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Efficient Leak Detection in Single and Branched Polymeric Pipeline Systems by Transient Wave Analysis

Bin Pan[a]; Caterina Capponi[b]; Silvia Meniconi[b];
Bruno Brunone[b]; Huan-Feng Duan[a]*

[a] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, 999077*
[b] *Department of Civil and Environmental Engineering, The University of Perugia, Via G. Duranti 93, Perugia 06125, Italy*

**Corresponding Author: hf.duan@polyu.edu.hk*

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Abstract: The widespread use of plastic pipes in different fluid conveyance systems has greatly driven the recent development and application of transient-based methods (TBMs) for leak detection in viscoelastic/polymeric pipelines. Current TBMs for viscoelastic pipe leak detection are usually achieved by a two-step procedure, namely viscoelastic parameters identification and leak detection, which requires the pre-knowledge of intact system states (i.e., non-leak) for comparative analysis. This paper presents an efficient single-step frequency domain inverse transient analysis (FDITA) method for simultaneous identifications of viscoelastic parameters and leaks in plastic pipes, so as to enhance the applicability and accuracy of TBMs. Both the single and branched polymeric pipe systems are applied for the method development and application. To this end, analytical solutions of single and branched systems from the transfer matrix method are firstly derived to represent the transient frequency responses of viscoelastic pipelines with leaks. A global optimized nonlinear curve fitting method is then employed to identify both viscoelastic parameters and potential leaks by knowing/measuring other system and flow conditions. Extensive experimental validations and numerical applications of both single and branched pipe systems demonstrate the very good efficiency and accuracy of the developed method for leak detection in different viscoelastic pipe systems. Furthermore, the mechanism of transient wave-leak-viscoelasticity is analysed based on these application results and theoretical evidence. Finally, a sensitivity analysis is performed to quantify and discuss the advantages and potential limitations of the developed method in the paper.

Keywords: polymeric pipeline; leak detection; viscoelastic parameters; transient-based method (TBM); frequency domain inverse transient analysis (FDITA)

1. Introduction

Transient based pipe anomaly detection method is becoming popular for its non-intrusive and nondestructive features during operation. Current transient-based anomaly detection studies are mainly developed and applied for elastic pipes [1-9], in which the effects of pipe-wall material properties on transient wave behavior are reflected in the value of the wave speed [2, 10]. However, in recent years, due to the substantial progress in material manufacture technology, more and more polymeric pipes (also termed as viscoelastic or plastic pipes), such as those made of PVC, PPR, PE, and HDPE materials, have been adopted in different water distribution systems from small to relatively large scales. Thus, extending and testing current transient-based methods (TBMs) for anomalies detection in polymeric pipes become important for increasing applications of TBMs in water distribution systems.

Compared with elastic pipes, viscoelastic/polymeric pipes have very different behavior under transient/dynamic flow conditions, which may impose a significant modification (magnitude damping and phase change) on pressure wave oscillations. This modification effect, on one hand, can be utilized to protect fluid piping systems from pressure surges [11-13]. On the other hand, it can also induce more complexities on the use of the developed methods to simulate transient traces and/or detect anomalies in viscoelastic pipelines [14, 15]. The different behavior of viscoelastic pipes stems from their long-chain molecular structures which will cause the time shift between pressure oscillations and circumferential strain and then the fast decay of the pressure wave and flow velocity [16]. To precisely characterize this behavior, the creep function is often adopted [14, 17-20]. In the function, a hysteresis response formed during the transient oscillation process (loading and unloading) is expressed by two sets of parameters, namely the retardation time and the creep compliance. In this regard, these viscoelastic parameters are thought to be crucial for the transient-based leak detection in viscoelastic pipes, as their inaccurate values may result in incorrect capture of viscoelastic behavior and thus faulty leak detection results.

To minimize the influence stemming from inaccurate viscoelastic parameters, the leak detection in viscoelastic pipes is usually performed by a two-step procedure, including: (i) viscoelastic parameters identification (from an equivalent intact system) and (ii) leak detection based on the known parameters from (i) [21-23]. This method is quite common in previous investigations as these material properties can be acquired by corresponding intact systems in laboratory or pilot experiments under controls (i.e., with different tests). However, in practice, it is almost impossible to acquire these material properties from the intact case for the pipeline system under operations. Although the transient trace of the intact system may be obtained by historical records or numerical simulations, the retarded response is, in fact, influenced by many factors (e.g., stress history, constraint conditions, temperature, etc.) [19, 21], which makes the obtained intact case (without anomalies) results invalid/unmatched to the anomalous case under investigation (e.g., with leaks). To this end, it is beneficial to develop the TBMs for leak detection in the commonly used viscoelastic/polymeric pipes using transient responses from the testing system only.

Generally, if there is a leak in the system, extraction of some invariant features in a transient signal may be a feasible way to identify viscoelastic parameters for a simple pipeline system with leaks, such as the Reservoir-Pipe-Valve (RPV) system. For example, Gong et al. 2016 [24] proposed a frequency domain method for viscoelastic parameters identification using only resonance peak locations, and this method is further improved in [25] to ensure that it could be further applied to a realistic pipe system even with a leak. The tenet of this method is to use the invariance of resonance peaks in intact or leaky systems in the frequency domain. In fact, this concept can also be extended to predict viscoelastic parameters in the time domain as the phase and period of pressure wave oscillations are in principle identical with the intact system if a leak causes little frequency shift [26]. Therefore, the steady-state cross times

(SSCTs) that are quantified by the transient wave cross the steady-state pressure can also be used to identify viscoelastic parameters. It is worth noting that in a simple system e.g., the single pipe RPV system, very limited information like the resonance peak locations and SSCTs can be adopted to identify viscoelastic parameters and then detect a leak [24, 26, 27]. However, it is not always possible to extract these invariant features from a transient trace in practice. Meanwhile, in a more complex system e.g., a branched system, the role of each polymeric pipe even with a short length is important and cannot be ignored/simplified [28, 29]. In this condition, the number of unknowns in the system may be much larger than that of single pipe systems, and the invariant properties (e.g., SSCTs or resonance peak locations) of the system are even limited to identify viscoelastic parameters, much less to locate a leak [7]. Therefore, the previously developed two-step strategy that calibrates the viscoelastic parameters firstly and then detects potential leaks using limited features (e.g., resonance peak locations) for a single pipeline system may not always be valid or accurate enough for more practical/complex pipeline systems (such as a branched pipe system). In this condition, further improving the previously developed identification procedure [27] to simultaneously identify viscoelastic parameters and leaks for both simple and complex systems is preferable for the development and application of TBMs, which is the motivation of this paper.

In order to diagnose polymeric pipelines, including viscoelastic parameters, leak size, and location, the inverse transient analysis (ITA) is a feasible way to take full use of all relevant information and identify the potential anomalies in pipelines based on the transient responses measured or simulated in the system [30-32]. Usually, performing the ITA in the time domain is a feasible way. However, because of the complexity of the time-domain equations (transient model), the identification process in the time domain is usually time-consuming. Meanwhile, since the calibration process has to match all possible signatures of transients in a system including turbulence and uncertainties (noises) [1, 21, 33], it is very possible for calibration results trapped within localized and inaccurate solutions [17] and affected by noises[33]. By contrast, in the frequency domain, transient equations can be analytically derived, so the ITA method is expected to have high efficiency and it is more suitable to perform the global optimization methods in the frequency domain to find the best solution for a specific system. Meanwhile, the influence of high-frequency noise can be reduced in the frequency domain as only the low-frequency part of the FRF which contains the main information of a system is used in analysis [34]. Therefore, it will be more desirable to perform the ITA method in the frequency domain than in the time domain.

To this end, the previously proposed frequency-domain method [27] is further modified and improved with aiming to develop an efficient and accurate frequency domain ITA method (termed as FDITA in this study) to simultaneously identify viscoelastic parameters and leaks. The low-frequency domain of the FRF, instead of only resonance peaks, is used in the identification to extend the application scope of the method from only simple single pipe RPV systems to more practical branched RPV systems. A global optimized nonlinear curve fitting method is adopted in the calibration to enhance the accuracy of identification results. The structure of this paper is as follows: followed the introduction, the method, and framework of the global optimized FDITA method for simultaneous identification of viscoelastic parameters and a leak in both single and branched RPV systems are described. Then, the proposed method is validated by experimental and extensive numerical tests to show the effectiveness and the suitable range of the method. Thereafter, the input signal extraction, limitations, and influential factors of the proposed method are discussed. The conclusions and finds of this paper are summarized at the end of the paper.

2. Methodology

2.1. Transfer matrix analysis of transient systems

In the literature, on one hand, the one-dimensional (1D) transient method in the time domain has been widely developed and used for simulating highly unsteady flows in water pipelines, which can be triggered commonly and frequently in water supply systems [2, 35]. On the other hand, the frequency domain equivalence of this 1D transient model can be obtained by the transfer matrix analysis so that the transient behavior of pipe flows can be understood and investigated in a comprehensive way [36]. In the analysis, the head and discharge perturbations at two ends of a pipe section can be expressed in a matrix form in the frequency domain as [1, 27, 37-39]:

$$\begin{pmatrix} q \\ h \end{pmatrix}^{DN} = \begin{pmatrix} \cosh \mu l & -\dfrac{\sinh \mu l}{Z} \\ -Z\sinh \mu l & \cosh \mu l \end{pmatrix} \begin{pmatrix} q \\ h \end{pmatrix}^{UP} \tag{1}$$

in which q and h are discharge and head perturbations during transient in the frequency domain; μ is the propagation operator; Z is the characteristic impedance; l is the distance between two locations of the pipe; superscripts "*UP*" and "*DN*" indicate the locations of perturbations.

In a polymeric pipe, the viscoelastic response is commonly simulated by a linearized Kelvin-Voigt (K-V) model (as shown in Fig.1) which comprises virtual springs and dashpots. In the K-V model, the elastic response of the polymeric material is represented by the first spring, and a spring and a dashpot which are connected in parallel stand for one set of K-V elements. By using different K-V elements, the retarded response of the pipe wall can be quantified. Since the retarded deformation caused by the pipe wall viscoelasticity during transient is tiny, the retarded response is quantified by a linear assumption given by [14]:

$$\begin{aligned} &\varepsilon_r = \sum_{k=1}^{n} \varepsilon_k, \varepsilon_k = \int_0^t \Psi(x, t-t^{'}) \frac{J_k}{\tau_k} e^{-\frac{t^{'}}{\tau_k}} dt^{'}, \\ &\Psi(x,t) = C(H(x,t) - H_0(x)), \\ &CJ_k H = \sum_{k=1}^{n} (\tau_k \frac{\partial \varepsilon_k}{\partial t} + \varepsilon_k) \end{aligned} \tag{2}$$

in which ε_r = total retarded strain of the pipe wall; ε_k = retarded strain caused by k^{th} K-V element; $C = \alpha\gamma D/2e$ is a pipe scale coefficient; α = pipe constraint coefficient; D = internal diameter of a viscoelastic pipe; e = thickness of pipe wall; $\gamma = \rho g$ is specific weight; g =

gravitational acceleration; H = piezometric head in the time domain; ρ = fluid density; n = the total number of K-V elements; $J_k = 1/B_k$ = creep compliance of the k^{th} K-V element; B_k = elastic modulus of k^{th} K-V element; s_k = viscosity of the dashpots of k^{th} K-V element; $\tau_k = s_k/B_k$ = retardation time of the k^{th} K-V element; t = time; x = coordinate along the pipe axis; the subscript "0" = initial conditions. It is worth pointing out that as a conceptual model, although the parameters of the K-V model have only a mathematical meaning [40], there may still be a link between the pipe period and retardation time as pointed out in [41, 42].

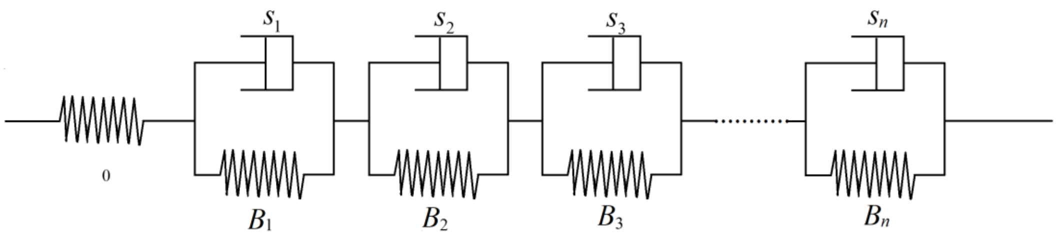

Fig.1 Generalized Kelvin-Voigt model

The influence of viscoelasticity in the transfer matrix method is reflected in the propagation operator (μ) and characteristic impedance (Z). When the pipe wall viscoelasticity and frictional effect are considered, μ and Z can be calculated as:

$$\mu = \frac{i\omega}{a}\sqrt{(1+2\frac{a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{1+i\omega\tau_k})(1+\mathrm{sign}(Q)\frac{fQ_0}{DAi\omega}+\frac{4\sqrt{\nu}}{D}\frac{1}{\sqrt{\lambda+i\omega}})}$$
$$Z = \frac{a}{gA}\sqrt{\frac{(1+\mathrm{sign}(Q)\frac{fQ_0}{DAi\omega}+\frac{4\sqrt{\nu}}{D}\frac{1}{\sqrt{\lambda+i\omega}})}{(1+2\frac{a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{1+i\omega\tau_k})}} \quad (3)$$

where ω = angular frequency; a = elastic wave speed of the viscoelastic pipe; A = cross-sectional area of the pipeline; f = skin friction factor, it is calculated by the Blasius equation ($f = 0.3164/(\mathsf{R}_0)^{0.25}$) in this study; $\mathsf{R} = VD/\nu$ is the Reynolds number; ν = kinematic viscosity of fluid; V = velocity of the fluid; Q = discharge rate in the time domain; λ = unsteady friction convolution coefficient for different flow conditions, which is obtained by considering velocity profiles changes in the unsteady flow[10]: and can be calculated by

$$\lambda = \frac{(0.54\nu \mathrm{R}_0)^{\lg\frac{14.3}{\mathrm{R}_0^{0.05}}}}{D^2} \tag{4}$$

Eq. (1) is the fundamental matrix for representing the transient response in any hydraulic element (pipes, faults, or devices), which thus can be assembled to simulate leaking or more complex systems [36]. For example, in a leaking single pipe or branched RPV system as shown in Fig. 2, its field matrix has the following general form [36]:

$$\begin{pmatrix} q \\ h \end{pmatrix}^D = [Y][\Theta][\Psi]\begin{pmatrix} q \\ h \end{pmatrix}^U = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}\begin{bmatrix} \theta_{11} & \theta_{12} \\ \theta_{21} & \theta_{22} \end{bmatrix}\begin{bmatrix} \psi_{11} & \psi_{12} \\ \psi_{21} & \psi_{22} \end{bmatrix}\begin{pmatrix} q \\ h \end{pmatrix}^U \tag{5}$$

where Y, Θ, Ψ are the matrixes representing different pipe sections in the system; y, θ, ψ are the elements of corresponding matrices.

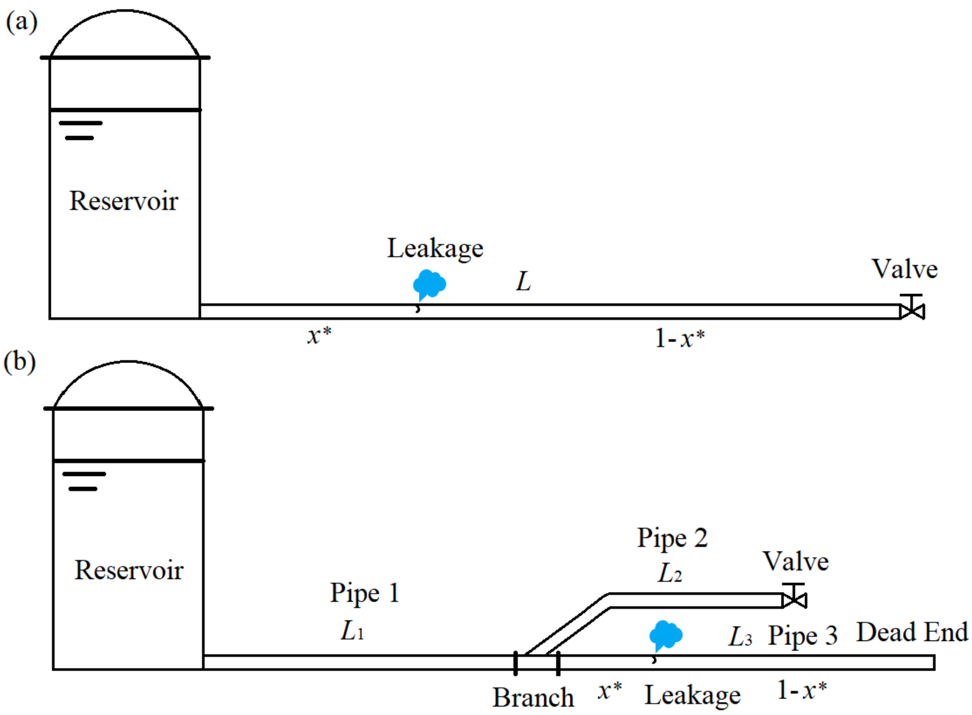

Fig. 2 Sketches of pipeline systems: (a) single pipe; (b) branched pipes

Specifically, in a leaking single-pipe system as in Fig. 2(a), Y and Ψ represent matrices of intact pipe sections at the upstream and downstream of a leak, respectively, and Θ is the point matrix of a leak. Meanwhile, in a leaky branched system as shown in Fig. 2(b), Y and Ψ

refer to matrices of pipe sections at the upstream and downstream of a branched junction and Θ is that of a branch junction. By injecting a unit perturbation in the system, the head response at the downstream can be obtained as:

$$\left|h^{D}\right| = \left|-\frac{U_{21}}{U_{11}}\right| = \left|-\frac{y_{21}\theta_{11}\psi_{11} + y_{22}\theta_{21}\psi_{11} + y_{21}\theta_{12}\psi_{21} + y_{22}\theta_{22}\psi_{21}}{y_{11}\theta_{11}\psi_{11} + y_{12}\theta_{21}\psi_{11} + y_{11}\theta_{12}\psi_{21} + y_{12}\theta_{22}\psi_{21}}\right| \tag{6}$$

As a result, if a leak location is represented in a dimensionless form x^{*} (= x_l/L, x_l = leak location measured from the upstream boundary; L = length of the pipe where a leak locates) as shown in Fig. 2(a), the head response of a leaky single pipe system measured at the downstream can be obtained:

$$\left|h_{D}\right| = \left|\frac{\sinh\mu L + \dfrac{Q_l}{2H_l} Z \sinh\mu L x^{*} \sinh\mu L(1-x^{*})}{\dfrac{\cosh\mu L}{Z} + \dfrac{Q_l}{2H_l}\cosh\mu L(1-x^{*})\sinh\mu L x^{*})}\right| \tag{7}$$

in which Q_l and H_l = the leaking rate and head at a leak in the steady-state, respectively. For the convenience of analysis, two dimensionless parameters are defined and used for quantifying the leak size: one is the percentage of leak discharge, $R_{leak} = 100\% \times Q_l/(Q_l+Q_0)$, and the other is the relative size of the leak area, $s^{*} = A_L/A$ (A_L is the leak effective area).

Similarly, for the branched pipe system in Fig. 2(b), there are three patterns for a single leak situation [7]:

(1) the leak at pipe 1:

$$\begin{aligned}\left|h^{U1}\right| &= \left|-\frac{U_{21}}{U_{11}}\right| \\ &= \left|\frac{\left\{\begin{aligned}&Z_2\sinh\mu_2L_2\cosh\mu_1L_1 + \left(\frac{Z_2\sinh\mu_2L_2\sinh\mu_3L_3}{Z_3\cosh\mu_3L_3} + \cosh\mu_2L_2\right)Z_1\sinh\mu_1L_1 + \frac{Q_l}{2H_l}\cosh\mu_1L_1(1-x^{*})Z_1\sinh\mu_1L_1x^{*}Z_2\sinh\mu_2L_2 \\ &+\frac{Q_l}{2H_l}Z_1^{2}\sinh\mu_1L_1x^{*}\sinh\mu_1L_1(1-x^{*})\left(\frac{Z_2\sinh\mu_2L_2\sinh\mu_3L_3}{Z_3\cosh\mu_3L_3} + \cosh\mu_2L_2\right)\end{aligned}\right\}}{\left\{\begin{aligned}&\cosh\mu_2L_2\cosh\mu_1L_1 + \left(\frac{\cosh\mu_2L_2\sinh\mu_3L_3}{Z_3\cosh\mu_3L_3} + \frac{\sinh\mu_2L_2}{Z_2}\right)Z_1\sinh\mu_1L_1 + \frac{Q_l}{2H_l}\cosh\mu_2L_2\cosh\mu_1L_1(1-x^{*})Z_1\sinh\mu_1L_1x^{*} \\ &+\left(\frac{\cosh\mu_2L_2\sinh\mu_3L_3}{Z_3\cosh\mu_3L_3} + \frac{\sinh\mu_2L_2}{Z_2}\right)\frac{Q_l}{2H_l}Z_1^{2}\sinh\mu_1L_1x^{*}\sinh\mu_1L_1(1-x^{*})\end{aligned}\right\}}\right|\end{aligned} \tag{8}$$

(2) the leak at pipe 2:

$$\left|h^{U1}\right| = \left|-\frac{U_{21}}{U_{11}}\right| = \left|\frac{\left\{\begin{aligned}&(\cosh\mu_1 L_1 + \frac{Z_1\sinh\mu_1 L_1\sinh\mu_3 L_3}{Z_3\cosh\mu_3 L_3})(Z_2\sinh\mu_2 L_2 + \frac{Q_l}{2H_l}Z_2{}^2\sinh\mu_2 L_2 x^*\sinh\mu_2 L_2(1-x^*))\\&+Z_1\sinh\mu_1 L_1(\cosh\mu_2 L_2 + \frac{Q_l}{2H_l}Z_2\cosh\mu_2 L_2 x^*\sinh\mu_2 L_2(1-x^*))\end{aligned}\right\}}{\left\{\begin{aligned}&(\cosh\mu_1 L_1 + \frac{Z_1\sinh\mu_1 L_1\sinh\mu_3 L_3}{Z_3\cosh\mu_3 L_3})(\cosh\mu_2 L_2 + \frac{Q_l}{2H_l}\cosh\mu_2 L_2(1-x^*)Z_2\sinh\mu_2 L_2 x^*)\\&+Z_1\sinh\mu_1 L_1(\frac{\sinh\mu_2 L_2}{Z_2} + \frac{Q_l}{2H_l}\cosh\mu_2 L_2(1-x^*)\cosh\mu_2 L_2 x^*)\end{aligned}\right\}}\right| \tag{9}$$

(3) the leak at pipe 3:

$$\left|h^{U1}\right| = \left|-\frac{U_{21}}{U_{11}}\right| = \left|\frac{\left\{\begin{aligned}&(Z_2\cosh\mu_1 L_1\sinh\mu_2 L_2 + Z_1\sinh\mu_1 L_1\cosh\mu_2 L_2)(\cosh\mu_3 L_3 + \frac{Q_l}{2H_l}\cosh\mu_3 L_3(1-x^*)Z_3\sinh\mu_3 L_3 x^*)\\&+\frac{Z_1 Z_2\sinh\mu_1 L_1\sinh\mu_2 L_2\sinh\mu_3 L_3}{Z_3} + Z_1 Z_2\frac{Q_l}{2H_l}\sinh\mu_1 L_1\sinh\mu_2 L_2\cosh\mu_3 L_3(1-x^*)\cosh\mu_3 L_3 x^*)\end{aligned}\right\}}{\left\{\begin{aligned}&(\cosh\mu_1 L_1\cosh\mu_2 L_2 + \frac{Z_1\sinh\mu_1 L_1\sinh\mu_2 L_2}{Z_2})(\cosh\mu_3 L_3 + \frac{Q_l}{2H_l}\cosh\mu_3 L_3(1-x^*)Z_3\sinh\mu_3 L_3 x^*)\\&+\frac{Z_1\sinh\mu_1 L_1\cosh\mu_2 L_2\sinh\mu_3 L_3}{Z_3} + Z_1\frac{Q_l}{2H_l}\sinh\mu_1 L_1\cosh\mu_2 L_2\cosh\mu_3 L_3(1-x^*)\cosh\mu_3 L_3 x^*\end{aligned}\right\}}\right| \tag{10}$$

in which L_1, L_2, L_3 = length of corresponding pipes as shown in Fig. 2(b).

Consequently, Eqs. (7-10) are derived relationships for expressing influence patterns of different factors and parameters on the system response in the frequency domain under different system characteristics and flow conditions. In fact, these analytical relationships are theoretical foundations of the FDITA method for the identification of viscoelastic parameters and leaks in both single and branched pipeline systems.

2.2. Principle and application procedure

The derived patterns in Eqs. (7-10) clearly demonstrate the dependence of the transient response in the frequency domain on the systematic and flow information. As a result, viscoelastic properties of viscoelastic pipes and potential leaks in a system can be identified inversely through solving the relevant pattern equation with knowing all other essential information in the equation. In this process, the unknowns to be identified include the number of K-V elements, corresponding retarded times and creep compliances, the leaking pipe number (in the branched system), and the size and location of leaks in the system, which are the main objective of the proposed FDITA methods.

To achieve accurate inverse analysis by the developed FDITA method, a global optimized least-square nonlinear curve fitting procedure is employed in this study. A trust region method is used in the optimization procedure to identifying the viscoelastic parameters and leak properties with a reasonable bound (e.g., J ~ 1e-8 to 1e-13 Pa^{-1}, τ ~ 1e-6 to 30 s, Q_l/H_l ~ 1e-11 to 1e-2 m^2/s (corresponding C_dA ~ 1.01e-11 to 1.01e-2 m^2 with H_{tank} = 20 m) and x^* ~ 0 to 1). With these constraints, the identification problem can be handled efficiently, so it is adopted in this research. The optimization method sets the objective function as the minimization of the total square error between calculated values and exact/measured values as shown in Eq. (11). A globally optimal solution is achieved by running the nonlinear curve fitting process repeatedly with different starting points. In tested cases of this paper, a hundred starting points which are uniformly distributed in the searching domain are selected for obtaining a globally optimized solution.

$$\operatorname*{Min}_{V} F = \sum_{i=1}^{N} (h_p^i - h_r^i)^2 \tag{11}$$

where F = objective function; N = number of used points; V = decision variable vector composed of unknown parameters; subscripts "p" and "r" represent prediction/calculation values and original/exact values, respectively. For clarity, the application procedure of the FDITA method is shown in Fig. 3 and elaborated as follows.

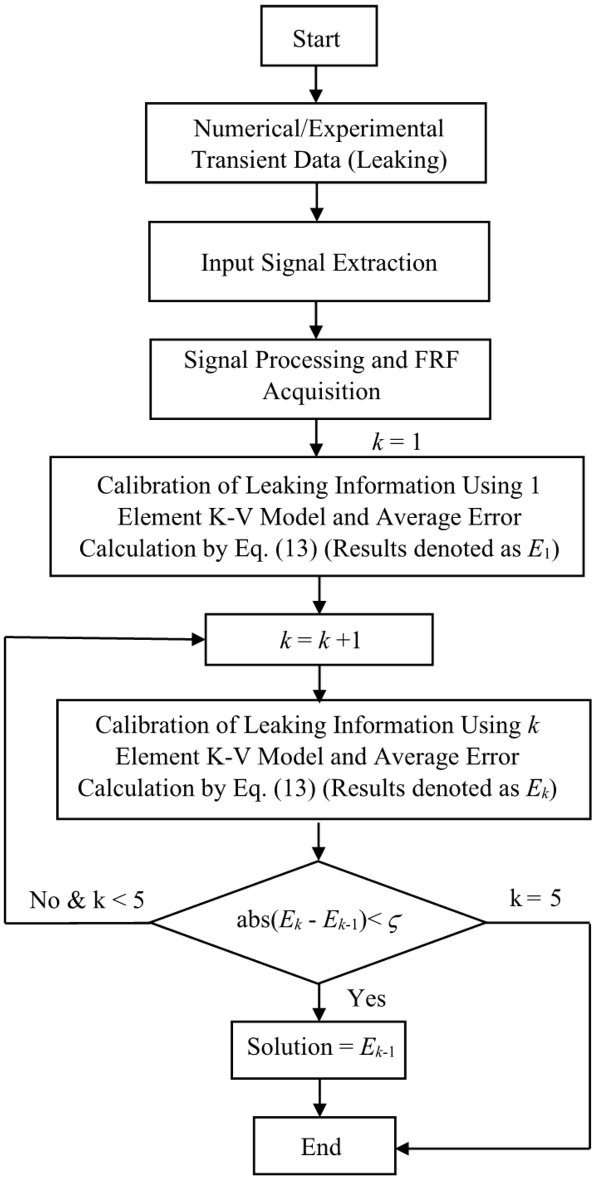

Fig. 3 Flowchart of the FDITA method application procedure

(1) The head perturbation during the valve closure is represented by a sigmoid curve (an example is shown in Fig. 4), which is used to extract the discharge rate (as the input) by:

$$Q_{us}(t_c) = Q_0\left(1 - \frac{H_{us}(t_c) - H_0}{H_{\max} - H_0}\right) \tag{12}$$

in which $Q_{us}(\cdot)$ and $H_{us}(\cdot)$ = discharge rate and the piezometric head during valve closure; $H_{\max}$ = maximum pressure surge obtained by a sigmoid curve; t_c = time coordinate ranging from 0 to t_v, and t_v = the time at which the valve is just fully closed;

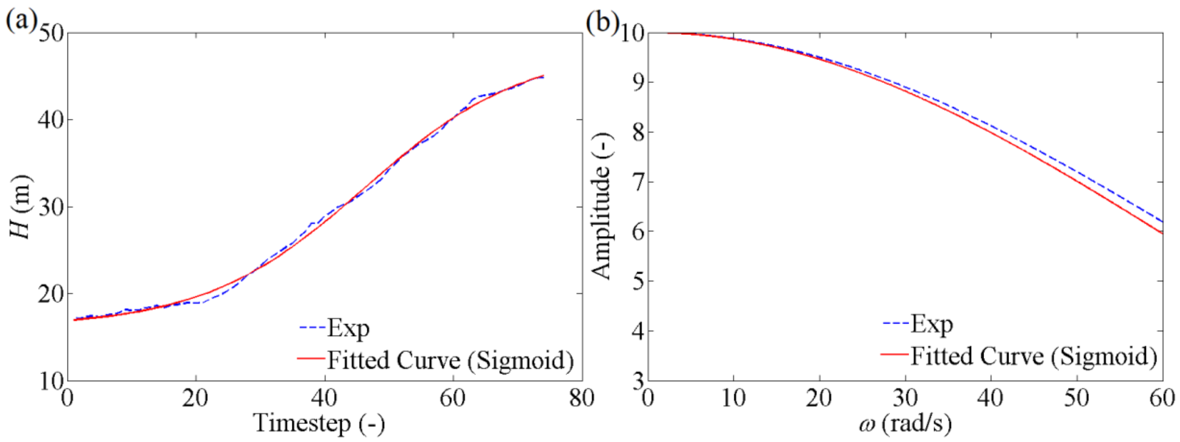

Fig. 4 A comparison of head perturbations represented by (a) a sigmoid curve and (b) corresponding frequency spectrums

(2) The frequency response function (FRF) of the system is obtained by a created pulse using a ten-timestep delayed-time-span (DTS) to overcome the nonlinear error caused by the fast fully closure of the downstream valve [27];

(3) Similar to the proposed K-V element identification in the literature [25], a step-by-step method is applied to determine the K-V elements (numbers and values) and at the same time, to predict the leak information ($x^*$and s^*), with following steps:

- *Step 1:* the 1-element K-V model is firstly applied to quantify both viscoelastic parameters and leak information, with the averaged residual (E_1) of calibrated results in the frequency domain used for performance evaluation based on Eq. (13):

$$E = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(h_p^{leak})_i - (h_r^{leak})_i}{(h_r^{leak})_i}\right| \quad (13)$$

  in which E = average error in current step identification; superscript '*leak*' stands for the transient trace of the leaky system;

- *Step 2:* One more element (e.g., 2-element) K-V model is used in the calibration procedure to predict the unknown material parameters and leak information, and the averaged residual is obtained as E_2;
- *Step k:* with repeating the above steps, a *k*-element K-V model is used in the

calibration procedure and the averaged residual of calibrated results is denoted as E_k. The total calibration process will stop when the following convergence criterion is achieved;

$$\left|E_k - E_{k-1}\right| \le \zeta \tag{14}$$

where ς = threshold to stop the calibration, and in calibrated cases of this study ς =2‰ is applied. For simplicity, the solution from step k-1 is adopted as the final answer of the FDITA. Meanwhile, the maximum number of K-V model elements is set as 5 serving as the other criterion for stopping the simulation and optimization process in this study [24-27].

2.3. Performance evaluation

To evaluate the performance of leak detection by the proposed FDITA method in this study, the following evaluation index is applied for all experimental and numerical applications:

$$\eta_x \text{or} \eta_s = \frac{\left|\phi_r - \phi_p\right|}{\phi_{scale}} \times 100\% \tag{15}$$

in which ϕ = value of the evaluated variable (e.g., s^* or x^*); η_x, η_s = error of calibration in leak location and size, respectively, and they are normalized by different scaling factor; ϕ_{scale} = the scaling factor, it is different for evaluating the predicted leak size and location. In leak size (s^*) evaluation ϕ_{scale} = exact dimensionless leak size, while for leak location (x^*) evaluation, ϕ_{scale} = 1 if the leaking pipe number is accurately identified, and otherwise ϕ_{scale} = 0 (or very small value). Specifically, ϕ_{scale} sets to 0 (i.e., η_x becomes infinite) for the branched pipe system when the leaking pipe number cannot be accurately identified, since it makes no sense to further identify the leak information if the located pipe number is not correct.

Meanwhile, the following expressions are used for evaluating the performance of viscoelastic parameters identification in the time and frequency domain respectively:

$$\eta_{VE}^{TD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(H_p^{intact})_i - (H_r^{intact})_i}{\Delta H_J}\right| \quad (16)$$

$$\eta_{VE}^{FD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(h_p^{intact})_i - (h_r^{intact})_i}{(h_r^{intact})_i}\right| \quad (17)$$

where ΔH_J = *Joukowsky* overhead; the superscripts: "*FD*" = the result in the frequency domain; "*TD*" = the result in the time domain, subscript "*VE*" = evaluation of viscoelastic parameters identification; superscript "*intact*" = the transient trace of the equivalent intact system by using "real"/calibrated viscoelastic parameters.

3. Results and Analysis

The results of laboratory experimental tests and numerical applications based on the developed FDITA method are presented in this section.

3.1. Experimental validation

3.1.1. Experimental setup

The effectiveness of the proposed FDITA method is experimentally validated by two experimental pipe systems in the Water Engineering Laboratory (WEL), University of Perugia, Italy. The first system is a single pipe system with a configuration as shown in Fig. 5(a) (Other information can also be found in [43]), and the second system is a branched system with a configuration shown in Fig. 5(b) (Other information can also be found in [22, 44, 45, 46]). A fast closure of the downstream ball valve is adopted to trigger transient flows in both systems. The test parameters for the two systems are listed in Table 1. Three leaking cases in the single pipe system and three leaking cases in the branched system are applied to validate this FDITA method and application procedure.

In the FRF-based leak detection method, previous studies have confirmed that information contains in the first several peaks is capable to identify systematic parameters and defects [7, 24, 25, 27, 39]. Meanwhile, the high-frequency part of the FRF which contains less transient energy is easily affected by noise. Therefore, only the low-frequency part of the FRF is adopted in the validation. For specific cases here, it is found that the frequency ranges of 0~9.5 Hz (for the single pipe system),0~7.2 Hz (for the branched system case B1 and B2), and 0 ~ 5.7 Hz (for the branched system case B3) are less affected by the background noise and are suitable for performing the identification. Therefore, FRFs of these frequency ranges are truncated and used in identification. Another important issue in identification is to determine the elastic wave speed of a viscoelastic pipe. For the single pipe system, the elastic wave speed is obtained directly from [43], while that of the branched system is calculated inversely by the *Joukowsky* overhead. Other systematic and testing information for these two systems is listed in Tables 2 and 3.

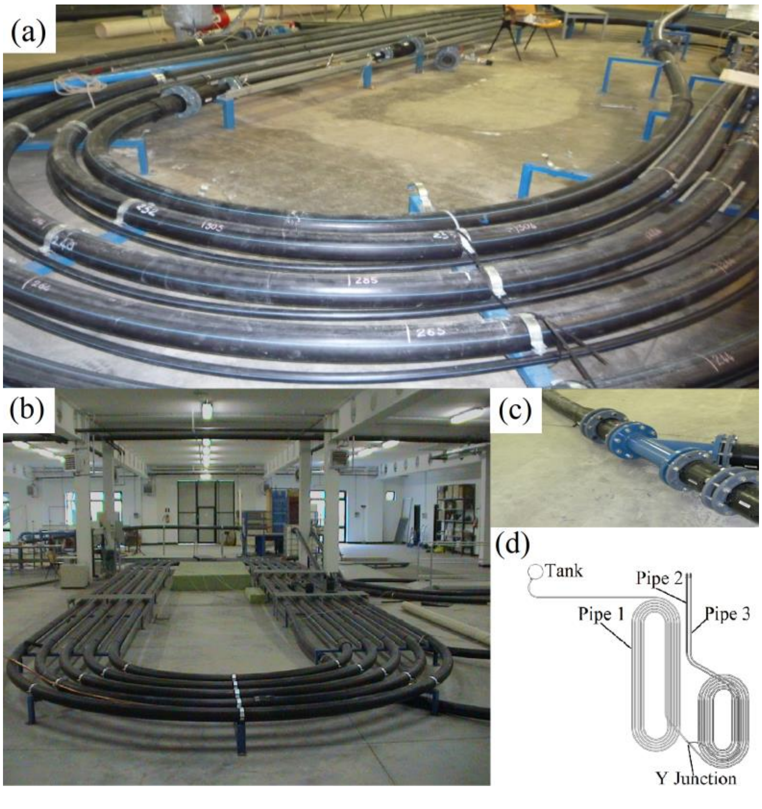

Fig. 5 Experimental facilities at the Water Engineering Laboratory, University of Perugia, Italy: (a) single pipe system; (b) branched pipe system; (c) Y junction used in branched pipe system; (d) the overall sketch of the experimental test system

Table 1 System parameters of experimental test systems

Type of the System	*D* (m)	*e* (m)	*L* (m)		
Single Pipe System			166.28		
Branched Pipe System	0.0933	0.0081	L_1(m)	L_2(m)	L_3(m)
			197.82	61.78	116.78

Table 2 Experimental setup for the single pipe system

Case No.	a (m/s)	s^* (-)	R_{leak} (-)	x^* (-)	Q_0 (L/s)	H_{tank} (m)	α	t_v (s)	f_s (Hz)
S1		4.91e-03	11.54%	0.3666	5.10	18.73		0.119	1024
S2	377.15	9.95e-03	22.08%	0.3666	4.75	19.27	1.23	0.071	
S3		1.61e-02	32.61%	0.7793	4.50	16.19		0.083	2048

Table 3 Experimental setup for the branched pipe system

Case No.	Leaking Pipe No.	a (m/s)	s^* (-)	R_{leak} (-)	x^* (-)	Q_0 (L/s)	H_{tank} (m)	α	t_v (s)	f_s (Hz)
B1	3		1.61e-02	42.08%	0.2071	3.0	23.57		0.053	
B2	3	383.03	8.78e-3	27.74%	0.2071	3.3	23.96	1.23	0.067	1000
B3	2		8.78e-3	51.57%	0.5856	1.21	24.19		0.050	

3.1.2. Experimental results

In the use of the FDITA method, the input signal conversion based on Eq. (12) is crucial to obtain the accurate FRF of the system, so as to produce an accurate transient frequency response pattern. For validated cases, the operation curve of valve closure for each test is firstly calibrated and listed in Table 4.

Table 4 Operation curves of head perturbation at the downstream valve

Type of System	Case No.	The Simulated Head
Single pipe system	S1	$H = 16.12 + \frac{32.03}{1 + 10^{35.63(0.0442 - t)}}$
	S2	$H = 17.88 + \frac{26.06}{1 + 10^{40.75(0.0514 - t)}}$
	S3	$H = 15.01 + \frac{25.83}{1 + 10^{38.49(0.0463 - t)}}$
Branched pipe system	B1	$H = 20.95 + \frac{20.05}{1 + 10^{48.70(0.0375 - t)}}$
	B2	$H = 22.16 + \frac{22.56}{1 + 10^{34.11(0.0456 - t)}}$
	B3	$H = 23.01 + \frac{9.43}{1 + 10^{35.18(0.0322 - t)}}$

Based on the application procedure of the FDITA method in Fig. 3, calibrated results of leak information and total identification time for different cases of two systems are presented in Tables 5 and 6. For the multiple-pipe branched system, two different strategies of K-V model application are adopted, namely, same and different values of viscoelastic parameters for three pipes in the system (termed as “same VE” and “different VE” respectively in Table 6). It is necessary to note that experimental tests herein are mainly applied for the validation of the proposed FDITA method for leak detection. In this connection, only are the detection results of leaks listed in Tables 5 and 6, while the results of viscoelastic parameters identification are not given here because the exact values for the tested pipes are unknown for comparison.

The results show that, compared with the time domain ITA method, the developed FDITA method has very high efficiency. This can be reflected by the fact that the identification process only takes half a minute to find out a globally optimized solution for all unknowns in the single pipe system. Although the difficulty and identification time increase with the increasing number of unknowns in the identification, the longest identification time in the branched system is still less than 3 mins. By contrast, it takes more than 130 mins to identify the globally optimized solution for all knowns (e.g., viscoelastic parameters and leak properties) by the time-domain ITA (TDITA) method for each case herein. Meanwhile, it is worth noting that although it takes a longer time, the TDITA still could not provide similar accuracy of leak detection (location and size) in these test cases due to the significant influences of noises in the measured time-domain signals.

Table 5 Leak detection results for the single pipe system

Case No.	s^* (-)	x^* (-)	η_s (%)	η_x (%)	Time of Identification (s)
S1	5.84e-03	0.357	18.75	0.96	33.10
S2	9.40e-03	0.378	5.44	1.14	19.15
S3	1.70e-02	0.779	5.45	0.03	30.27

Table 6 Leak detection results for the branched pipe system

Calibration Strategy	Case No.	s^* (-)	x^* (-)	η_s (%)	η_x (%)	Consumption Time (s)
Same VE	B1	1.54e-02	0.2028	5.05	0.43	49.96
	B2	4.71e-3	0.2283	46.40	2.13	78.77
	B3	8.87e-03	0.5980	1.07	1.24	73.19
Different VE	B1	1.88e-02	0.188	16.58	1.91	87.38
	B2	9.64e-3	0.1947	9.76	1.24	157.07
	B3	1.07e-2	0.6196	21.49	3.40	99.86

For leak detection results by FDITA, on one hand, the detection results of both tables suggest that the method is relatively more accurate to locate a leak than to size it, which is consistent with the common transient-based leak detection method in the literature [27]. This may be due to the inaccurate capture of the input signal in the system as it directly affects the accuracy of the FRF. Compared with large variation in errors of predicting leak size, predicting errors in leak location are stable and are within 4% for all tests. This confirms the acceptable accuracy of the proposed FDITA method and procedure on practical applications [1, 18]. Moreover, the similar accuracy range in leak positioning for both single and branched pipeline systems demonstrates the successful extension and enhanced applicability of the transient-based leak detection method on the basis of previous studies (e.g., [1, 7]).

On the other hand, different from the single pipe system, the leak detection results for the multiple-pipe system are highly dependent on the strategies adopted for the viscoelastic parameters identification. Specifically, for the experimental system herein, it is more suitable for applying the same viscoelastic parameters for all branched pipes to obtain more accurate leak positioning results. This result indicates clearly the significant influences of the identifications of viscoelastic parameters on the overall leak detection results during the application of the proposed FDITA method in this study. In fact, such identification strategy-dependent results have also been observed in many previous studies regarding the viscoelastic parameters identification (e.g., [14, 44]). However, the exact values of viscoelastic parameters of the tested pipes are unknown in advance; it is not convenient or rational to further quantify and discuss such influences of viscoelastic parameters on identification strategies by using these experimental tests. Therefore, more detailed analysis and discussion are conducted through extensive numerical applications with exact viscoelastic parameters known/given later in this study.

3.2. Numerical Applications

Although all the leaks are successfully located in experimental tests, the method still needs to be systematically evaluated for different influence factors (e.g., s^*/R_{leak}, x^*, and system complexity) to demonstrate the applicability range and limitations of this method. In practical applications, it is more important to locate leaks accurately in pipes before it is able to quantify their sizes or discharges precisely. On this basis, only the results of detecting leak location are analysed and discussed in the following investigation for method assessment.

3.2.1. Settings for numerical simulation

The method is assessed numerically by both single and branched RPV systems. Three cases of single pipe systems with basic information listed in Table 7 and one case of the branched system which has the same setting with experimental facilities are used to evaluate the FDITA method. Other information (e.g., values of viscoelastic parameters, s^* or R_{leak}, and x^*) is shown in Tables 8 & 9. In the investigation, a step input with the same pattern (as shown in Fig. 6(a)) is used in each case to trigger the transient flow, so as to set inputs with the same bandwidth for comparison (as shown in Fig. 6(b)). It is worth noting that the adopted input has a sigmoid shape and is to simulate discharge rate change of a ball valve closure just as experimental tests in the Water Engineering Laboratory, University of Perugia, Italy. For simplicity, only steady friction is considered in the numerical model to show initial-flow-rate-dependent behavior, since the effect of pipe wall viscoelasticity and steady friction is dominant in the tested systems of this study, and there is no significant difference between the results with and without unsteady friction based on preliminary numerical analysis.

The transient traces with a duration of 120 s are used in the analysis to cover almost the complete transient process (over 99.9%). To illustrate this, the transient traces of the tested systems without defects (leak-free) are shown in Figs. 7 (a)-(d). The results suggest that the fluid is almost static in 120 s. Therefore, the obtained FRF can well characterize the system properties and information, thereby is preferable for performing the FDITA.

Table 7 Settings of numerical tests in single pipe systems

Item	a (m/s)	L (m)	D (m)	e (m)	H_{tank} (m)	α	Q_0 (L/s)	f_s (Hz)	t_v (s)
Value	385	200 300 400	0.06	0.006	20.0	1.25	0.56	1024	0.048

Table 8 Settings of viscoelastic parameters for single and branched pipe systems

No. of K-V Elements	J_1 ($*10^{-10}$ Pa^{-1})	τ_1 (s)	J_2 ($*10^{-10}$ Pa^{-1})	τ_2 (s)
2	0.6	0.06	1.6	0.4

Table 9 Range of tested leaking properties

Item	System Type	Min	max
R_{leak}	Single	1%	65%
	Branched	5%	65%
s^*	Single	1.01e-4	1.86e-2
	Branched	1.17e-3	4.12e-2
x^*	For All	0.1	0.9

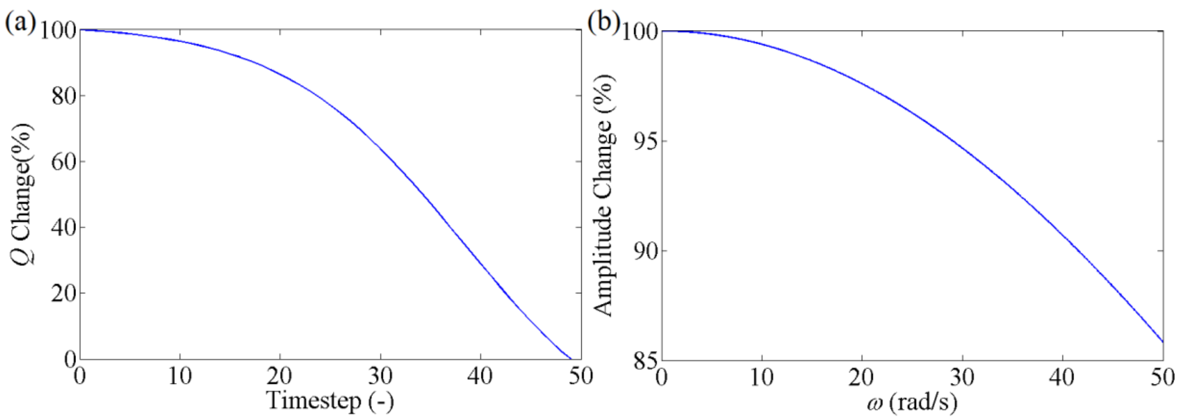

Fig. 6 Discharge curve of valve closure: (a) transient generation; and (b) corresponding frequency spectrum

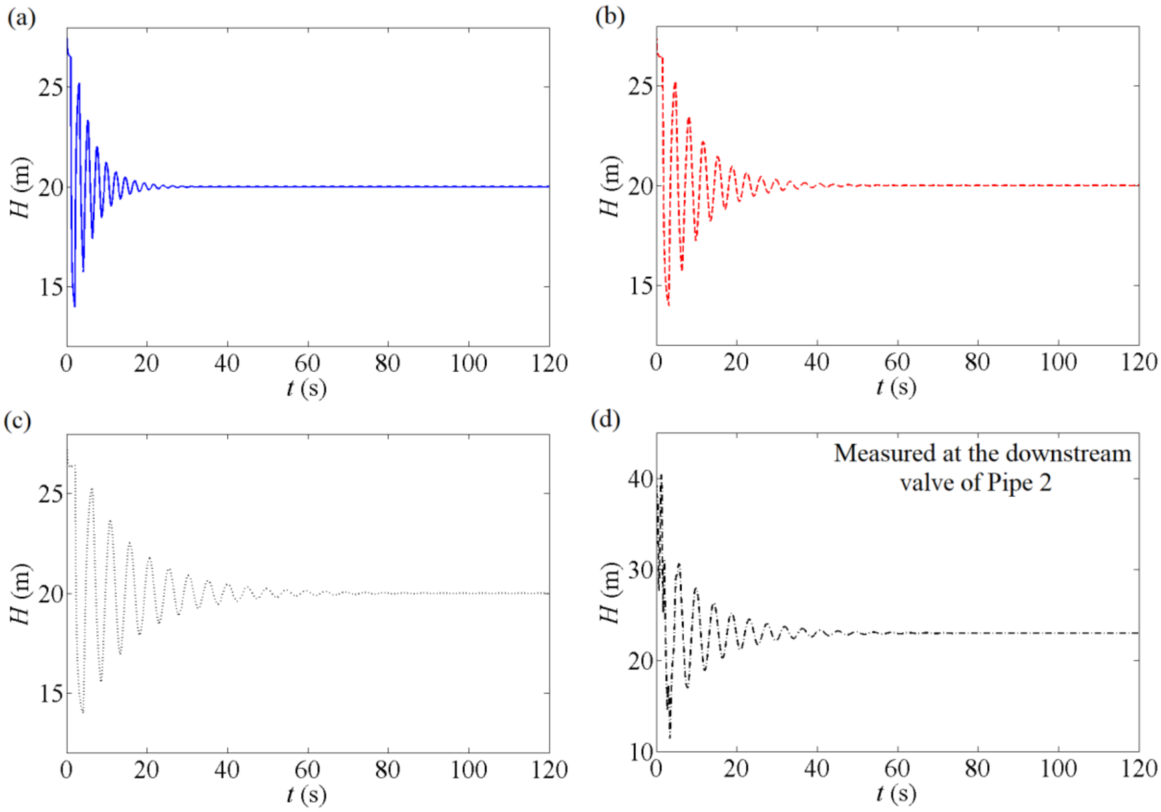

Fig. 7 Transient traces of the tested systems during 120 s: (a) single pipeline (L=200 m); (b) single pipeline (L=300 m); (c) single pipeline (L=400 m); (d) branched pipe system (Table 1)

With using the FRF based method, previous research has confirmed that the information contained in initial resonance peaks are enough to identify systematic properties [24, 27], so it is not necessary to use the total FRF in the analysis as long as the used part of the FRF can reflect a clear pattern of viscoelasticity and a leak. In the specific cases here, the information of the first ten peaks of single pipe systems and the first seventeen peaks of the branched system are enough to exhibit all needed information of corresponding systems and are employed in the analysis.

3.2.2. Performance of the FDITA for leak detection

Previous studies have shown the influence of viscoelasticity is different from that of other factors (e.g., friction) and cannot be ignored in both simulation and defect detection [25, 27, 39]. To emphasize the importance of viscoelastic parameters to the application of the FDITA, the detection results of single pipe systems using viscoelastic and elastic models are compared in Fig. 8. The results show that the detection method based on the elastic model (without viscoelasticity) may induce very large errors for locating leaks in viscoelastic pipes (η_x >10% for almost all cases here), while the proposed FDITA method considering pipe-wall viscoelasticity can locate the potential leaks in different viscoelastic pipes accurately (with η_x < 1%), except cases with very small leak sizes (e.g., s^* < 6.4e-4 or R_{leak} < 6%). Therefore, the results confirm the findings in the literature [26-27] that the importance of viscoelasticity in characterizing the system response and should not be neglected in leak detection.

Furthermore, the results of Fig. 8 imply that, despite the consideration of viscoelasticity, the identification performance is still influenced by s^*(or R_{leak}). For example, the maximum errors in three kinds of systems may attain over 50% for cases with very small leaks (e.g., s^* < 6.4e-4 or R_{leak} < 6%). Meanwhile, the accuracy of leak detection can be improved significantly with the increase of s^*. Specifically, a leak can be successfully identified with very high accuracy (η_x < 1%) when the exact leak size exceeds the above-mentioned limit (s^* > 6.4e-4 or R_{leak} > 6%) for the studied cases herein. This application result confirms again the validity and acceptable accuracy of the proposed method for leak detection in viscoelastic pipes for most situations except the extremely small leak cases.

In addition to the leak detection in single pipe systems, the proposed FDITA method is also validated by a branched pipe system, and the detection results are shown in Fig.9. From the leak detection point of view, leaks in all tested cases can be identified with very high accuracy (with η_x < 0.8%) by the FDITA method, which evidences again the very high accuracy and the successful extension of the FDITA method in leak detection from single to branched pipeline systems. Specifically, this proposed method may provide acceptable accuracy of leak detection in both types of pipeline systems, indicating the applicability of the FDITA in multipipeline systems.

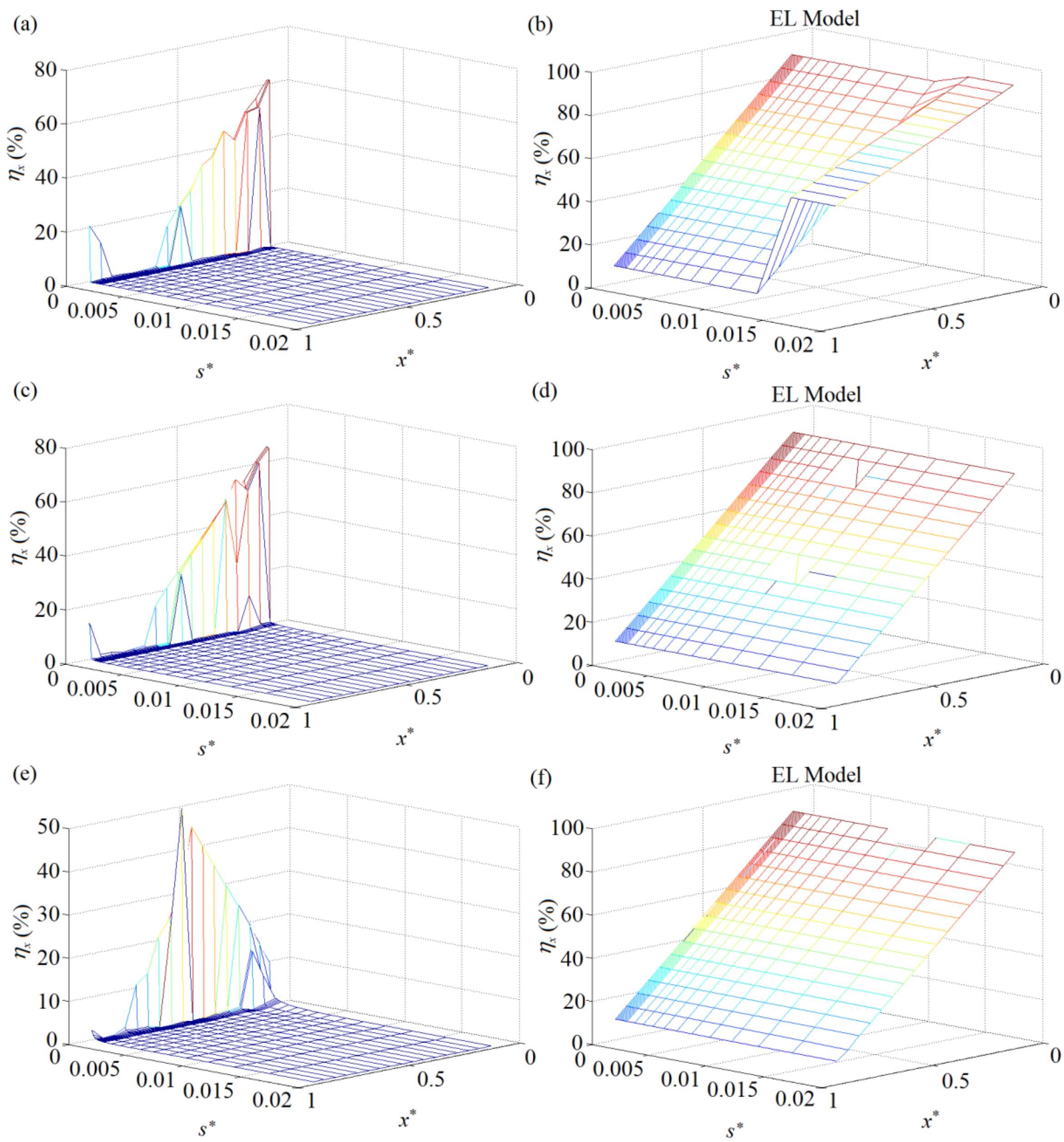

Fig. 8 Detection results of different leaks by the FDITA in single pipe system (a) and (b) L = 200 m; (c) and (d) L = 300 m; (e) and (f) L = 400 m (“EL Model” for results by the corresponding elastic model)

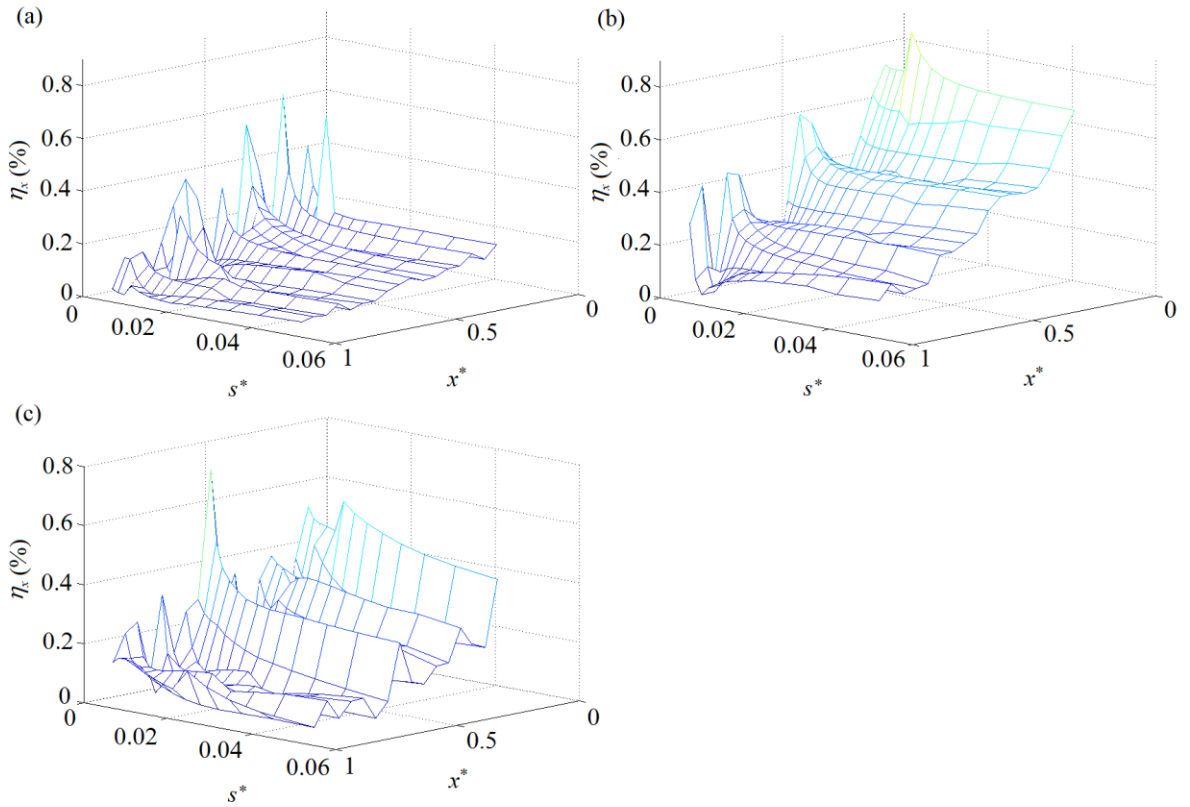

Fig. 9 Detection results of different leaks by the FDITA in the branched pipe system with a leak at (a) pipe 1; (b) pipe 2; (c) pipe 3

3.2.3. Performance of the FDITA for viscoelastic parameters identification

In addition to evaluating the performance of leak detection, the FDITA method is also assessed by viscoelastic parameters identification through the results of reproducing transient traces of the equivalent intact system in both time and frequency domains. In this connection, the expressions defined in Eqs. (16) and (17) are applied for evaluating the FDITA method on viscoelastic parameters identification.

The performances of viscoelastic parameters identification in a single pipe (L = 300 m) and branched systems (with a leak at pipe 2) are shown in Figs. 10 and 11 with a similar pattern. Both results reveal that the calibrated viscoelastic parameters are more suitable for describing transient behavior in the frequency domain than that in the time domain, with the errors in the frequency domain much smaller than the corresponding ones in the time domain. This is more significant in the branched system as the maximum error for reproducing the transient trace in the time domain can reach up to 11% while that in the frequency domain is only about 2.9%.

Furthermore, it is very interesting to note that the identified viscoelastic parameters can better characterize viscoelasticity at small leaks (e.g., $s^* < 1.1\text{e-}3$ or $R_{leak} < 10\%$), while for cases with a large leak, identified material parameters have relatively large errors in describing hysteresis effects of polymeric pipes. This is almost opposite to the trend of the leak detection results from single pipe systems (as shown in Fig. 8) in which the proposed method may not be able to identify an accurate leak location for cases with a very small leak size.

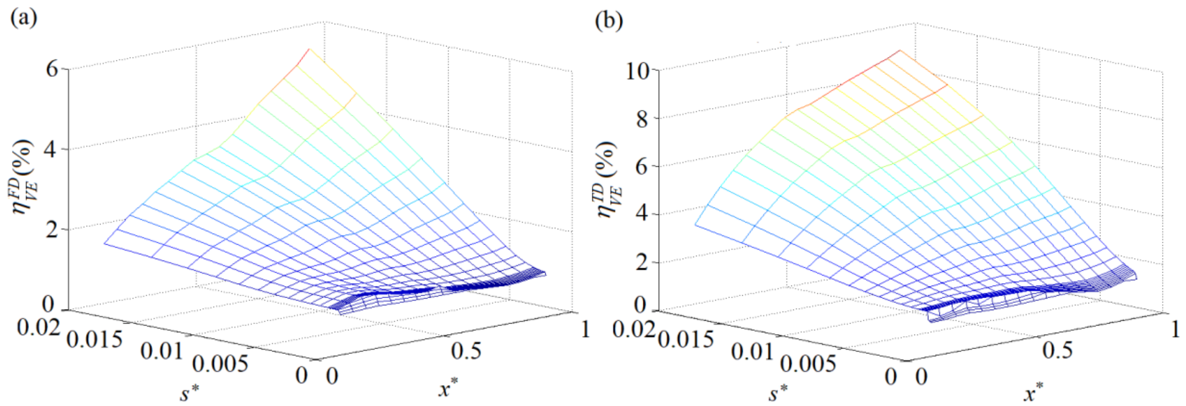

Fig. 10 Errors of viscoelastic parameters identification for reproducing transient traces for the single pipe system: (a) in the frequency domain, (b) in the time domain

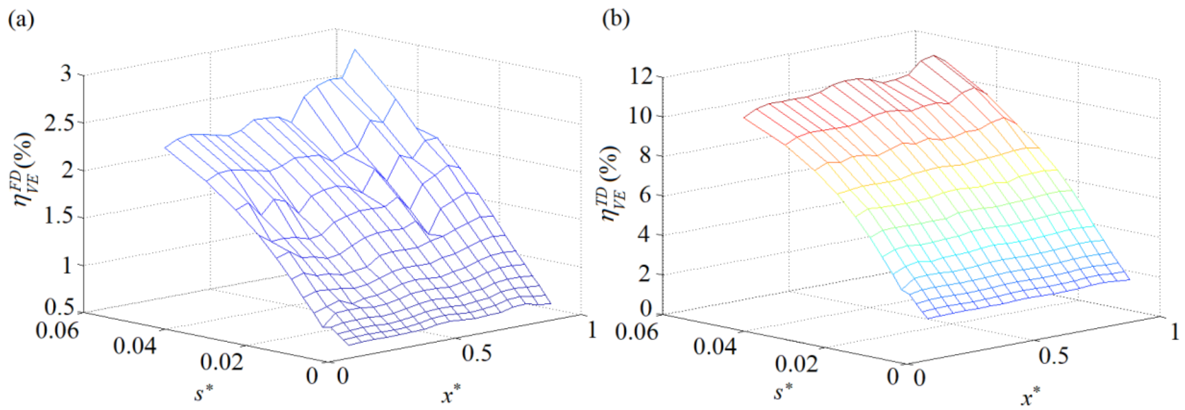

Fig. 11 Errors of viscoelastic parameters identification for reproducing transient traces for the branched system (a) in the frequency domain and (b) in the time domain

4. Results Discussion

The application results have shown that the developed FDITA method is applicable for simultaneous identification of viscoelastic parameters and leaks in both single and branched pipeline systems. However, the range of the signal selection, the extraction of the input signal, the reasons causing the discrepancy between the performance of viscoelastic parameters identification and leak detection at relatively small and large leaks, and influential factors affecting the performance of the method are worthy of further discussion.

4.1. The signal range for calibration

In the application of the FDITA method, different ranges of the FRF may be used for leak identification, and the results show that the width of the FRF range used for calibration does not significantly affect the leak detection results as long as the selected range is wide enough for identifying all the knowns. This is similar to the previous findings that the FRF can be used to identifying viscoelastic parameters once the number of resonance peaks is enough for viscoelastic parameters identification [25]. To better illustrate this, the selected FRF ranges of the three cases for the single pipe system used in *Section 3.1* are reduced by 40% respectively (as shown in Fig. 12), and the leak detection results are obtained and listed in Table 10. By comparison, the results reveal that the performance of the proposed FDITA method is not sensitive to the change of the calibration range since there are no significant changes between Tables 5 and 10, and the leak can be identified accurately in these cases. This is because the selected ranges of the FRF results, even though shortened herein, still can contain enough information (e.g., FRF peaks) to identify all unknowns (numbers and values of viscoelastic parameters and leak information) in the derived expressions (e.g., Eq. (7)).

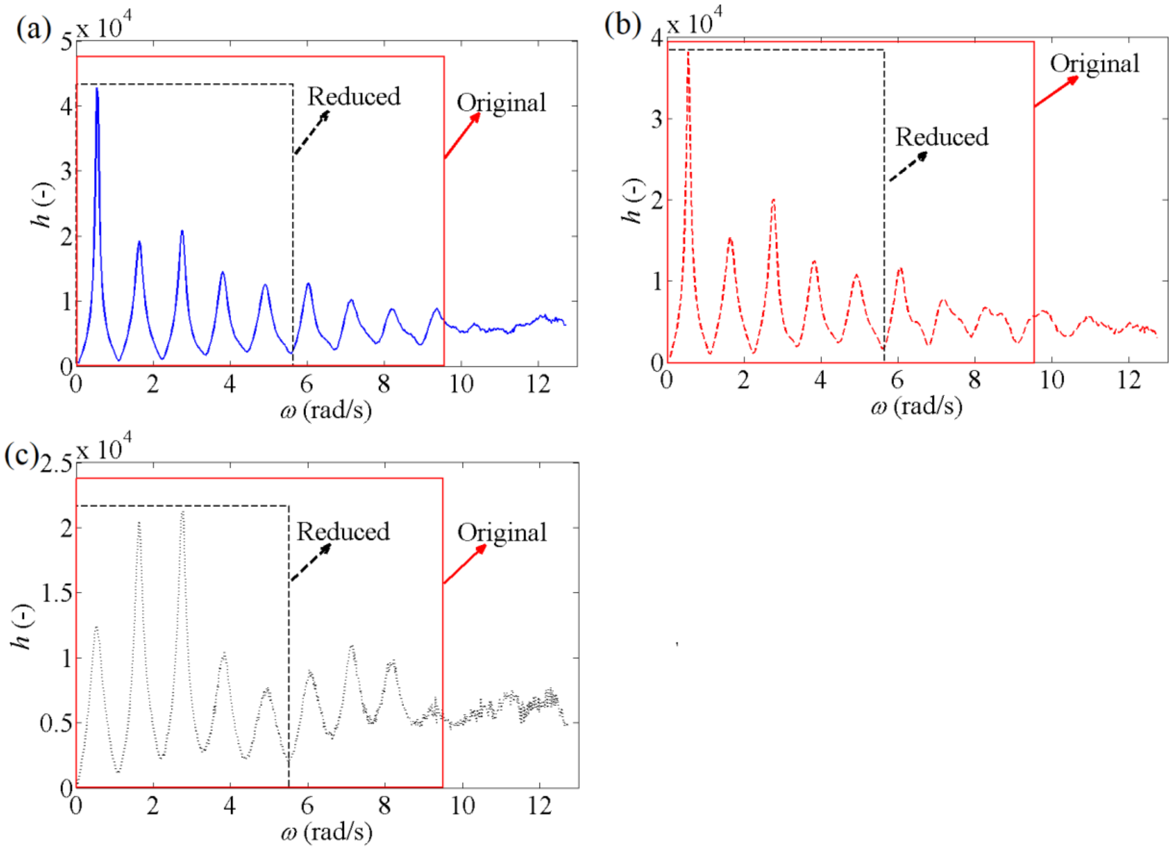

Fig. 12 The frequency response diagrams of the single pipe experimental systems: (a) case 1; (b) case 2; (c) case 3;

Table 10 Leak detection results for a reduced FRF range

Case No.	s^* (-)	x^* (-)	η_s (%)	η_x (%)
S1	4.65e-03	0.379	5.3	1.24
S2	8.64e-03	0.376	13.2	0.94
S3	1.83e-02	0.771	13.9	0.08

Consequently, the selection of the FRF range should fulfill the following principles for the application of the FDITA method:

(1) the FRF range is wide enough to identify all unknowns;

(2) the selected FRF range carries the main information of a system;

(3) the used FRF involves less noises to improve the accuracy.

For a finite time valve maneuver (e.g., fast closure of the downstream valve in this study), the low-frequency domain of the FRF results (which involves the first several peak harmonics) is dominant in the frequency spectrum and is enough to characterize a system, so it is preferable for performing the FDITA method. Meanwhile, it should be noted that although the range of the FRF does not significantly affect the FRF results, it is still recommended to select a valid FRF range as wide as possible to enhance the robustness of the FDITA.

4.2. Impact of input signal extraction

The FDITA is based on the FRF, and an effective extraction of the input signal is essential to acheive the accurate results of the proposed method. In the literature, the input parameter can be represented by either dimensionless valve-opening coefficient perturbations or flow perturbations [47], but the performance of these two kinds of input parameters is different. In transfer matrix analysis, forms of the head response by these two kinds of input parameters are slightly different. If valve-opening coefficient perturbations are used as the input, perturbations during valve maneuver are represent by a linearized orifice equation in the FRF. This kind of input is relatively accurate for small perturbations, while for large perturbations (e.g., the fast closure of the valve in this research), it will induce large errors and distort the FRF [47]. To overcome this, the flow perturbations are used and recommended in this study as it is effective and accurate in quantifying the input signal.

Although an accurate FRF can be obtained by using flow perturbations, accurately acquiring discharge perturbations in a short duration is still difficult. In this paper, the longest duration of valve closure is about 0.12 s in which it is very difficult to measure the discharge rate directly and accurately. In this condition, flow perturbations are usually inversely calculated by either the *Joukowsky* overhead or an equivalent elastic numerical model [27, 47]. As indicated formerly, ignoring viscoelasticity effect in the input signal extraction may cause significant errors to the leak detection results. Inclusion of viscoelastic parameters in the input extraction, of course, can minimize the error in the input, but viscoelastic parameters are not always known in advance, and identifying them with unknown leaks is difficult, time-consuming, and sometimes even impossible. In this regard, it is necessary to use the known/measured information (e.g., the head surge) to estimate the input. To this end, a linear relationship (Eq. (12)) that considers the pressure surge in a viscoelastic system is used. To illustrate its performance on quantifying flow perturbations in viscoelastic systems, the initial head perturbations and corresponding discharge rates (which are considered as the precise input) from a numerical test are extracted; then they are used to obtain the inputs by three mentioned methods (namely, Eq. (12), the elastic model (E.M.) and the *Joukowsky* overhead (Jouk.)). The results of these inputs are compared with the precise input in Fig. 13. It is clear that the performance of the extracted inputs which are based on the elastic assumptions (e.g., denoted as E.M., and Jouk. in the figure) becomes poorer with the increase of time and angular frequency, while the input obtained by the proposed equation can well represent the discharge perturbations in both time and frequency domains. Thus, it is adopted and recommended to characterize the input signal in viscoelastic systems.

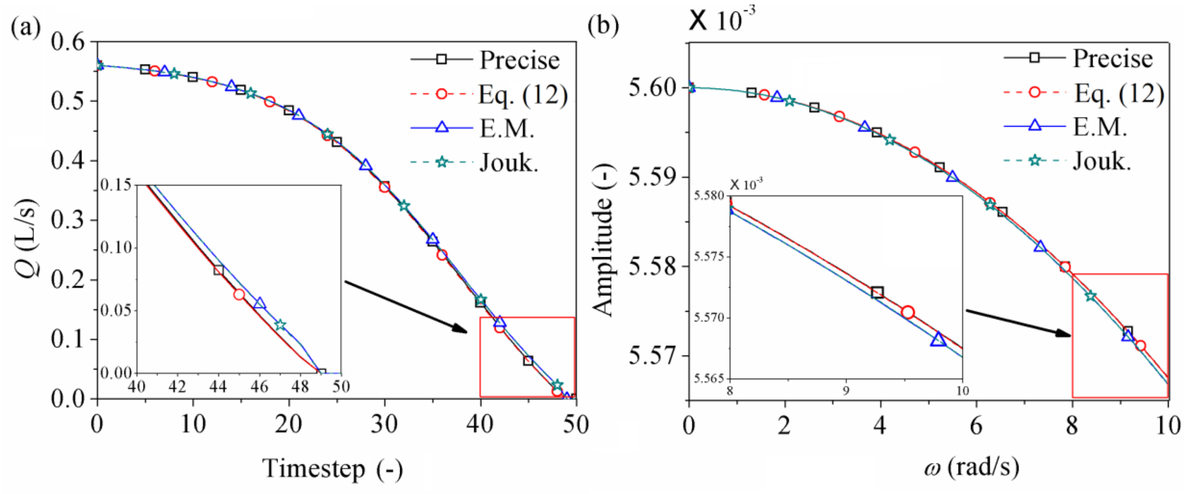

Fig.13 Comparison of input signal extractions by three kinds of methods with the precise input (a) in the time domain (b) in the frequency domain with DTS = 10 timesteps (0.01 s)

Besides, another important issue in input extraction is to minimize/reduce the influence of noise in the input signal. In practice, a measured transient signal (usually the head) always contains (random and systematic)noises, which can be evidenced by small fluctuations in the measured head response in Fig. 4, and the previous investigation has shown that the background noise may contain both low and high-frequency components [27]. In the input signal extraction, the measure response (e.g., *H*) during valve maneuver is used in Eq. (12). Because of the short duration (< less than 0.12 s in the study), the noise in the measured signal may greatly affect the performance/accuracy of the extracted input. To reduce the influence of noise, a sigmoid curve is used to simulate head perturbations caused by the valve closure and then to extract the input signal. This is, on one hand, due to the characteristic curve of valve perturbations used in both experimental and numerical tests in this study. In experimental and numerical tests, ball valves were installed/simulated to control the flow rate and cause transients, and the characteristic curve of a ball valve has a sigmoid shape (as shown in Fig. 4(a)). Therefore, using a sigmoid curve to simulate the head response and then to extract the input signal can well describe the transient response during the valve maneuver. On the other hand, using a sigmoid curve can also reduce the influence of noise in the signal. To illustrate this, the transient trace (noise-free) of a numerical test (L = 300 m) in the previous section is used as shown in Fig. 14(a), and the (numerical) random noise with the mean value of 0 m and the variance of 0.025 m is added into the signal as shown in Fig. 14(b). The extracted inputs (by Eq.(12)), namely input with noise and its fitted input using a sigmoid curve (denoted as noise and sigmoid, respectively), and their corresponding frequency spectrums of the converted pulses with DTS = 10 timesteps are compared with the precise input (noise-free) in Figs. 14(c-d). The results suggest that if accurate discharge perturbations cannot be measured directly or the measured signal contains noise, using a sigmoid curve can well simulate the ball valve maneuver, characterize the input parameter and overcome the influence of noise.

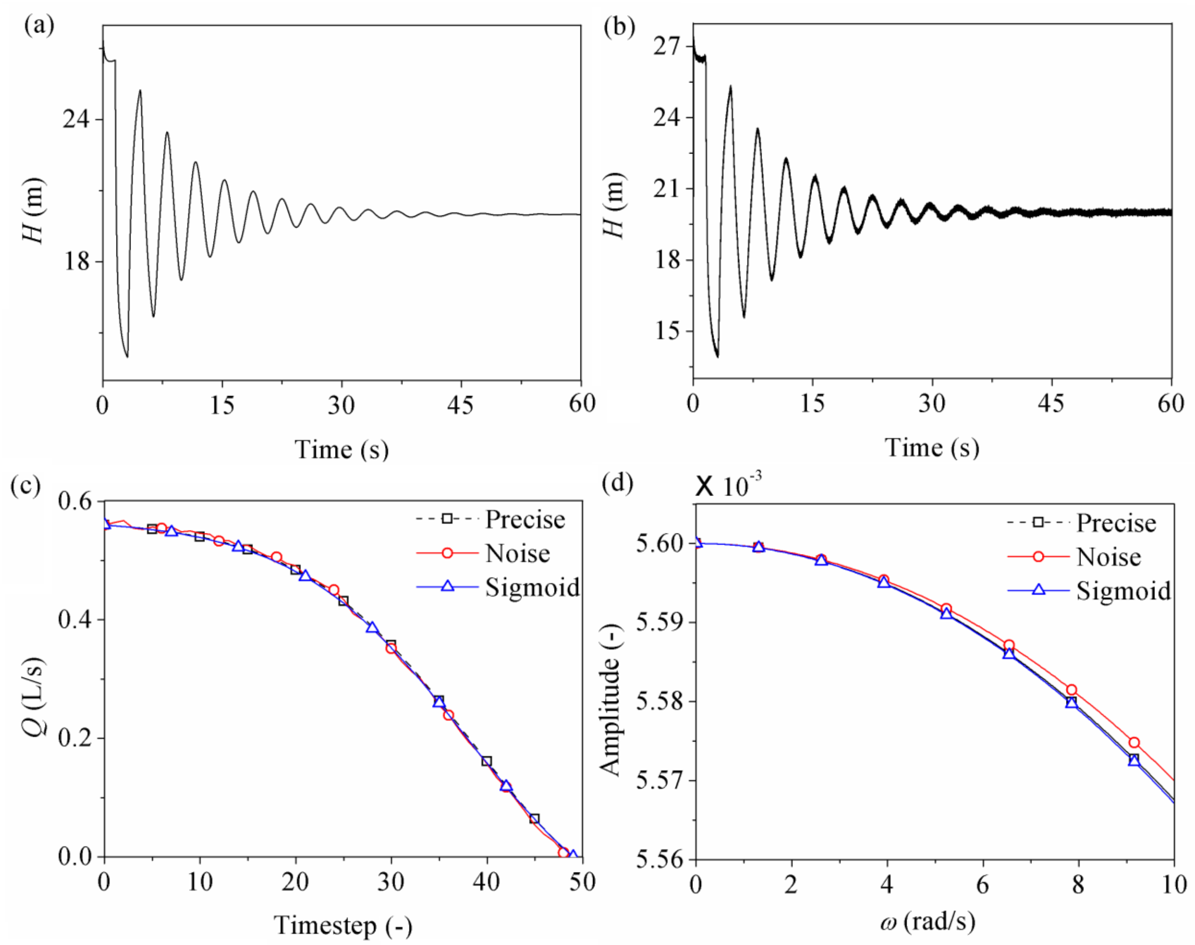

Fig.14 The influence of noise in the input extraction: (a) orignal signal (numerical); (b) orignal signal plus (numerical) noise; (c) comparsion of extrated inputs with the precise input in the time domain; (d) frequency spectrums of these inputs with DTS = 10 timesteps

4.3. Correlation between viscoelasticity identification and leak detection

Identifying accurate values for viscoelastic parameters and leak information is the main objective of the FDITA method, but the application results suggest that when one factor is accurately identified, the accuracy of the identification results of the other factor will be affected adversely. In leaking systems, different leak properties (e.g., s^* and x^*) may affect the role of pipe wall viscoelasticity. From a perspective of energy analysis, the percentage of energy attenuated by viscoelasticity and a leak in the pipeline is different for different leaks [48]. For example, when a large leak locates near the downstream, most of the transient energy will leak out of the system during the transient flow process, so the influence of such leak may surpass that of pipe-wall viscoelasticity. As a result, the leak-induced pattern is overwhelming in the FRF (compared to that induced by viscoelasticity). By contrast, the pipe wall will attenuate most of the transient energy in the pipeline system with a relatively small leak near the upstream tank; thus, the pattern induced by the pipe viscoelasticity becomes more dominant than that by the leak in the FRF. In fact, these two factors (leak and viscoelasticity) may affect the behavior and response of each other during the transient process, and thus impose inter-dependence on their detection results by the proposed method. This can also be observed through the analytical expression derived in Eqs. (7-10) as well as the numerical application results in Figs. 10 and 11. On this point, the inter-dependence of these two factors and their influence on the detection results have been systematically investigated in the former study [27], and their results confirmed the importance of the accurate identification of each factor to the successful detection of the other one. This is also the motivation of the current study to develop the simultaneous identification method (FDITA) for both factors, so as to gain more accurate and physical results of viscoelastic parameters and leaks as well as to improve the detection efficiency. In this condition, it is difficult to eliminate the influence of one dominant factor and identify the remaining factor precisely and simultaneously. This is also a limitation of simultaneous identification of viscoelasticity and a leak by the FDITA method.

Despite it is unlikely to exclude the influence of a large leak and then to identify viscoelastic parameters accurately, it is still possible to locate a large leak precisely in the frequency domain if the errors of identified viscoelastic parameters are within an appropriate range. Compared with describing viscoelastic behavior in the time domain, the viscoelastic effect is not influenced by individual viscoelastic parameter but governed by a combined relationship of all viscoelastic parameters in the frequency domain [27]. As indicated in Eq. (18), in the frequency domain, the viscoelastic effect is frequency dependent and relies mainly on a lumped coefficient R_{VE}.

$$R_{VE}(\omega) = \sum_{k=1}^{n} \frac{J_k}{1 + i\omega\tau_k} \tag{18}$$

in which R_{VE} $(\cdot)$ = the ratio to quantify the relationship between creep compliance and retardation time in the frequency domain.

Therefore, viscoelastic parameters which can constitute accurate values of R_{VE} in the frequency domain can be treated as one of the approximate solutions for describing viscoelastic behavior in the frequency domain, but they may not be exactly accurate to represent viscoelastic behavior in the time domain, especially for large leaks at which identified viscoelastic parameters have large errors in reproducing the trainset trace of equivalent intact systems. From this perspective, the frequency domain method may have a larger error tolerance in detecting a leak to the identification of viscoelastic parameters, which, in turn, is an advantage of the proposed FDITA method for leak detection in viscoelastic pipes.

4.4. Theoretical evidence on the applicability of the FDITA method

Similar to the leak reflection-based method which detects a leak based on the leak reflection in the time domain [49], the proposed FDITA method relies on the leak-induced pattern which is also associated with the reflection of a leak [50]. For simplicity, a leak in a single pipe system as shown in Fig. 15 is used as an example to show the theoretical evidence of different factors on the leak reflection.

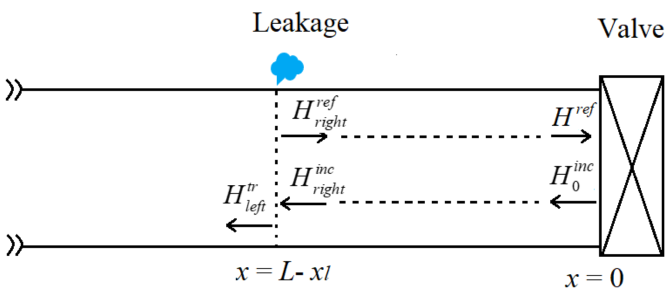

Fig. 15 The viscoelastic pipe system with a leak (no reflection from the left boundary)

If ignoring the reflection from the left-hand boundary, the reflection ratio of a leak at the downstream end can be derived based on the wave propagation theory:

$$R_w(\omega) = \left|\frac{H^{ref}}{H_{inc}}\right| = \left|\frac{a_{VE} s^* \beta e^{-2iWL(1-x^*)}}{(e^{-2iWL(1-x^*)} + 1 - a_{VE} s^* \beta e^{-2iWL(1-x^*)})}\right| \quad (19)$$

in which $R_w(\cdot)$ = reflection ratio at a specific frequency; H^{ref} = amplitude of the reflected wave at the downstream boundary; H_0^{inc} = amplitude of the incident wave at the downstream; H_{right}^{inc} = amplitude of the incident wave at the just right-hand side of the leak; H_{right}^{ref} = amplitude of the reflected wave at the just right-hand side of the leak; H_{left}^{tr} = amplitude of the transmitted wave at the just left-hand side of the leak; $\beta = \sqrt{2/g\Delta H_{leak}}$ is a coefficient; a_{VE} and W are the wave speed and the wavenumber of the viscoelastic pipe [51-54]:

$$a_{VE} = a / \sqrt{1 + \frac{2a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{(i\omega\tau_k + 1)})} \; ; \; W = \frac{\omega}{a}\sqrt{1 + \frac{2a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{(i\omega\tau_k + 1)})} \quad (20)$$

For this simple pipeline system, Eq. (19) suggests that leak properties (e.g., s^* and x^*), the head at the leak, length of the pipe (or distance of wave propagation), and viscoelastic parameters can affect the reflection of a leak together. To clearly show the influence of these factors, the averaged reflection ratios of the first ten peaks in the frequency domain of a single pipe system (L = 300 m) which configuration is the same as shown in Table 7 are visualized in Fig. 16(a). Meanwhile, Fig. 16(a) is compared with Fig. 16 (b) which is about the result of the same pipeline with smaller creep compliances (as listed in Table 11) to show the influence of viscoelastic parameters.

Table 11 Settings of viscoelastic parameters for relatively rigid polymeric pipeline

No. of K-V Elements	J_1 (*10^{-10} Pa^{-1})	τ_1 (s)	J_2 (*10^{-10} Pa^{-1})	τ_2 (s)
2	0.1	0.06	1.0	0.4

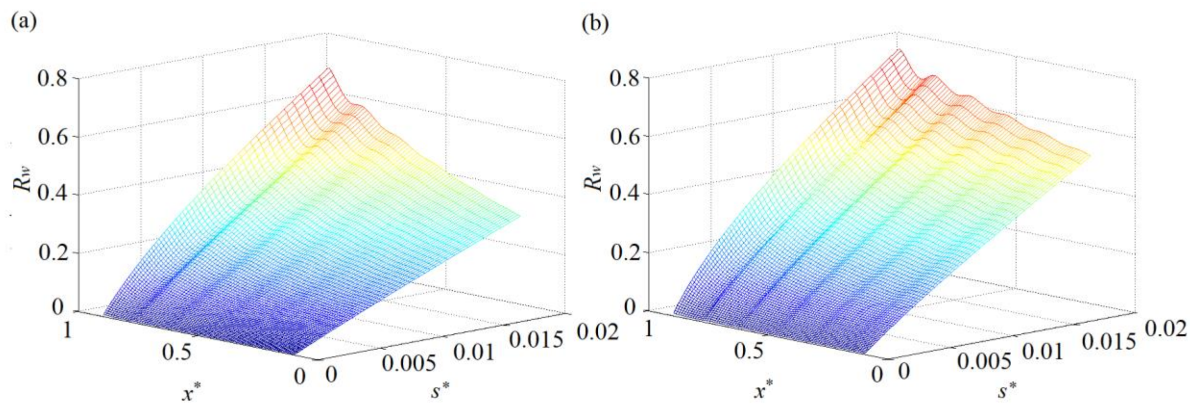

Fig. 16 Wave reflection ratio by different leaks of: (a) a soft viscoelastic pipeline (with larger viscoelastic effect); (b) a rigid viscoelastic pipeline (with smaller viscoelastic effect)

The results in Fig. 16 reveal that the influence of these factors shows similar patterns for both cases but with different levels, and it is not surprising that Fig. 16(a) has the same trend with Fig. 10 because the reflection ratio directly reflects the role of a leak in the FRF and then affects the accuracy of the FDITA method. Overall, a large leak size will cause relatively large reflection, and a leak located closer to the measurement will generate more reflection energy [52]. Specifically, based on the results and analysis from Figs. 8 and 16, the main findings can be gained as follows.

(1) the reflection ratio is a monotone increasing function for s^*; thus, the leak reflection ratio increases with the value of s^*. Therefore, a case with relatively large s^* is expected to have a clear leak-induced pattern in the FRF, which can improve the accuracy of leak detection using the FDITA method;

(2) the wave reflection decays significantly with the increase of the distance between a leak and a measurement, i.e., $L(1-x^*)$ in viscoelastic pipes. Under this condition, the leak-induced pattern becomes less significant in the FRF, which brings difficulties in leak detection. By contrast, a leak closer to the downstream end may gain a larger reflection for the measurement and thereby a better accuracy may be achieved for leak detection. To address this problem, multiple measurements may be necessary

to practical system applications (because leak location is unknown) [54];

(3) a leak in a stiffer pipeline (with relatively high rigidity) will have a large reflection ratio, suggesting that the FDITA becomes more accurate for leak detection in stiffer pipelines where the influence of pipe viscoelasticity becomes smaller.

5. Summary and Conclusions

This paper presents a frequency domain inverse transient analysis (FDITA) method for simultaneous identification of viscoelastic parameters and leaks in viscoelastic pipelines. This FDITA method is developed by the transfer matrix method for both single and branched pipeline systems where the viscoelastic characteristics of polymeric pipes and potential leaks in the system can be identified in an efficient one-step procedure. This developed method and application procedure has been validated by the laboratory experimental tests, and the results are analyzed and discussed through extensive numerical applications. The main results and findings of this study are summarized as follows.

First, the application results demonstrate clearly that viscoelasticity of the pipe wall is important for leak detection in viscoelastic pipes using the transient wave. The program determined viscoelastic parameters can be treated as one of the approximate solutions to describe the retarded response of the pipe wall in the frequency domain.

Second, the viscoelasticity of viscoelastic pipes and potential leaks in a system can be identified at the same time by performing a global optimized FDITA method, but the importance/influence of a leak or viscoelasticity is different from case to case. In the calibration, when the influence of one factor is dominant/overwhelming, it is hard to quantify the other one precisely at the same time, which is a limitation of simultaneous identification of these two factors using the FDITA method.

Third, the leak-induced pattern is directly associated with the wave reflection from the leak, and a clear pattern is important for accurate leak identification in using the FRF-based method. In this circumstance, the proposed method is more suitable to detect a leak that will cause a significant reflection or a leak in a rigid polymeric pipeline.

Last but not least, the current work is preliminary and investigated systems are still very simple. In the future, more complex systems should be used to validate this method. Also, it is worth noting that this study is based on the measurement from only one point, and measurements from multiple points may be used to enhance the accuracy of the global optimized FDITA method for simultaneous identification of a leak and viscoelastic parameters in systems of different complexities.

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