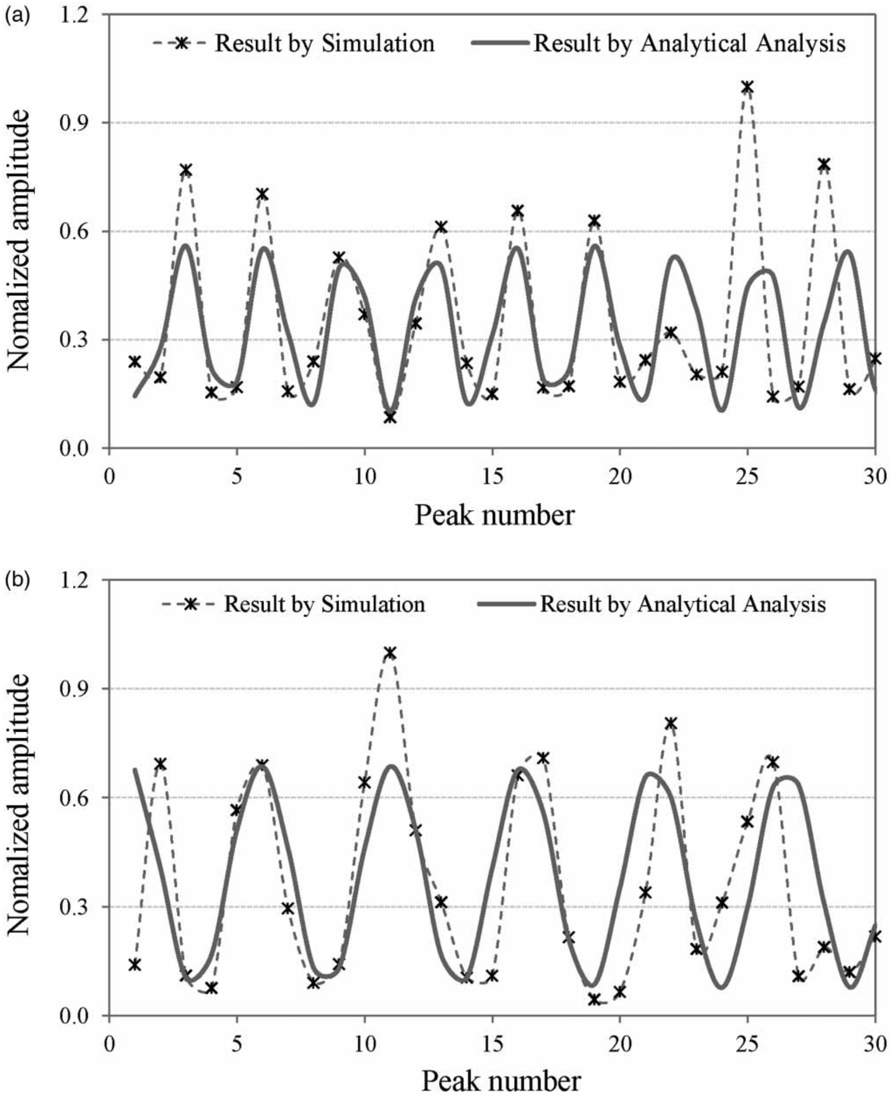

Figure 6 | Leak-induced patterns of system TFR results for: (a) test no. 8; (b) test no. 10.

method by considering the simplified form given in Lee *et al.* (2005) and Duan *et al.* (2011).

3. Assumption of relatively small leakage capacity to main pipeline discharge, so that the linearized orifice equation (as indicated by K_L) can be applied to simulate the leakage effect (Lee *et al.* 2006, 2013).

Meanwhile, different system influence factors may also contribute to the discrepancies of leakage prediction results, including the following:

1. Errors of data collections and treatment: such as the sample frequency of the time-domain data; trace cutting length of time-domain data (e.g. number of wave periods for analysis); and the discrete Fourier transform for frequency data analysis.
2. Inaccuracy of the inverse analysis process (e.g. GA-based optimization in this study): such as the convergence and error of inverse analysis process; and the non-uniqueness of solutions to the leak-induced patterns for complex pipe systems.
3. Uncertainties and complexities of initial and boundary conditions in practical pipeline systems: such as the external noises and instabilities in water piping systems; and the complex interactions of transient wave, flow turbulence and system components (e.g. junctions and devices).

With these limitations and influence factors, it is necessary to improve the transient model and methods for the accurate extension and application of the developed TFR-based leak detection in practical situations, for example, through the following aspects:

(a) Improvement of 1D transient models (in time and frequency domains) to accurately represent the physics and process of transient pipe flows in complex pipe systems such as unsteady friction and turbulence, wave-junction interaction, and wave-leak interaction.
(b) Selection of optimal injected transient signals to capture the full picture of the leakage characteristics, for example appropriate bandwidth of signals as suggested in Duan *et al.* (2010, 2011); and meanwhile, multiple signal injections and response collections may also be helpful to improve the accuracy of the proposed method (Lee *et al.* 2015).
(c) Robustness of the inverse analysis algorithm for obtaining optimal and physical solutions of the derived leak-induced patterns, especially for the applications of large-scale and complex pipe systems.

Finally, it is important to point out that only the numerical applications are conducted in this paper for the preliminary validations of the developed TFR-based leak detection method. In the future work, further experimental tests (laboratory and field) are required and designed to validate and verify the accuracy, tolerance and sensitivity of this developed method for practical cases under the influences of inevitable noises and uncertainties in practical water pipe systems.

SUMMARY AND CONCLUSIONS

This paper investigates the possibility of the application of the TFR-based leak detection method in pipeline systems with different pipe junctions. The systems of simple branched and looped pipeline systems are considered and investigated in this study. The influence of different pipe junctions to system transient responses (TFRs) is firstly examined by numerical simulations in the time and frequency domains, which highlights the merits of using the frequency domain responses for characterizing the transient system behaviors. The system TFRs are then derived by the linear transfer matrix method for both the pipe systems with single branch and loop connections, which are then used for the detection of pipe leakage information in this study.

The analytical results indicate that both the typical branched and looped pipe junctions may have great influences to the system TFRs but have little impacts on the leak-induced patterns. The GA-based optimization is then proposed for solving the analytically derived leak-induced patterns to obtain the leakage information in the system. The developed TFR-based method and application procedure are validated through different numerical tests for pipe systems with single branched, single looped and two branched pipe junctions respectively. The results demonstrate the applicability and accuracy of the developed method for leakage identification and detection in these multiple-pipeline systems. However, the results also imply that this method is more accurate to locate the pipe leakage than to size the leakage in these applications.

The results analysis and discussion of this study provide the evidences and confirmations for the extension of the TFR-based method to pipe systems with different connection junctions. It is also noted that extensive experimental tests (laboratory and field) are demanded for further validating the accuracy and sensitivity of the proposed method in practical applications. Furthermore, the feasibility and applicability of the TFR-based method for practical water distribution networks still need more investigations in future work.

ACKNOWLEDGEMENTS

This paper was supported by research grants from: (1) the Hong Kong Polytechnic University (HKPU) under projects with numbers 1-ZVCD, 1-ZVGF, 3-RBAB and G-YBHR; and (2) the Hong Kong Research Grant Council (RGC) under project numbers 25200616 and T21-602/15-R. The author would like to thank Mr T. C. Che for his kind help in plotting the figures in this paper.

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First received 11 January 2016; accepted in revised form 18 July 2016. Available online 23 August 2016