Multistage Frequency-domain Transient-based Method for the Analysis of Viscoelastic Parameters of Plastic Pipes

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Abstract

Plastic/viscoelastic pipes such as polyvinyl chloride (PVC), polyethylene (PE) and high-density polyethylene (HDPE) pipes have been increasingly applied in fluid piping systems. The understanding of the hydrodynamic behavior and features of such pipe materials is important in their practical applications. This paper develops an effective Frequency-Domain Transient-Based Method (FDTBM) for the efficient and accurate identification of viscoelastic parameters of plastic pipes. The analytical expression of transient frequency response in a typical viscoelastic pipeline system is first derived to describe the dependence relationship among different factors and coefficients in the system (e.g., pipe and fluid properties). The obtained result is then applied to inversely identify the viscoelastic parameters of plastic pipes under different flow and operational conditions. A multistage analysis framework is proposed to enhance the robustness and effectiveness of the proposed FDTBM in order to obtain accurate and unique solutions of viscoelastic parameters for the plastic pipes used in this study. The proposed method and analysis framework have been validated and evaluated through various experimental tests and numerical simulations.

Keywords: transients, plastic pipes, viscoelastic parameters, multi-stage analysis, frequency domain method

Introduction

Transient flows (also termed as transients, water hammer, or pressure surges) are commonly and frequently triggered by suddenly changing the flow entity under various factors/operations, which may cause serious problems (e.g., pipeline burst, air pockets growth and water contamination) in pipe systems (Collins et al., 2012; Chaudhry, 2014; Wylie et al., 1993). In the last couple of decades, it has been shown that transient waves, rich of information as propagating through the pipelines, allow assessing pipe conditions by pointing out possible defects, such as pipe leaks (e.g., Covas et al., 2005b; Duan et al., 2012b; Lee et al., 2006, 2007; Gong et al., 2013), partial blockages (e.g., Meniconi et al., 2011a), and unknown branches (e.g., Meniconi et al., 2011b, Duan and Lee, 2016). In literature, this approach for fault detection in pressurized pipes is termed the transient-based method (TBM) (Colombo et al., 2009; Duan et al., 2010a; Xu and Karney, 2017). Within the TBM, experimental transient data can be analyzed straightforwardly in the time-domain or frequency-domain by considering the additional pressure decay due to the potential fault with respect to the fault-free pipe (Ayati et al., 2019; Covas and Ramos, 2001; Covas et al., 2005b). For example, a leak will induce additional damping in harmonic peaks in the frequency domain while blockages in the pipeline will cause both frequency shifts and damping in harmonic peaks (Duan et al., 2012a; Lee et al., 2006; Brunone et al., 2019). Theoretically, the fault detection can be achieved by minimizing the difference between the measured data and the results of a numerical model based on the transient governing equations within a calibration procedure (Covas and Ramos, 2010; Soares et al., 2010). In this latter case, it has also been noticed and confirmed through various applications that the TBM results are sometimes not accurate enough to detect pipe faults for realistic pipe systems. One possible reason for this problem involves that the current TBM may not be accurate enough or may be influenced significantly by the uncertainties (e.g., noise and fluctuation in discharge or head) in the system. Also, the boundary conditions (e.g., connection methods, pipe properties, facilities and devices in the system) of the real pipe system are often unknown, which may greatly affect the reliability of the diagnosis procedure (Mitosek and Chorzelskis 2003; Meniconi et al., 2018). As a consequence, current TBMs are mainly applied for simple and idealized pipeline systems (i.e., a simple pipeline with elastic pipe-wall materials). From this perspective, it is of great practical significance to extend this innovative method to more realistic pipeline systems. The main aim of this paper is to improve the performance of the existing models with respect to the simulation of the transient response of plastic pipes, e.g., polyethylene (PE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), chlorinated polypropylene (CPP) pipes. In fact, such pipes (also named as viscoelastic ones in the literature) have been widely and progressively used in pipe systems due to their easiness and economics of construction, operation and maintenance (Bergant et al., 2008a; Covas et al., 2004; Duan et al., 2010b). A recent statistical report (Folkman, 2018) showed that approximately 30% of pipelines are made of viscoelastic materials in the USA. Additionally, in Hong Kong, new pipes used in its replacement and rehabilitation scheme are primarily comprised of viscoelastic pipes (HK-WSD, 2018; Tang, 2000). Therefore, understanding and quantifying transient behaviors and features of such plastic pipes under different flow and system operational conditions have become important and necessary to improve and enhance their applications in practical water pipe systems.

In the literature, transient models and theory have been applied with substantial progress and achievement for traditional elastic pipes (e.g., concrete and steel). Examples include one-dimensional (1D) and two-dimensional (2D) water hammer models (Ghidaoui et al., 2005), unsteady friction (UF) or turbulence models for transient pipe flows (Bergant et al., 2008b;

Brunone and Golia, 2008; Duan et al., 2018; Trikha, 1975; Vardy and Brown, 1995), viscoelastic pipe-wall formulation (Covas et al., 2005a; Duan et al., 2012b; Pezzinga et al., 2016; Soares et al., 2008), and uncertainty and sensitivity analysis (Duan, 2016). In particular for the viscoelastic model, both numerical and experimental tests have been conducted in the literature to capture the impacts of pipe-wall viscoelasticity (VE) (deformability) on transient flow responses (pressure and velocity) in the pipes. Through a review of the literature, most of these studies in terms of viscoelastic modeling were mainly based on the conceptual Kelvin-Voigt (K-V) model, which is represented by two sets of parameters – retarded time scale (τ) and creep compliance (J) (Covas et al., 2005a; Duan et al., 2010b; Gally et al., 1979; Pezzinga et al., 2016; Urbanowicz et al., 2016). Therefore, determining these two sets of viscoelastic parameters becomes crucial for transient flow modeling and analysis in the use of plastic/viscoelastic pipes.

In the research field of pipe fluid transients, the viscoelastic model of transient pipe flows was initially developed in the 1970s (Gally et al., 1979; Rieutord et al., 1972, 1979; Rieutord, 1982) and was thereafter widely adopted by researchers in this field for the modeling and analysis of transient flow behaviors caused by various factors and operations in different plastic pipes (Covas et al., 2005a; Duan et al., 2012b; Meniconi et al., 2012b; Soares et al., 2008; Urbanowicz et al., 2016, 2018). In these previous studies, the viscoelastic parameters are usually calibrated and determined by preliminary experimental tests before the viscoelastic model would be applied to examine and/or predict transient responses in a specified plastic pipeline system. Moreover, in most of these studies, the retarded time scales (τ) are usually fixed/known in advance based on the previous studies (e.g., Covas et al., 2005a) during the inverse calibration process, to reduce the number of unknown variables (τ and J) and at the same time to improve solution robustness/uniqueness. For example, the values of τ have been fixed in the study of

Covas et al. (2005a) based on a trial-and-error process. Thereafter, these fixed values of τ were used by many other studies regarding transient modeling and analysis of transient flows in viscoelastic pipes, even though the pipe materials and properties (pipe scales) and system operations are completely different (Duan et al., 2010c; Gong et al., 2016; Soares et al., 2008). As a result, the viscoelastic parameters and modeling results of these studies are found to be non-unique or inaccurate for fully capturing the entire transient process (Covas et al., 2005a; Duan et al., 2010c). This is mainly because of the inappropriate time scales (τ) fixed in advance, which results in the inaccuracy of other parameters (J), so that the calibrated parameters (τ and J) may be only valid/accurate (but not universal) for the calibration cases. However, the time scale parameters (τ) are also system dependent (Pezzinga et al., 2016), which have to be considered as key parameters, together with compliance parameters (J), for complete calibration.

Recently, Gong et al. (2016) proposed a TBM by using resonance peak frequencies to identify the dynamic wave speed and the creep compliance in viscoelastic pipes. An analytical expression of transient frequency response for viscoelastic pipeline systems has been derived in their study, followed by extensive numerical tests for the purpose of validation. Nevertheless, the times scales (τs) are still fixed in advance during the inverse analysis by following previous study (Covas et al., 2005a), with some adaption through a trial-and-error process for their studied numerical systems. Therefore, the overall procedure of their proposed method is still time consuming since the time domain inverse calibration method is still needed to acquire these pre-fixed retardation time scales (τs). Meanwhile, the method they used for identifying the influence of UF is based on the influence of the UF in elastic pipes, which ignores the nonlinearly combined effect between VE and UF. This is another issue to be addressed in this study.

This paper aims to further develop the frequency-domain TBM (i.e., FDTBM) for the analysis of viscoelastic parameters for plastic pipe flows. A full expression of analytical results is first obtained by transfer matrix analysis for describing the dependence of transient responses on pipe and fluid properties (including pipe-wall VE) and system conditions in the frequency domain. That relationship is then adopted for the analysis of viscoelastic parameters by measuring other parameters such as the friction factor and the UF convolution coefficient in the system. To obtain robust (unique and accurate) solutions, a multistage analysis method is proposed in this study for inversely solving the derived expression of the FDTBM. Thereafter, the developed method together with the application procedure is validated and analyzed through extensive laboratory experiments and numerical simulations that cover a wide range of pipe and system configurations. Finally, the results and achievements of this study are discussed regarding the implications on transient modeling and analysis of viscoelastic pipe flows, and relevant conclusions are drawn at the end of this paper.

Models and method of investigation

One-dimensional transient flow model for viscoelastic pipes

The continuity and momentum equations for 1D transient flows in pipe fluid systems considering both friction (with steady friction (SF) and UF components) and pipe-wall VE effects can be expressed as (Duan et al., 2010c)

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

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{\partial H}{\partial x}+\frac{\pi D}{\rho g A}(sign(Q)\frac{\rho f Q^2}{8A^2}+\frac{4\rho\nu}{DA}\int_0^t W(t-t^{'})\frac{\partial Q(t^{'})}{\partial t^{'}}dt^{'})=0, \tag{2}$$

where Q and H are the discharge and piezometric head, respectively; g = gravitational acceleration; a = elastic wave speed; D = internal pipe diameter; e = pipe thickness; A = cross sectional area; x = spatial coordinate; t = time coordinate; ρ = the fluid density; f = the friction factor; ε_r = the total retarded strain of the pipe wall due to the pipe VE; ν = the kinematic viscosity. In this paper, the linearized K-V model is used to estimate the retarded strain, which is defined as (Covas et al., 2005a; Güney, 1983)

$$CJ_k H = \sum_{k=1}^{n}(\tau_k \frac{\partial \varepsilon_k}{\partial t} + \varepsilon_k), \tag{3}$$

$$C = \frac{\alpha\gamma D}{2e}; \varepsilon_k = \int_0^t Y(x, t - t')\frac{J_k}{\tau_k} e^{-\frac{t'}{\tau_k}} dt', Y(x,t) = C(H(x,t) - H_0(x)) \tag{4}$$

where α = the dimensionless parameter, which considers both cross section dimensions and pipe axis constraint conditions; ε_k = strain caused by the k^{th} K-V element; Y= Stress; $\gamma = \rho g$ is the specific weight; H_0 = the piezometric head of the initial steady state; $W(t)$ is the weighting function of the UF model, which is given by Vardy and Brown (1995) as follows:

$$W(t) = \frac{D}{4\sqrt{\nu}} \frac{e^{-\lambda t}}{\sqrt{\pi t}}, \tag{5}$$

where λ = the UF convolution coefficient for different flow conditions, which can be calculated by the following formula for turbulent transient flows:

$$\lambda = \frac{(0.54 \nu \mathsf{R}_0^{\lg\frac{14.3}{\mathsf{R}_0^{0.05}}})}{D^2}, \tag{6}$$

where R_0 = the initial Reynolds number, which can be calculated by $V_0 D/\nu$, and V_0 is the initial steady-state velocity in the pipeline.

Frequency-domain transient-based analysis

For a typical transient event in water pipelines, the variables can be rewritten as a mean value (i.e., the steady component) plus a perturbation (i.e., the transient component) (Duan et al., 2012b):

$$H = H_0 + h; Q = Q_0 + q; \varepsilon_r = \varepsilon_0 + \varepsilon, \tag{7}$$

in which the subscript 0 represents the corresponding variables in the initial steady state; and *h*, *q*, *ε* are the perturbation variables. By substituting the above terms into the continuity and momentum Eq. (1) and Eq. (2) above and after essential mathematical operations and transformations by transfer matrix analysis, the equivalent equations in the frequency domain can be obtained (Chaudhry, 2014; Duan et al., 2012b):

$$\begin{pmatrix} h \\ q \end{pmatrix}^D = \begin{pmatrix} \cosh \mu_1 x & -\dfrac{\sinh \mu_1 x}{Z} \\ -Z \sinh \mu_1 x & \cosh \mu_1 x \end{pmatrix} \begin{pmatrix} h \\ q \end{pmatrix}^U, \tag{8}$$

where the superscripts *U* and *D* represent the upstream and downstream boundaries, respectively; μ_1 = the propagation operator and 1/Z = the characteristic impedance, which can be expressed as follows:

$$\mu_1 = \frac{i\omega}{a}\sqrt{(1 + 2\frac{a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{1 + i\omega\tau_k})(1 + \mathrm{sign}(Q)\frac{fQ_0}{DAi\omega} + \frac{4\sqrt{\nu}}{D}\frac{1}{\sqrt{\lambda + i\omega}})}, \tag{9}$$

$$Z = \frac{gA}{a}\sqrt{\frac{(1 + 2\frac{a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{1 + i\omega\tau_k})}{(1 + \mathrm{sign}(Q)\frac{fQ_0}{DAi\omega} + \frac{4\sqrt{\nu}}{D}\frac{1}{\sqrt{\lambda + i\omega}})}}, \tag{10}$$

in which ω = the angular frequency; and i = the imaginary unit.

Based on Eq. (8), under an initial condition of a unit transient perturbation imposed in a typical Reservoir-Pipeline-Valve (RPV) system as shown in Fig. 1, the resonant response of the pressure head at the downstream valve in the system can be solved as:

$$h^{D} = \frac{-i\sin i\mu_1 x}{Z\cos i\mu_1 x}, \qquad (11)$$

The above equation has the same form with the one derived from the elastic pipe with a different propagation operator as shown in Eq. (12)

$$h_{EL}^{D} = \frac{-i\sin i\mu_2 x}{Z_{EL}\cos i\mu_2 x}, \qquad (12)$$

where h_{EL}^{D} = the response of the piezometric head in an elastic pipe at the downstream valve; $1/Z_{EL}$ = the characteristic impedance in the elastic pipe; μ_2 = the propagation operator of the elastic pipe ($=i\omega/a$). Combining the resonance condition of both elastic and viscoelastic pipes gives:

$$(2m-1)\frac{\varsigma_{EL}}{a} = \frac{\varsigma_m}{a}\sqrt{T} \text{ with } m = 1,2,3\ldots, \qquad (13)$$

$$T \approx 1 + T_f^r + T_{VE}^r + T_{VE}^i T_f^i, \qquad (14)$$

$$T_{VE}^r \approx 2\frac{a^2}{g}\sum_{k=1}^{n}\frac{CJ_k}{1+(2\pi\varsigma_m)^2\tau_k^2}; T_f^r \approx \frac{2\sqrt{2\nu}}{D}\frac{\sqrt{\sqrt{\lambda^2+(2\pi\varsigma_m)^2}+\lambda}}{\sqrt{\lambda^2+(2\pi\varsigma_m)^2}};$$

$$T_{VE}^i \approx -2\frac{a^2}{g}\sum_{k=1}^{n}\frac{i(2\pi\varsigma_m)\tau_k CJ_k}{1+(2\pi\varsigma_m)^2\tau_k^2}; T_f^i \approx -\frac{ifQ_0}{2\pi DA\varsigma_m} - \frac{2\sqrt{2\nu}}{D}\frac{\sqrt{\sqrt{\lambda^2+(2\pi\varsigma_m)^2}-\lambda}}{\sqrt{\lambda^2+(2\pi\varsigma_m)^2}}, \qquad (15)$$

where $\zeta_{EL} = a/4L$ is the fundamental frequency of an equivalent elastic pipeline with the same wave speed and system configuration; ζ_m is the frequency of the m^{th} resonance peak of the transient pressure response in the frequency domain, which can be obtained by transferring the pressure signal (measured or simulated) into the frequency domain using the fast Fourier transform (FFT) technique (Cochran et al., 1967); T = the frequency shift caused by friction (both UF and SF), VE and their nonlinearly combined effect; T_{VE} = the frequency shift caused by pipe-wall VE; T_f = the frequency shift caused by friction terms (both SF and UF); and the superscripts r and i represent the real and imaginary parts of the corresponding terms, respectively.

It is revealed from Eq. (13) that the resonance frequency of a viscoelastic pipe system can be modified by: (1) the friction effect (SF & UF), (2) the pipe-wall VE effect, and (3) the nonlinear combination of those two effects. With the use of the expression of Eq. (13), the viscoelastic parameters of plastic pipes (e.g., τ and J) can be inversely identified as long as the other variables and coefficients can be known (measured or calculated) in advance under specific system and hydraulic conditions. This is actually the main principle of the proposed FDTBM for viscoelastic parameters identification in this study.

Application and evaluation of FDTBM for viscoelastic parameters analysis

In the application of FDTBM in real plastic pipe systems, the number of K-V elements is usually not known in advance (i.e., k in Eq. (15) is also unknown) in the analysis process. In the literature, the number of the K-V elements used in the Hydraulic Transient Solver (HTS) is usually chosen through an initial understanding of the system or a trial-and-error process to minimize the transient calibration difference (Covas et al., 2005a; Soares et al., 2008, 2010). Based on these previous studies, the mechanical response of viscoelastic materials can usually be better described with the increase of the K-V element number. However, previous researches have pointed out that the performance of 1D HTS is unlikely to be further improved significantly when the number of K-V elements is greater than 4 (Covas et al., 2005a). Consequently, the situations of 1 ~ 3 K-V elements were usually used in most previous studies to describe the viscoelastic behaviors of different plastic pipe systems, and their results have confirmed the adequacy of 4 or less K-V elements in the HTS for describing the pipe viscoelastic behaviors during transient simulations (Meniconi et al., 2012b; Soares et al., 2010). Nevertheless, there is no scientific foundation for the determination of this number. In this paper, the selection strategy of the K-V element number is determined by the following proposed multistage analysis procedure:

(1) Stage 1: a 1-element K-V model is used in the FDTBM to gain the values of creep compliance (J_1) and retardation time (τ_1) in the K-V model;

(2) Stage 2: a 2-element K-V model is adopted in the proposed method, but one of the retardation times (τ_1) is fixed at the value obtained from the previous stage; then the other parameters such as creep compliance ($J_{1,2}$) and retardation time (τ_2) are identified;

(3) Stage 3: by putting the acquired 2 parameters ($\tau_{1,2}$) in the 3-element K-V model, the other four parameters (τ_3, $J_{1,2,3}$) are then obtained accordingly by the calibration process;

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(k) Stage k: by fixing the obtained (k-1) values of τ, the k values of J ($J_1 \sim J_k$) and τ_k are obtained by the similar process above.

$$\frac{\min(J_{1,2\ldots k})}{\max(J_{1,2\ldots k})} \ll 1 \tag{16}$$

The entire analysis process is stopped when the obtained one of the obtained J values is much smaller than other J values as shown in Eq. (16). As a result, the number of K-V models is determined as (k-1), and the obtained (k-1) sets of τ and J values in stage (k-1) are the analytical results of the VE parameters based on the proposed multistage method in this study. For clarity, this multistage analysis method for FDTBM is depicted in Fig. 2.

For the application of the FDTBM, one (or more) transient pressure signals will first be used as benchmark data for calibration and identification of viscoelastic parameters, and the obtained parameters are then applied to test other cases (e.g., with different initial flows or transient operations) for verification and evaluation of the method's effectiveness. In this study, there are three sets of experimental test rigs for investigation, and for each test rig, one of the experimental test data series is used for the calibration by the FDTBM, and the obtained viscoelastic parameters for the tested case are then applied for modeling and analysis of all other test cases in the same rig. To evaluate the validity of the proposed multistage calibration method of the FDTBM, the following expressions defined by the relative differences between the measured and modeled results of transient pressure head are used for characterizing the accuracy (or defined as error) of the transient amplitude (positive and negative) and phase, respectively:

$$\Delta H_m^* = \frac{|H_{m^{\mathrm{th}}\ \mathrm{peak}}^{HTS} - H_{m^{\mathrm{th}}\ \mathrm{peak}}^{exp}|}{\Delta H_J} \quad m = 2,3\ldots, \tag{17}$$

As a result, the overall performance of the developed method can be evaluated by the average error for the whole specified transient domain:

$$\eta(\%) = \frac{\sum_{m=1}^{N}(\Delta H_{m+1^{\mathrm{th}}\ \mathrm{peak}}^* + \Delta H_{m^{\mathrm{th}}\ \mathrm{valley}}^*)}{2N} \times 100\%, \tag{18}$$

$$\sigma_m(\%) = \frac{|\omega_m^{exp} - \omega_m^{HTS}|}{\omega_{EL}} \times 100\%, \tag{19}$$

where ΔH^* = the dimensionless pressure difference; ω_m = the angular frequency of the m^{th} resonance peak in the frequency domain, the subscript m^{th} indicates the number of peaks or valleys of the data; N= the number of periods used for evaluation such that $2N$ is the total number of peaks (both positive and negative); the superscript *exp* = the results from experimental data, and the superscript *HTS* = the results from the HTS; ΔH_J = the Joukowsky overhead; and σ and η are errors in the transient amplitude and phase, respectively. It is noted that for all the numerical and experimental tests in this study, the first 10 periods of numerical data and the first 5 peaks of the measured experimental data are adopted for the results analysis and evaluation.

It is also necessary to point out that only viscoelastic parameters (i.e., τ and J) will be calibrated and analyzed in this paper based on the method proposed above, since all the other parameters and coefficients in the system (e.g., friction factor and elastic wave speed) are assumed to be known by preliminary analysis (as in Meniconi et al., 2015). For instance, the initial steady state can be used to calculate f and λ and Joukowsky overhead so as to obtain elastic wave speed for the transients induced by the fast closure of the end valve (e.g., Fig. 1) (i.e., maneuver duration < $2L/a$). Meanwhile, the proposed method and application procedure of this study as shown in Fig. 2 are extendable and applicable for other situations in the system where other parameters and coefficients (in addition to VE parameters) are to be determined, as long as the peak frequencies are enough and accurate from the measurement (i.e., ζ_m in Eq. (13)).

Experimental setup and tests

To verify the effectiveness of the FDTBM, extensive experimental tests for different Reservoir-Pipe-Valve (RPV) systems with viscoelastic pipes were tested in the Water Engineering Laboratory (WEL) at the University of Perugia, Italy (see the test framework in Fig. 3). Three high-density polyethylene (HDPE) pipes with different configurations were applied in the tests to examine the accuracy and validity of the FDTBM under different system conditions. In all these tests, the transients were induced by the fast closure of the downstream ball valve (with maneuver duration $t_v < L/a$), as shown in Fig. 1. Detailed descriptions of the three test systems (denoted as #1, #2 and #3 systems) and corresponding operation conditions are presented in Tables 1-4 below. The pressure signals were collected by the pressure transducer installed at the immediate upstream of the downstream end valve, and the sampling frequency (denoted as ω_{sp}) was 204.8 Hz for the #1 system and 2000 Hz for the #2 and #3 systems.

Based on the former studies for similar test rigs (Meniconi et al., 2012a), the dimensionless parameters (α) in Eq. (4) of each system are calculated as:

$$\alpha = \frac{D}{D+e} + \frac{2e}{D}(1+2\nu_p), \tag{20}$$

where ν_p = the Poisson ratio, which is 0.46 in these three systems (Meniconi et al., 2014). The fiction factors in Tables 2-4 are calculated using the Blasius correlations (i.e., Eq. (21)) according to experiments (Brunone and Berni, 2010).

$$f = \frac{0.3164}{\mathrm{R}_0^{0.25}}, \tag{21}$$

The UF convolution coefficient λ is obtained via Eq. (6) for turbulent flows. Other information listed in Tables 2-4 is based on experimental data.

The system configuration for numerical comparison

The numerical simulation using pre-known viscoelastic parameters may be an effective method to compare the proposed frequency-domain method and the traditional time-domain calibration method. Thus, to demonstrate the effectiveness and advantages of the proposed multistage FDTBM, 2 elements K-V model is adopted in this part. For simplicity, a frictionless RPV system is adopted and the used value of the dimensionless constraint coefficient (α) is 1. The remaining pipe parameters used in the numerical model are 300 m (length), 0.06 m (diameter) and 0.006 m (thickness) respectively. After the numerical transient trace (used as the benchmark) is generated using the preset values, the proposed method and the traditional time-domain method are performed respectively to identify the viscoelastic parameters. It is worth noting that 3 K-V models containing 1~3 K-V elements are adopted in the time-domain calibration and for the K-V models which contain more than 1 elements their retardation times are previously fixed based on previous studies (Covas et al., 2005a; Soares et al., 2008; Duan et al., 2010c). Once identified, these obtained viscoelastic parameters from time- and frequency-domain calibration method are put into the HTS, and then the generated transient traces are compared with the benchmark curve.

Parametric analysis and numerical tests

The analytical solution of Eqs. (13-15) indicates that the frequency shift of a transient response is governed by the coefficients and parameters of the system and operation, which means that different systems may have different performances on using the proposed method for viscoelastic parameter identification. To gain more universal results for the analysis, a parametric analysis is performed in this study to obtain relevant dimensionless parameters that affect the transient frequency shift in the system.

In water supply systems, the transient response (e.g., H) in a viscoelastic pipe is a function of the parameters and coefficients (with symbols defined previously) as follows:

$$H = F(e, L, D, \rho, a, \nu, V_0, J, \tau), \tag{22}$$

According to π theorem, Eq. (22) can be rewritten in a dimensionless form as below:

$$H^* = F(\frac{L}{D}, \frac{D}{e}, \mathsf{M}_0, \mathsf{R}_0, JE_0, \frac{\tau}{T_W}). \tag{23}$$

where $H^*=H/\rho V_0^2$ is the dimensionless pressure head; $\mathsf{M}_0 = V_0/a$ is the initial Mach number; $T_w = L/a$ is the wave timescale; and E_0 is the instantaneous Young modulus of elasticity of the viscoelastic pipe. Therefore, the calibrated results of J and τ may be affected by these dimensionless parameters described in Eq. (23), and R_0 (or $f\mathsf{R}_0$) is the dimensionless parameter that can reflect the resistance force (i.e., SF and UF) in flows.

To perform a systematic analysis, extensive numerical tests are conducted in this study based on the proposed method in Eq. (13) and the procedure in Fig. 2 to understand and examine the validity range and effectiveness of the developed method for viscoelastic parameter identification. The typical ranges of system configurations and operation conditions are shown in Table 5, which may cover most of the situations in realistic pipe systems (Covas et al., 2005a; Duan et al., 2012c; Gong et al., 2016). The situations of k = 1, 2, 3 for the K-V model are adopted for numerical simulations and analysis. The values of J and τ are calibrated using the proposed procedure by the Genetic Algorithm (GA) (Duan et al., 2010d). Then the accuracy of the proposed method under different flow conditions is evaluated based on Eqs. (18-19) in this study. It is noted that the dimensional analysis based on the extensive numerical applications in this study is aimed at examining the accuracy and validity of the developed FDTBM and the multistage calibration approach under different conditions rather than the dependence of viscoelastic parameters of plastic pipes on these system factors and conditions.

Application results and discussion

Experimental validation

For test systems in Table 1, one of the test data values (with the maximum flow velocity) is used herein for the inverse identification of the viscoelastic parameters. The calibrated results of viscoelastic parameters for these three test systems are listed in Table 6. To check the calibration process of the proposed FDTBM, the corresponding time domain results of pressure traces (of different stages) for the tests are retrieved and plotted in Fig. 4 for comparison. The stage-by-stage calibration errors are shown in Fig. 5. In general, the calibrated results could be improved with the increase in calibration stages, in which the most significant improvement is from the first stage to the second stage. More specifically, the amplitude prediction errors of these three systems may attain approximately 20% when only one stage of the calibration process is achieved, which reduce quickly to an acceptable level (<5%) with stage-by-stage evolution of the calibration process as shown in Fig. 5. Particularly, for the #1 test system, the prediction error is less than 2% when the first three calibration stages are achieved. However, for the #3 system, an acceptable result can be obtained by the first two stages. In this regard, the application results have demonstrated the feasibility and advantages (accuracy and efficiency) of the proposed multistage calibration process for the developed FDTBM in this study. In the meantime, the effective number of the K-V model has also been determined upon the achievement of the multistage calibration process in the frequency domain, which confirms again the effectiveness and robustness of the proposed method in this study.

In addition to transient amplitude damping, the frequency shift (corresponding phase difference in the time domain) is also investigated by evaluating the errors of first 5 resonance peak frequencies between the numerical data and the experimental data in the frequency domain, and the results are shown in Table 7. It is clearly shown from this table that there are relatively small differences between the errors of resonance frequencies using different stages in the same system and that the proposed method can accurately capture the resonance peaks of the first 3 peaks (errors < 6%). This result indicates that the proposed multistage method captures the main features of transient phases (frequencies) firstly and then improves the amplitudes stage by stage (see Fig. 4). This is the inherent tenet of the developed FDTBM that is mainly dependent on the resonance frequencies (or their shifts) from the measurement and/or simulation data.

It is also noting from the obtained results that the frequency shift is mainly caused by the first τ (the smallest) identified in the frequency domain while the frequency shift caused by other retardation times is much less dominant and will decrease with the increase of τ. In fact, these identified retardation time scales modify different transient wave frequency ranges, which can be partially reflected from stress-and-strain curves of different K-V elements. For example, the stress-and-strain curves of the three K-V elements in the test #1 system are retrieved and shown in Fig. 6. The results reveal clearly that the stress-and-strain curves stemmed from different retardation times are different as they modify different frequency ranges. Specifically, the first identified τ interacts with or impacts on the mainstream wave mode (with an order of $\sim L/a$ time scale), while the remaining ones mainly influences/modifies the wave modes with relatively low frequencies such as induced by pipe skin friction and radial wall deformation ("smoothing" and "detuning" effects with relatively low speeds, with an approximate order of $\sim D/V_0f^{0.5}$). Therefore, the first identified K-V element has contributed to the overall frequency shift as it is mainly related to the overall phase of transient signal in the time domain (or the fundamental frequency in the frequency domain). While for the other necessary elements (e.g., the second & third elements in this case), they may provide further "smoothing" and "detuning" effects on the transient signal, so as to improve the shape (i.e., low frequency mode) and amplitude of the signal during calibration process.

Results verification and evaluation

Previous studies have demonstrated the independence of viscoelastic parameters in the K-V model on the system operation and initial flow information because they are properties of the viscoelastic materials and therefore they only change with material conditions and relevant influence factors (Duan et al., 2010c; Mitosek and Chorzelski, 2003; Wineman and Rajagopal, 2000). In that regard, the calibrated parameters are, in principle, applicable to any other test cases in the same system if only other test environment (e.g., temperature) and data collection techniques (e.g., uncertainties and noises) are kept similar. Accordingly, the application results of the calibrated parameters in Table 6 to other test conditions are obtained and plotted in Fig. 7 for the three test systems, with the errors in the transient frequency shift of these applied cases evaluated and listed in Table 8.

The overall results presented in Fig. 8 and Table 8 reveal that the viscoelastic parameters from the multistage FDTBM can reproduce pressure oscillations with acceptable accuracy (errors in amplitude < 5% and errors in peaks location ≤ 3.1% for the first 3 peaks) for different scenarios in each test system. As observed in the former results of Fig. 4, the frequency shifts caused by different factors can be easily captured by the first stage of the proposed method because the errors in resonance frequencies from different stages are almost the same (with relatively small errors as in Table 8) in comparison with the resonance frequencies of the experimental data. For the amplitude simulation, the error evolution of the application cases (together with the calibration cases) with the initial condition (Reynolds number or unsteady friction) is given in Fig. 8, which demonstrates the obvious improvements in transient amplitude matching with calibration stages, and the final convergence results are of acceptable accuracy (i.e., errors in amplitude < 5%). These application results imply again the effectiveness of the proposed method for the analysis and identification of viscoelastic parameters in different pipe systems. In addition, the results also confirm the former finding that the viscoelastic parameters are indeed independent of initial flow conditions.

As shown in former studies (Duan et al., 2012c, 2016; Meniconi et al., 2014), the UF effect highly depends on initial flow conditions (e.g., Reynolds number). Therefore, based on the findings in Eq. (13) to Eq. (15), the influences and nonlinearly combined relationships between different factors (such as SF, UF and VE) could be well distinguished and identified by the proposed method of this study. It is also noted that the different obtained values of viscoelastic parameters from different pipeline configurations that are all made of the same HDPE material indicate that apart from the stress history, the viscoelastic properties under transient flow conditions may be greatly influenced by pipe axis and circumferential supports (Covas et al., 2005a; Gong et al., 2016; Zanganeh et al., 2015) as well as the pipe scales (e.g., length, size, and thickness) (Covas et al., 2005a; Pezzinga et al., 2016). As explained in a former study of Duan et al. (2010b), this is mainly because of the different energy transfers and interactions between viscoelastic pipe-walls and internal fluids resulting from the different configurations of pipelines.

It is also interesting to note that almost all of the calibrated values of τ_2 and τ_3 in Table 6 are larger than the elastic wave time scale of the specific pipeline system, i.e., $2L/a$ = 1.10 s, 0.472 s, and 0.484 s for the #1, #2 and #3 systems, respectively, which may significantly affect the energy transfer and exchange between pipe-wall and fluid during a transient process (Duan et al., 2010b; Gong et al., 2016). Furthermore, the obtained retardation time scales (τ s) are not exactly consistent with (i.e., partially agree, and partially not agree) the statement made in many previous studies (e.g., Covas et al., 2005a; Gong et al., 2016; Ramos et al., 2004, Keramat and Haghighi, 2014), in which the pre-specified retardation time scales of different K-V elements are suggested to be less than the wave cycle time scale ($2L/a$) so that different viscoelastic parameters can be accurately identified from the measured transient wave signals. From a perspective of wave dynamics and acoustics, the viscoelastic transient response (i.e., transient waves) can be regarded as a multiscale wave superposition process with different retardation time values corresponding to different wave frequency ranges. When the retardation time is larger than $2L/a$, the time duration that allows for energy absorption/dissipation in viscoelastic pipe wall is not enough (Duan et al., 2010b; Gong et al., 2016, Keramat and Haghighi, 2014). Under this circumstance, the viscoelastic properties of the pipe wall cannot be fully reflected in the transient traces measured, which poses a barrier for viscoelastic parameters identification. However, in a realistic pipeline system (e.g., the test systems of interest in this study), this preset condition/assumption might not be appropriate or satisfied for the analysis of viscoelastic parameters since the relatively small retardation times mainly describe the short-term/high frequency behaviors of viscoelastic materials and thus the long-term influence (low frequency modes) of viscoelasticity/other factors cannot be well reflected. Thus, using such a constraint condition may not be appropriate.

The application results and findings of this study further demonstrate the effectiveness of the proposed FDTBM and the multistage calibration procedure. In addition, the consistent accuracies of different test cases for the same system also confirm another advantage of the FDTBM – high tolerance against other potential influence factors such as noise and friction factors – because it relies mainly on the resonance frequencies of the transient system that are relatively independent of (or high tolerant to) those influential factors (e.g., Duan et al., 2012b; Duan, 2016).

Comparison of multistage FDTBM with traditional method

To further demonstrate the effectiveness of the proposed multistage FDTBM, a numerical case with specified theoretical values of viscoelastic parameters shown in Table 9 is applied to compared with the traditional time domain method. The obtained results of viscoelastic parameters calibration by the proposed method and the traditional method are listed in Table 9.

The comparative results reveal that the proposed FDTBM and multistage application procedure can effectively identify both the number and corresponding values of the viscoelastic parameters, while the traditional time-domain method may produce relatively larger errors in the calibration results by prefixing the retarded time scales as conducted in the literature. In the meanwhile, the results of obtained pressure traces by these two methods are plotted in Fig. 9. It is clearly shown that the proposed multistage approach could provide obvious evolution process of the calibration stages to finally obtain the accurate results for both the number and values of viscoelastic parameters). From this perspective, the results comparison and analysis in Table 9 and Fig. 9 demonstrate again that the effectiveness and preference of the proposed FDTBM and multistage application approach.

Further analysis and discussion of FDTBM

Apart from the experimental tests and results analysis, extensive numerical applications of viscoelastic pipeline systems with different typical ranges of settings and parameters (e.g., wave speed, diameter, and thickness) are conducted in this study in order to further examine the performance of the proposed FDTBM and the analysis approach. Since the former experimental analysis (in addition to the following numerical analysis) has shown that the proposed FDTBM could accurately capture the frequency shift of transient responses, only the errors in reproducing the transient pressure amplitudes are presented and examined in the following analysis. Based on the numerical applications and experimental tests, a systematic analysis is performed to investigate the influences of different factors in water pipeline systems, including initial flow conditions (UF or R_0), pipe scales (L, D, and e) and pipe materials (VE), on the accuracy and applicability of the developed FDTBM.

Influence of initial flow condition

The mentioned negligible importance of the initial Reynold number, R_0, is confirmed by the final experimental results plotted in Fig. 10. Precisely, the overall results of both numerical and experimental tests are plotted in Fig. 10(a), which depicts the errors of different stages and K-V elements used in the simulation, and the final experimental results (i.e., for the final calibration stage) and numerical results are described in Fig. 10(b). The relatively smaller errors (i.e., <5%) in Fig. 10(b) demonstrate the accuracy and validity of the developed method. Also, they reveal that the application procedure is almost independent of the initial flow condition, which is evidenced by the relatively constant errors (with average value of approximately 2%) in predicting pressure oscillations for the tested 1-element K-V model. It is also noted that although the error levels of using different number of K-V elements are slightly different, the errors in predicting the transient data which use the same number of K-V elements are relatively stable and are still within 5%. These results and findings show the relatively small influence of the initial flow condition on the accuracy of the FDTBM. Furthermore, the stage-by-stage experimental analysis results in Fig. 10(a) also clearly indicate the evolution and improvement of the analysis process for the transient responses by the multistage calibration approach, which evidences again the effectiveness of the proposed FDTBM and application procedure.

Influence of pipe scales

Recent studies by Pezzinga et al. (2016) and Mitosek and Chorzelski (2003) reveal that the pipe scales (e.g., length, size and thickness) could significantly affect transient behaviors (amplitude and phase) in viscoelastic pipes and thus may influence the application of the proposed FDTBM in present work. Based on the dimensional analysis in this study, these pipe scale effects are reflected through two dimensionless parameters, D/e and L/D, as shown in Eq. (23). To highlight and investigate the influence of these pipe scale parameters, the numerical tests considering the frictionless pipeline only are conducted herein for analysis. By applying the developed FDTBM to the extensive numerical cases listed in Table 5, the results are obtained and evaluated as given in Fig. 11.

The plots in Fig. 11 demonstrate clearly the relatively high sensitivity of the FDTBM to the pipe scales. On one hand, the results of only 1-element K-V model in Fig. 11(a) show that the identification error (and its deviation) increases with an approximately linear trend (from 0.5% to approximately 2.5%) with D/e within the whole test domain. Although predicting errors for multiple K-V elements model are obviously larger than those from the single K-V element model, a similarly increasing trend indicates that the method may become relatively more sensitive (less accurate) for the viscoelastic parameter identification for plastic pipelines with larger sizes and thinner walls (e.g., flexible pipe-walls). On the other hand, the results of Fig. 11(b) reveal the consistent trend of the influence of L/D parameter to D/e. In other words, the identification error is decreasing with L/D, which means that it becomes less accurate for applying the developed FDTBM to plastic pipelines with shorter lengths and larger sizes. In fact, the viscoelastic materials have strong time dependent strain properties, so that it requires sufficient time to complete their viscoelastic deformation during the transient oscillation process. In this regard, it is relatively difficult for the relatively short and/or large pipes to achieve the complete viscoelastic performance during the fast transient process (insufficient wave time to achieve a complete viscoelastic hysteresis). As a result, it is unlikely for the viscoelastic model (in transient simulation) to fully capturing viscoelastic (deformation) features of the pipes, and thus the pipe will be identified with more elastic behaviors (higher wave speed) than viscous behaviors in relatively short pipes (Mitosek and Chorzelski, 2003). This is again due to the use of the conceptual K-V model in which only can an analogous process of viscoelastic deformation be mimicked, but not the complete physical mechanism of the viscoelastic material.

It is also noticed from Fig. 11 that the tested parameter range covers most of pipe sizes in the water supply system (Duan et al., 2012c) and the maximum error of all the tests covered in this study is about 11% only, which confirms the effectiveness of the developed FDTBM and application procedure for the identification of viscoelastic parameters for most situations of plastic pipes in water supply systems.

Influence of pipe material properties

It is clearly shown in the analytical analysis (e.g., Eq. (15) and Eq. (23)) that transient responses in plastic pipes are highly dependent on the viscoelastic properties (i.e., dimensionless parameters, JE_0 and τ/T_w in Table 5). Therefore, it is not surprising that these viscoelastic properties may directly influence the identification process and accuracy of the FDTBM. Based on the extensive numerical tests planned in Table 5, the application results are evaluated and plotted in Fig. 12. The overall results show the decreasing trend of identification accuracy with both parameters (JE_0 and τ/T_w). By definition, the parameter of JE_0 represents the relative deformability of the plastic pipe (i.e., range of retarded deformation), and τ/T_w represents the time available for the energy transfer between the pipe-wall and the initial fluid during each wave cycle. As a result, the results of Fig. 12 can be interpreted as follows: (1) the proposed FDTBM becomes less accurate in its application to the plastic pipes with relatively higher deformability, and (2) it is more accurate to identify those pipes with relatively larger lengths and/or faster deformation speed so that the viscoelastic features of plastic pipes could be fully reflected by and included in the transient responses. Through the results comparison of Figs. 12(a) and (b), it is found that the FDTBM is more sensitive to the parameter of τ/T_w (with maximum error exceeding 10%) than of JE_0 (with maximum error below 3%). Therefore, the deformation speed and degree of the plastic pipes (i.e., deformability) are crucial to the application of the developed FDTBM in this study.

From the results analysis and discussion, it can be concluded the developed FDTBM and the application procedure in this study are effective in the identification and analysis of viscoelastic parameters of plastic pipes, and its accuracy could be affected by different factors with different deformation degrees in the system. Specifically, the systematic analysis of this study indicates that the deformability (viscoelastic creep speed and extension degree) is the most influential factor, followed by the pipe scales and initial flow conditions, for the applicability and accuracy of the developed FDTBM.

Summary and conclusions

This research presents a frequency-domain transient-based method (FDTBM) for the analysis of viscoelastic parameters (i.e., creep compliance and retardation time) of plastic pipes. The transient frequency response of plastic pipes is first derived from 1D water hammer equations and then used for viscoelastic parameter identification based on a proposed multistage calibration process in this study.

Three sets of laboratory experimental test systems with different pipe configurations and initial flow conditions were applied to examine the effectiveness of the proposed method and application procedure. The experimental results and analysis demonstrate that the proposed

FDTBM and the multistage calibration process can efficiently provide unique and accurate results for viscoelastic parameter analysis.

Extensive numerical tests are further applied to the systematic analysis of the influences of different factors in the system, including initial flow condition, pipe scales and viscoelastic properties. The results and analysis indicate that the FDTBM is applicable to most situations of viscoelastic parameters identification, and its accuracy and applicability could be affected potentially by both viscoelastic properties and pipe scales (e.g., errors within 20% for all tests in this study) but remain relatively constant with initial flow conditions (e.g., errors < 3% herein).

Finally, it is necessary in future work to further investigate the influences of other complex factors in practical pipeline systems, such as system connection complexities and devices operations, on the developed FDTBM.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request (including Analytical, numerical and experimental test data).

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Tables

Table 1. System Configuration Information

System No.	#1	#2	#3
L (m)	199.8	99.80	101.4
D (mm)	93.3	38.3	26.6
e (mm)	8.1	5.9	3.1
ω_{sp} (Hz)	204.8	2000	2000
α	1.25	1.46	1.34

Table 2. Hydraulic Information for the #1 System

Test No.	Test 1	Test 2	Test 3
Q (L/s)	1.00	3.43	4.40
R_0	1.36e4	4.68e4	6.00e4
f	2.93e-2	2.15e-2	2.02e-2
λ	0.519	1.25	1.49
Initial Head (m)	20.41	18.80	17.97
Maximum Head (m)	25.85	36.95	41.34
t_v (s)	0.107	0.162	0.164

Table 3. Hydraulic Information for the #2 System

Test No.	Test 1	Test 2
Q (L/s)	0. 414	0. 271
R_0	1.98e4	1.30e4
f	2.67e-2	2.97e-2
λ	8.40	6.15
Initial Head (m)	16.68	18.43
Maximum Head (m)	48.54	40.06
t_v (s)	0.355	0.324

Table 4. Hydraulic Information for the #3 System

Test No.	Test 1	Test 2	Test 3
Q (L/s)	0. 436	0. 591	0. 810
R_0	1.44e4	1.97e4	2.69e4
f	2.89e-2	2.67e-2	2.47e-2
λ	3.22	4.03	5.05
Initial Head (m)	20.04	19.57	18.44
Maximum Head (m)	36.66	42.21	49.22
t_v (s)	0.127	0.140	0.165

Table 5. Test Ranges of Dimensionless Parameters

Parameter	L/D	D/e	$f\mathsf{R}_0$	JE_0	τ/T_w
Minimum	1600	5.0	100	0.092	0.04
Maximum	8000	20.0	1200	0.46	0.80

Table 6. Identification Results of VE Parameters for Three Test Systems

No. of Stage	System and Test	VE Parameters					
		J_1 (Pa^{-1})	τ_1 (s)	J_2 (Pa^{-1})	τ_2 (s)	J_3 (Pa^{-1})	τ_3 (s)
Stage-1	#1 Test 3	7.48e-11	0.119				
	#2 Test 1	4.86e-11	0.0586				
	#3 Test 3	5.45e-11	0.0499				
Stage-2	#1 Test 3	6.97e-11	0.119	8.26e-11	1.05		
	#2 Test 1	4.38e-11	0.0586	8.53e-11	0.491		
	#3 Test 3	5.02e-11	0.0499	1.56e-11	0.672		
Stage-3	#1 Test 3	6.98e-11	0.119	8.27e-11	1.05	6.90e-11	39.9
	#2 Test 1	4.38e-11	0.0586	9.51e-11	0.491	4.87e-10	15.0

Table 7. Errors in Transient Frequency Shift of the Calibration Results for Three Test Systems (N/A Indicates not Necessary/Measured for this Stage)

Errors in Phase	Stage-1			Stage-2			Stage-3		
	#1	#2	#3	#1	#2	#3	#1	#2	#3
σ_1 (%)	0	0.01	0.01	0	0.01	0.01	0	0.01	N/A
σ_2 (%)	5.5	0	3.1	0	0	3.1	0	0	N/A
σ_3 (%)	0	0	3.2	0	0	3.2	0	0	N/A
σ_4 (%)	5.5	0	12.5	5.5	0	12.5	5.5	0	N/A
σ_5 %)	5.5	N/A	15.6	5.5	N/A	15.6	5.5	N/A	N/A

Table 8. Application Errors in Transient Frequency Shift of Three Test Systems

Errors in Phase	Stage-1			Stage-2			Stage-3		
	#1	#2	#3	#1	#2	#3	#1	#2	#3
σ_1 (%)	0	0.01	0.01	0	0.01	0.01	0	0.01	N/A
σ_2 (%)	2.7±3.9	0	3.1	2.7±3.9	0	3.1	2.7±3.9	0	N/A
σ_3 (%)	0	0	3.1	0	0	3.1	0	0	N/A
σ_4 (%)	2.7±3.9	0	6.2	2.7±3.9	0	6.2	2.7±3.9	0	N/A
σ_5 (%)	8.2±3.9	N/A	9.3±4.4	8.2±3.9	N/A	9.3±4.4	8.2±3.9	N/A	N/A

Table. 9 Numerical comparison of the proposed FDTBM and traditional time-domain method

Items		J_1 ($\times 10^{-10}$ Pa^{-1})	τ_1 (s)	J_2 ($\times 10^{-10}$ Pa^{-1})	τ_2 (s)	J_3 ($\times 10^{-10}$ Pa^{-1})	τ_3 (s)
2-Element K-V Parameters for Numerical Test		0.200	0.0150	1.50	0.800		
Proposed FDTBM	Stage-1	0.218	0.0168				
	Stage-2	0.210	0.0168	1.58	0.792		
	Stage-3	0.210	0.0168	1.67	0.792	0.000167	0.806
Traditional Time-Domain Method	1-element	1.30	0.519				
	2-element	0.08	0.05(fixed)	1.17	0.5(fixed)		
	3-element	0.233	0.05(fixed)	0.445	0.5(fixed)	1.312	1.5(fixed)

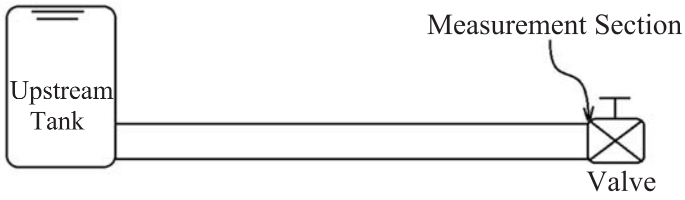

Fig. 1 Sketch of the PRV system

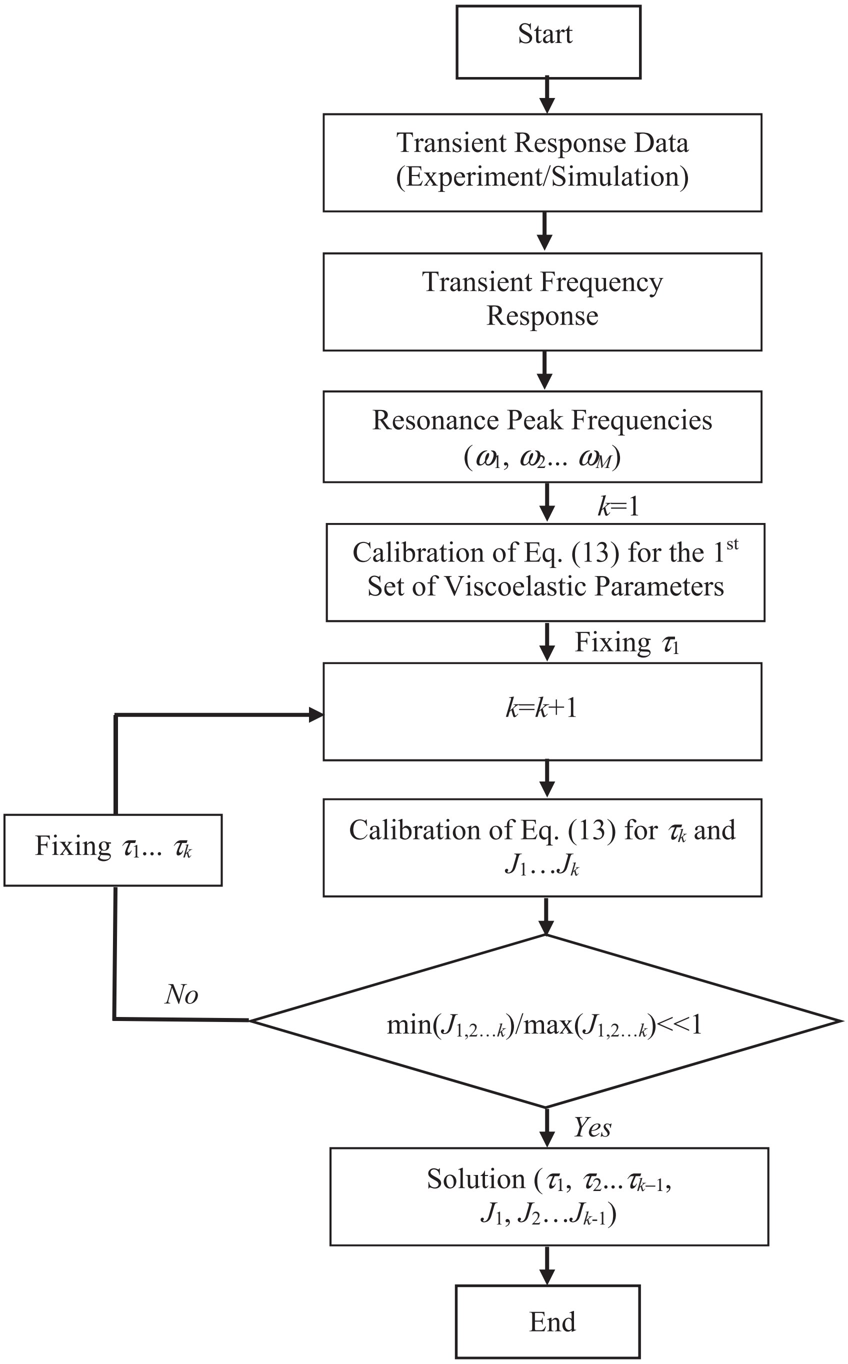

Fig. 2 Overall procedure for the multistage FDTBM

Fig. 3 Experimental facilities at the University of Perugia, Italy: (a) pressurized air vessel; (b) pressure transducer; (c) HDPE pipes

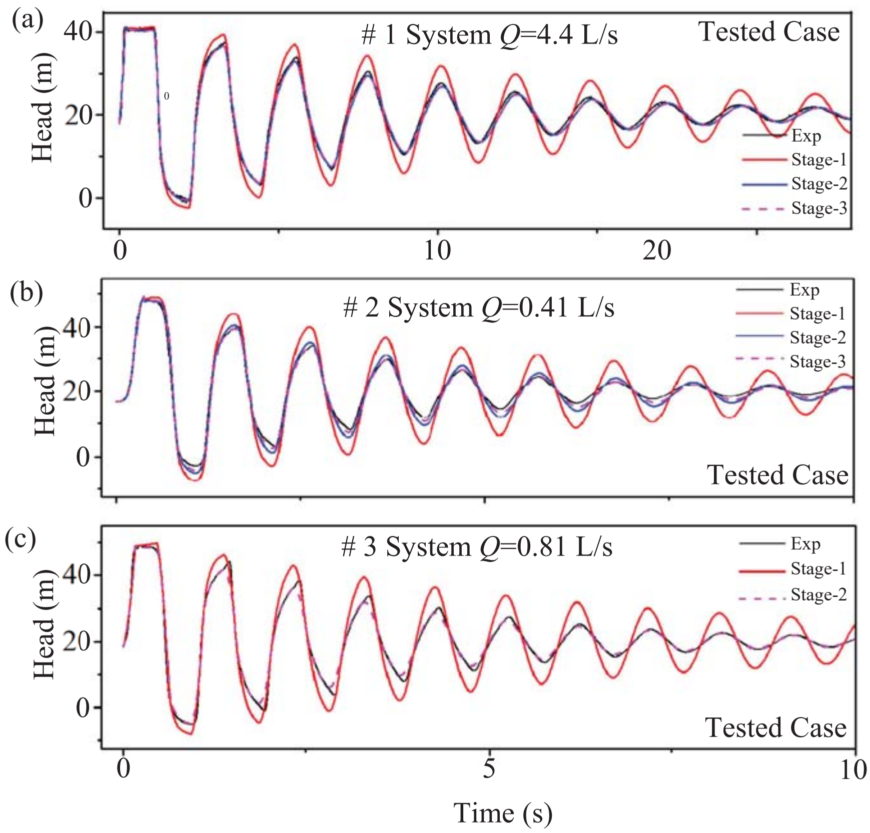

Fig. 4 Calibrated and measured results of transient pressure traces: (a) #1 system; (b) #2 system; (c) #3 system

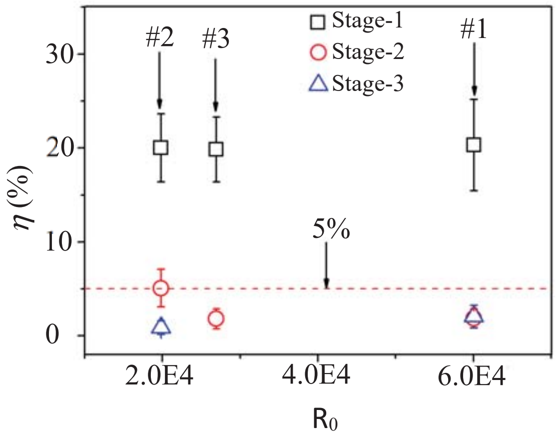

Fig. 5 Stage-by-stage evolution of the errors in transient pressure amplitudes for the multistage calibration procedure of FDTBM

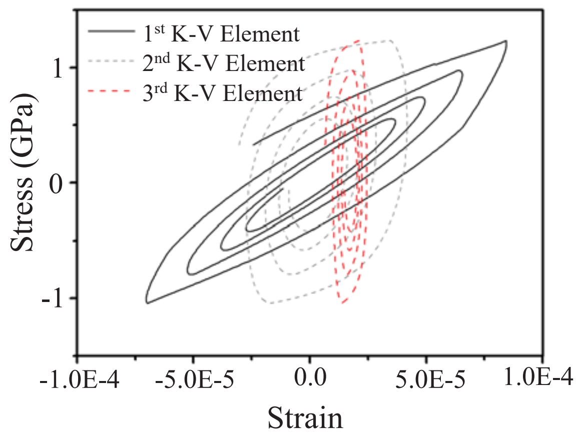

Fig. 6 Stress-and-strain curve of the calibrated three K-V elements in the test #1 system

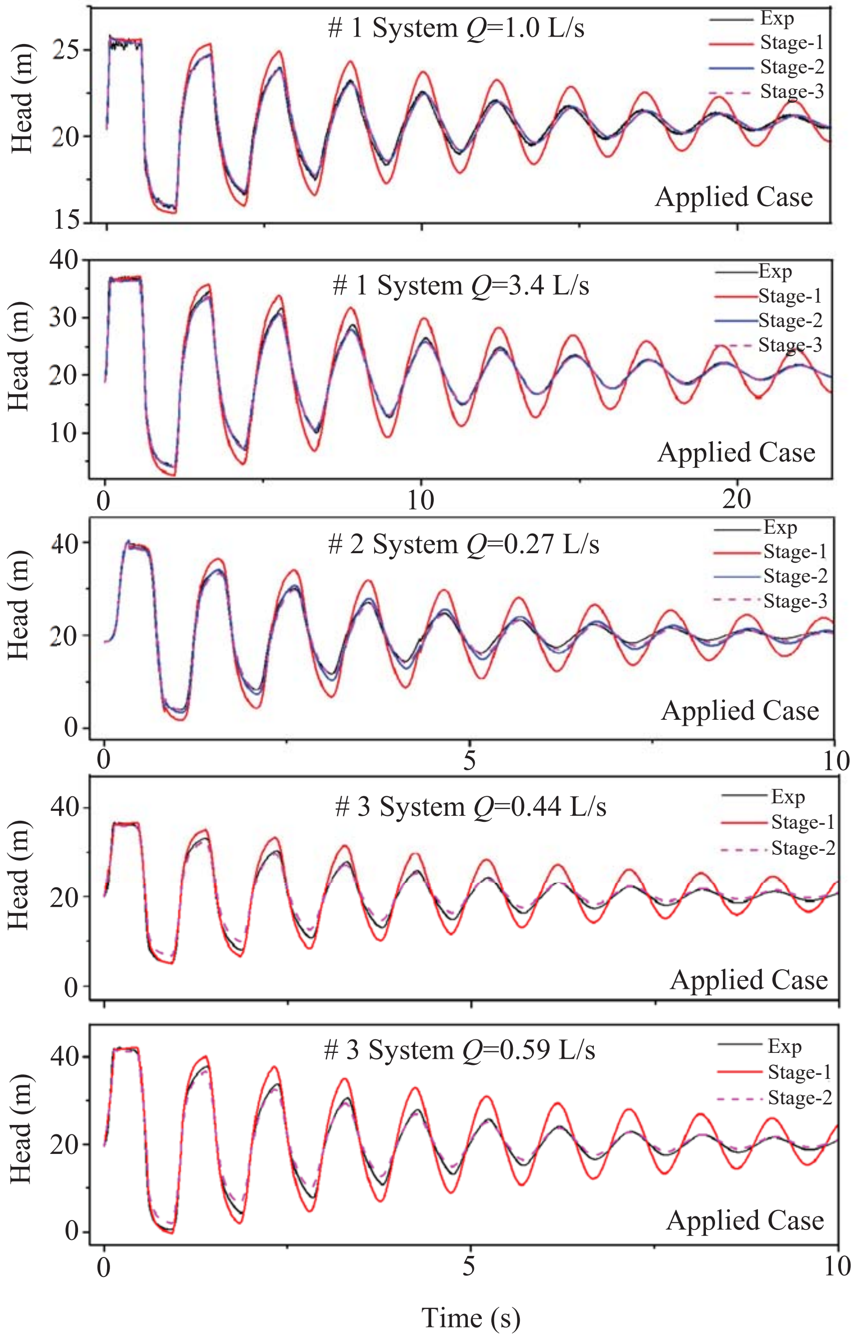

Fig. 7 Application results of the calibrated results for different test and system conditions

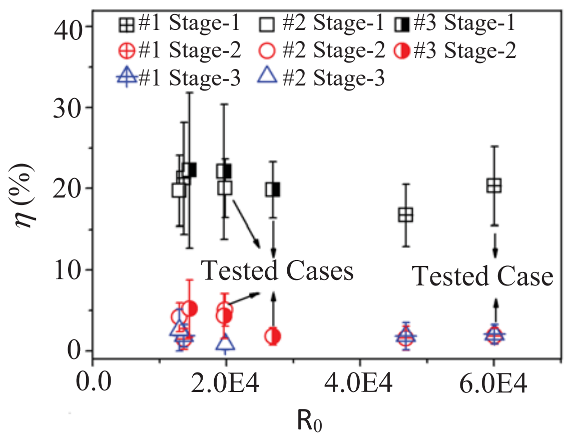

Fig. 8 Stage-by-stage evolution of application errors for different cases of three test systems

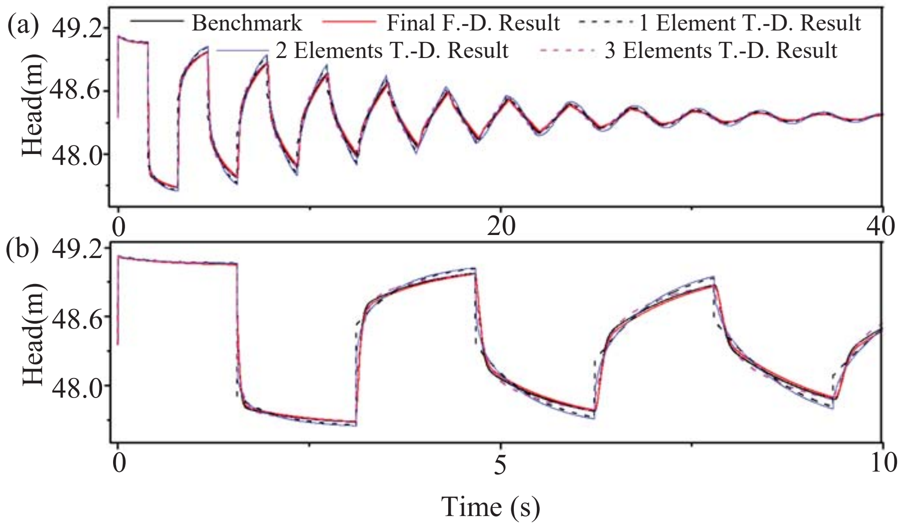

Fig. 9 Results comparison of transient traces using calibrated K-V elements from the Time-Domain (T.-D.) and Frequency-Domain (F.-D.) methods (a) overview of the whole simulation traces; (b) enlarged part of the first 2 wave cycles.

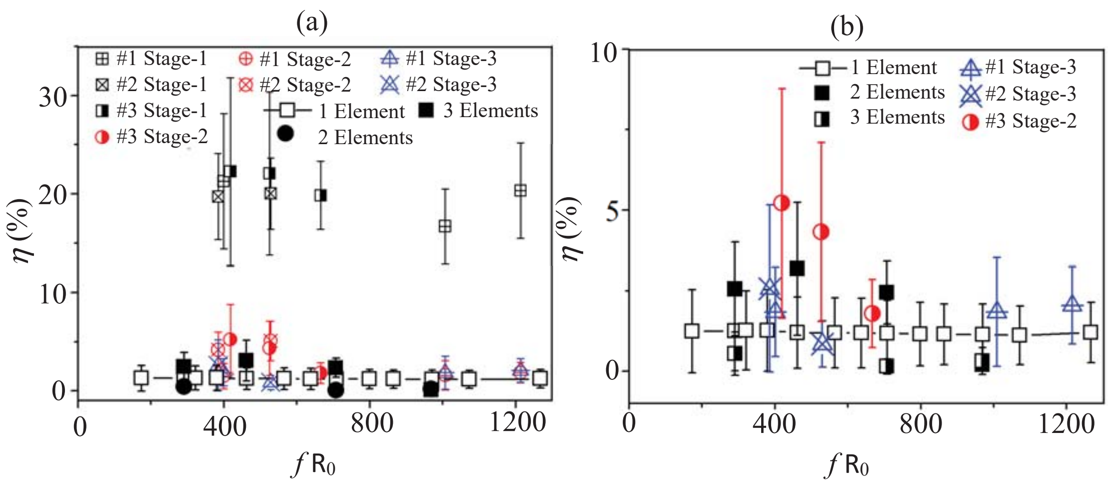

Fig. 10 Influence of unsteady friction on the application of the developed FDTBM: (a) the evolution of the multistage calibration process for the numerical and experimental tests; (b) final results of numerical and experimental applications for different tests and systems

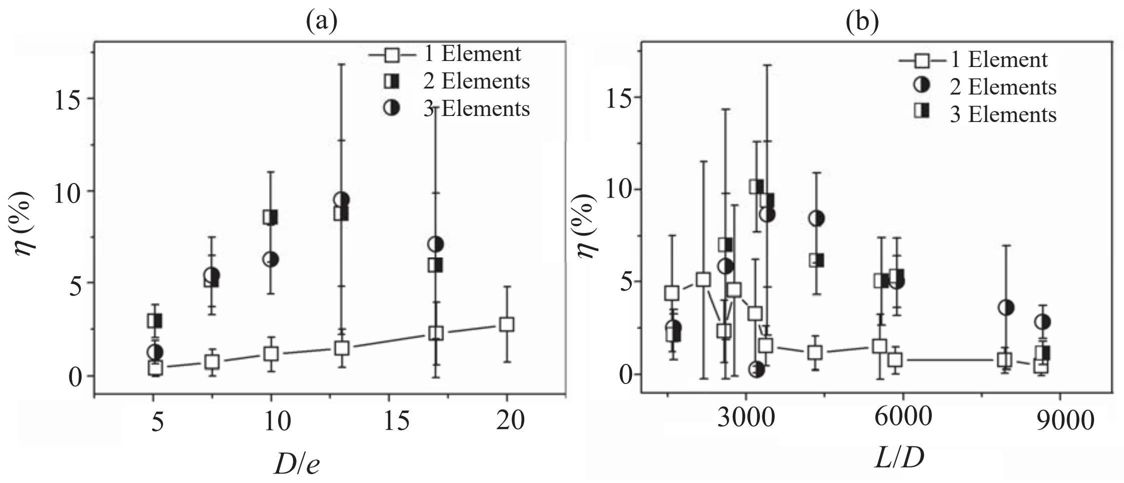

Fig. 11 Influence of pipe scale parameters on the developed FDTBM: (a) diameter-thickness ratio; (b) length-diameter ratio

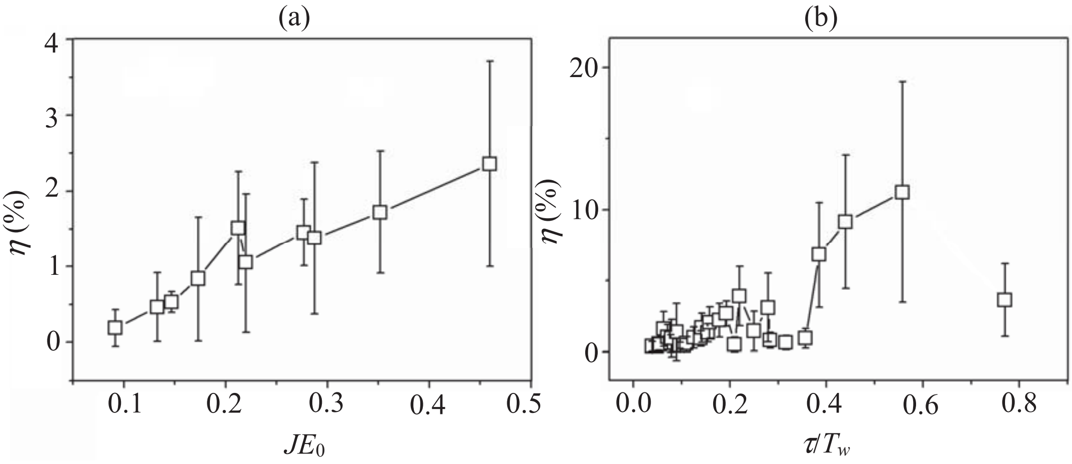

Fig. 12 Influence of pipe material properties on the developed FDTBM: (a) ratio of the viscoelastic modulus and elastic modulus; (b) ratio of the retardation time scale and wave time scale

Caption List of Figues