Transient Energy Analysis in Water-filled Viscoelastic Pipelines

B. Pan[1], **A. Keramat**[2], **C. Capponi**[3], **S. Meniconi**[4],

B. Brunone, M.ASCE [5], **H.F. Duan**, M.ASCE [6]

[1] *Ph.D. Candidate, Department of Civil and Environment Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR 999077, PR China. Email: bin.pan@connect.polyu.hk*

[2] *Research Assistant Professor, Department of Civil and Environment Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR 999077, PR China. Email: alireza.keramat@polyu.edu.hk*

[3] *Research Fellow, Department of Civil and Environmental Engineering, The University of Perugia, G. Duranti 93, Perugia 06125, Italy. E-mail: caterina.capponi@unipg.it*

[4] *Associate Professor, Department of Civil and Environmental Engineering, The University of Perugia, G. Duranti 93, Perugia 06125, Italy. E-mail: silvia.meniconi@unipg.it*

[5] *Professor, Department of Civil and Environmental Engineering, The University of Perugia, G. Duranti 93, Perugia 06125, Italy. E-mail: bruno.brunone@unipg.it*

[6] *Associate Professor, Department of Civil and Environment Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR 999077, PR China (corresponding author). Email: hf.duan@polyu.edu.hk*

Abstract

The transient flow phenomenon in a pipeline accounts for the flow variations with time and space. The transient energy analysis overlooks the process as it sums the energy of the entire pipe domain and reports it at each moment. The current research takes advantage of this approach to investigate different influential factors in water pipelines, including steady friction, unsteady friction, and pipe wall viscoelasticity, to figure out the energy conversion and dissipation during a transient flow process. To this end, energy expressions are derived and compared for both elastic and viscoelastic pipeline systems. Two different viscoelastic materials – Oriented Polyvinyl Chloride (PVC-O) and High-Density Polyethylene (HDPE) – are applied in the analysis to compare the proportions of the energy dissipation by different influential factors. The results reveal that at small transient perturbations, the influence of the steady friction is dominant in the energy dissipation, and the impact of viscoelasticity grows with the excitation intensity and valve's oscillation frequency. Besides, spatial variations of energy dissipation (per unit of length) along the pipeline have been investigated in single and branched systems, demonstrating significant deviations by distance from the excitation source.

Keywords: transient energy analysis; viscoelastic pipelines; water hammer; viscoelasticity; steady friction; unsteady friction; energy diagram

Introduction

Transient research started by analyzing the destructive effects of water hammer (hydraulic transients) over a hundred years ago. Despite the potentially damaging risks to pipe systems, transient waves are full of information that can be used to assess pipeline conditions (Che, et al., 2021; Duan, et al., 2017a and 2020; Lee, 2005; Louati et al., 2020; Liggett and Chen 1994; Meniconi et al. 2013; Pan et al. 2021; Wang and Ghidaoui, 2018). Thus, different transient-based anomaly detection methods (TBADMs) have been proposed and developed for pipeline condition assessment (Duan, 2016, 2018). In the majority of TBADMs, the required unknowns (e.g., leak size or location) are extracted from transient traces (Che et al., 2019; Duan an Lee, 2016; Keramat et al., 2019; Kim, 2017; Louati et al., 2020; Liggett and Chen 1994; Meniconi et al., 2013 and 2021; Pan et al., 2021; Sun et al., 2016; Wang and Ghidaoui, 2018). These traces are usually observed on the piezometric heads that are collected at specific locations, as demonstrated in many previous studies (Covas, et al., 2005; Capponi, et al., 2020; Keramat and Haghighi, 2014; Meniconi, et al., 2012 and 2016; Pan, et al., 2020). Consequently, the transient signals collected from a few sections are supposed to render system properties. However, this approach is ineffective for extensive properties like friction and pipe-wall viscoelasticity. In other words, the effect of these factors has distinct traces throughout the pipe, which in turn indicates that the knowledge acquired from one specific location cannot fully characterize a system (Duan et al. 2017b).

In this circumstance, Karney (1990) proposed the transient energy analysis (TEA) and derived the corresponding formulations from the one-dimensional water hammer equations. The TEA views the transient phenomenon from a different angle, in which the state of the entire pipeline at each time is summarized by one quantity. Consequently, the energy approach performs like an amplification tool to capture latent information hidden in the transient trace to enhance its observability. In other words, the energy diagram renders information about the system as a whole rather than at some specific locations (Karney, 1990; Karney, et al., 2014; Lee, 2013; Duan, et al., 2017b). For example, Duan et al. (2010b) used the TEA approach to study the retarded behavior of the viscoelastic pipes and understood bidirectional energy transmission between the pipe wall and the contained fluid.

Beyond that, TEA is also used to evaluate the performance of different influential factors and developed transient solvers. For example, Duan et al. (2017b) compared the performance of two unsteady friction models, namely, the instantaneous acceleration-based (IAB) (Brunone, et al., 1995 and 2008) and the weighting function-based model (WFB) (Vardy and Brown, 1995, 2003 and 2004) from the energy point of view and found that the WFB model has a better performance in predicting both amplitudes and phase in a transient simulation. Besides, Lee (2013) used this approach to evaluate the linearization error in frequency response models (FRMs) of transient waves through energy phase diagrams. Ranginkaman et al. (2019) conducted a similar research method to validate their proposed virtual valves methods in reducing the linearization errors of FRMs.

In any transient event, energy transfer and exchange is the driving force for forming and maintaining the oscillations. Various forms of energy are generated and evolved differently during transients, so quantifying and characterizing them in the system can deepen the understanding of a transient. Furthermore, the energy transfer due to the time lag between imposed pressure force and the resulting strain in viscoelastic pipes is not addressed so far. Because these pipes are made of polymers such as Oriented Polyvinyl Chloride (PVC-O) and High-Density Polyethylene (HDPE), which have a long-chain molecular structure, their mechanical response lags behind the imposed stresses producing a significant damping effect on a pressure surge (Roberts, 1998, Wineman, et al., 2000, Pezzinga, et al., 2014). Although the energy behavior of viscoelasticity and the importance of different influential factors on the pressure damping have been investigated in previous studies (Duan et al., 2010a and 2010b), they lack a systematic investigation of different energy terms and comparison of various viscoelastic systems, which form the key scope of this research.

The notion of transient energy may even shed light on ways to harvest energy from pipe networks in the near future. As another motive, the energy dissipation mechanism of viscoelasticity (the energy storage and release over time) allows for using them as energy dissipators in pipe systems (Ben Iffa and Triki, 2019), so that such TEA studies are wanted.

This paper aims to investigate the energy exchange phenomenon during a transient event in viscoelastic pipeline systems, considering both steady and unsteady friction effects through deriving the energy formulations directly from the governing equations. Two types of viscoelastic pipes – PVC-O and HDPE pipelines – are applied to investigate the energy phase diagrams and energy variations over time. The importance of influential factors (including steady and unsteady friction and viscoelasticity) in the system are also systematically investigated subject to the various system conditions.

Methodology of the Investigation

Energy relations for pipe flow transients

A typical water supply pipeline system with a reservoir-pipeline-valve (RPV) configuration is considered as depicted in Fig. 1. The desired energy equation of this pipeline system can be directly derived by integrating the mass and momentum equations. Specifically, in the case of an isothermal elastic pipe (Karney, 1990), it yields:

$$\begin{aligned}\frac{\rho A g^2}{2a^2}\frac{d}{dt}\int_0^L H^2(x,t)dx + \frac{\rho}{2A}\frac{d}{dt}\int_0^L Q^2(x,t)dx + \frac{4}{D}\int_0^L \psi_w Q(x,t)dx \\ + \rho g\left[H(L,t)Q(L,t) - H(0,t)Q(0,t)\right] = 0\end{aligned} \tag{1}$$

in which H = piezometric head ($\rho g H$ = gauge pressure); g = gravitational acceleration; ρ = fluid density; Q = discharge rate; D = internal diameter of the pipe; L = length of the pipe; x = position coordinate along the pipe ranging from 0 to L; t = time coordinate; A = area of the pipe; a = elastic wave speed; f = frictional factor which is calculated based on the Blasius formula (f

$= 0.3164/(\mathrm{R}_0)^{0.25}$) in this study according to Brunone and Berni (2010); $\mathrm{R}_0 = \rho D V_0/\nu$ = initial Reynolds number; ν = kinematic viscosity; $\psi_w = \psi_{sw}+\psi_{uw}$ = shear stress with ψ_{sw} = steady-state component and ψ_{uw} = unsteady-state component, given by (Duan, et al., 2018):

$$\psi_{sw} = \frac{\rho f}{8A^2} Q(x,t)\left|Q(x,t)\right|; \quad \psi_{uw} = \frac{4\rho\nu}{DA}\int_0^t W(t-t')\frac{\partial Q(x,t')}{\partial t'}dt'; \tag{2}$$

in which $W(t) = \dfrac{D}{4\sqrt{\nu}}\dfrac{e^{-\lambda t}}{\sqrt{\pi t}}$ = weighting function with $\lambda = \dfrac{(0.54\nu \mathrm{R}_0^{\log_{10}(\frac{14.3}{\mathrm{R}_0^{0.05}})})}{D^2}$ being a lumped coefficient for transient diffusion (Vardy and Brown, 1995, 2003 and 2004).

In the case of a viscoelastic pipe, the continuity equation has an additional term to capture the mass balance during the retarded pipe expansion and contraction (Duan et al., 2010b). This will form another term in the isothermal energy equation for a viscoelastic pipe (the last term) in comparison to the elastic energy counterpart provided in Eq. (1):

$$\begin{aligned}&\frac{\rho A g^2}{2a^2}\frac{d}{dt}\int_0^L H^2(x,t)dx + \frac{\rho}{2A}\frac{d}{dt}\int_0^L Q^2(x,t)dx + \rho g\left[H(L,t)Q(L,t) - H(0,t)Q(0,t)\right] + \\ &\frac{4}{D}\int_0^L \psi_w Q(x,t)dx + \frac{\alpha A D \rho^2 g^2}{e}\int_0^L H(x,t)\left\{\begin{array}{l}\left[H(x,t)-H(x,0)\right]\sum_{k=1}^{N}\dfrac{J_k}{\vartheta_k} - \\ \sum_{k=1}^{N}\int_0^t\left[H(x,t-t')-H(x,0)\right]\dfrac{J_k}{\vartheta_k^2}e^{-\frac{t'}{\vartheta_k}}dt'\end{array}\right\}dx = 0\end{aligned} \tag{3}$$

in which α = pipe constraint coefficient, J = creep compliance, and ϑ = retardation time of viscoelastic pipe wall deformation.

Equations (1) and (3) show the energy relationship between elastic energy (also termed as internal energy in the literature (Duan et al. 2010b; Lee, 2013), kinetic energy, and other forms of energy in elastic and viscoelastic pipes. The only difference with respect to the previous studies of TEA (Karney, 1990; Lee, 2013) is that viscoelasticity is considered and compared, and the energy exchange mechanism of viscoelasticity (storage, release, and dissipation), which causes the transient energy attenuation is discussed below.

Different forms of transient energy

From Eqs. (1)-(3), the transient energy in a pipeline can be divided into different forms (Duan et al., 2010; Karney, 1990; Lee, 2013): (i) energy of elasticity (elastic energy), (ii) kinetic energy, (iii) energy entry/exit through the boundaries, (iv) energy corresponding to the frictional mechanism, and (v) energy associated with the viscoelastic behavior. These different energy forms of a transient pipe flow system are defined and elaborated as follows.

(1) Instantaneous energy of elasticity:

$$E_p(t) = \frac{\rho A g^2}{2a^2}\int_0^L H^2(x,t)dx \tag{4}$$

noting that when the energy from boundaries is ignored, the steady-state energy should be deducted in the elastic energy; thus, Eq. (4) is converted to the net elastic energy as:

$$\tilde{E}_p(t) = \frac{\rho A g^2}{2a^2}\int_0^L \left[H(x,t) - H_0\right]^2 dx \tag{5}$$

(2) Instantaneous kinetic energy:

$$E_k(t) = \frac{\rho}{2A}\int_0^L Q^2(x,t)dx \tag{6}$$

(3) Energy exchange through boundaries:

$$E_{\text{inout}}\big|_{t_1}^{t_2} = \int_{t_1}^{t_2} \rho g\left[H(L,t)Q(L,t) - H(0,t)Q(0,t)\right]dt \tag{7}$$

in which t_2-t_1 = the time duration of the investigation. In particular, a positive value of E_{inout} means that energy flows out of the system, while a negative value of E_{inout} means energy streams into the system.

(4) Energy form of frictional effect:

$$E_f\big|_{t_1}^{t_2} = \frac{4}{D}\int_{t_1}^{t_2}\int_0^L \psi_w Q(x,t)dxdt \tag{8}$$

where considering different frictional components in transient pipe flows, Eq. (8) is further divided into the steady friction (denoted as E_{SF}) and unsteady friction (denoted as E_{UF}):

$$E_f\big|_{t_1}^{t_2} = E_{SF}\big|_{t_1}^{t_2} + E_{UF}\big|_{t_1}^{t_2} \tag{9-a}$$

$$E_{SF}\Big|_{t_1}^{t_2} = \frac{\rho f}{2DA^2}\int_{t_1}^{t_2}\int_0^L \left|Q(x,t)\right|^3 dxdt; \tag{9-b}$$

$$E_{UF}\Big|_{t_1}^{t_2} = \frac{4\pi\rho\nu}{A^2}\int_{t_1}^{t_2}\int_0^L \left[\int_0^t W(t-t')\frac{\partial Q(x,t')}{\partial t'}dt'\right] Q(x,t)dxdt; \tag{9-c}$$

(5) Energy form of the retarded viscoelastic behavior:

$$E_{VE}^{p}\Big|_{t_1}^{t_2} = \frac{\alpha AD\rho^2 g^2}{e}\int_{t_1}^{t_2}\int_0^L H(x,t)\left\{\begin{array}{l} \left[H(x,t)-H(x,0)\right]\sum_{k=1}^{N}\frac{J_k}{\vartheta_k} - \\ \sum_{k=1}^{N}\int_0^t\left[H(x,t-t')-H(x,0)\right]\frac{J_k}{\vartheta_k^2}e^{-\frac{t'}{\vartheta_k}}dt' \end{array}\right\} dxdt \tag{10}$$

The Eqs. (3)-(10) calculate different forms of energy in any transient system. It is worth noting that the positive values of Eqs. (8)-(10) represent energy dissipation, while the negative values stand for the energy conversion from a specific factor (e.g., pipe viscoelasticity) to the fluid.

The total mechanical energy defined in the following, which is the sum of kinetic and elastic energy, is usually used for analyzing the energy variations in a system:

$$M(t) = E_p(t) + E_k(t) \quad \text{or} \quad \tilde{M}(t) = \tilde{E}_p(t) + E_k(t) \tag{11}$$

in which M = total mechanical energy and $\tilde{M}$ = total net mechanical energy.

The contribution of each energy form

The pipe system's energy of different influential components (including the steady, unsteady, and pipe wall viscoelasticity) can be calculated from Eqs. (8)-(10); nevertheless, their respective values are now converted to proportions to provide a pragmatic comparison of different cases or different components in the same system. The proportions of dissipated energy by different factors in the system can be defined as:

$$\gamma_{factor} = \frac{E_{factor}\Big|_{t_1}^{t_2}}{E_{VE}\Big|_{t_1}^{t_2} + E_{UF}\Big|_{t_1}^{t_2} + E_{SF}\Big|_{t_1}^{t_2}} \times 100\% \tag{12}$$

in which γ = percentage of energy dissipation due to a specific factor; "*factor*" stands for an influential factor in the evaluation that herein can be replaced by *SF*, *UF*, or *VE*.

The essential idea of the energy evaluation is to accumulate the transient event characteristics that magnify the dominant components and facilitate understanding their contribution and importance. Such a summation may be implemented over time at each discrete section of the pipe, that is, to integrate the dissipated energy per unit length at each section x:

$$u_{SF}(x)\,|_{t_1}^{t_2} = \frac{\rho f}{2DA^2}\int_{t_1}^{t_2}\left|Q(x,t)\right|^3 dt; \tag{13-a}$$

$$u_{UF}(x)\,|_{t_1}^{t_2} = \frac{4\pi\rho\nu}{A^2}\int_{t_1}^{t_2}\left[\int_0^t W(t-t^{'})\frac{\partial Q(x,t^{'})}{\partial t^{'}}dt^{'}\right]Q(x,t)dt; \tag{13-b}$$

$$u_{VE}(x)\,|_{t_1}^{t_2} = \frac{\alpha AD\rho^2 g^2}{e}\int_{t_1}^{t_2}\left[H(x,t)\left\{\begin{array}{l}\left[H(x,t)-H(x,0)\right]\displaystyle\sum_{k=1}^{N}\frac{J_k}{\vartheta_k}- \\ \displaystyle\sum_{k=1}^{N}\int_0^t\left[H(x,t-t^{'})-H(x,0)\right]\frac{J_k}{\vartheta_k^2}e^{-\frac{t^{'}}{\vartheta_k}}dt^{'}\end{array}\right\}\right]dt \tag{13-c}$$

where $u(x,t)$ = instantaneous energy dissipated per unit length at x. It is worth noting that considering Eqs. (9), (10), and (13), the following relations hold:

$$\begin{array}{l} E_{SF}\,|_{t_1}^{t_2} = \dfrac{\rho f}{2DA^2}\displaystyle\int_{t_1}^{t_2}\int_0^L\left|Q(x,t)\right|^3 dxdt = \dfrac{\rho f}{2DA^2}\int_0^L\int_{t_1}^{t_1}\left|Q(x,t)\right|^3 dtdx = \int_0^L u_{SF}(x)\,|_{t_1}^{t_2}\,dx; \\ E_{VE}\,|_{t_1}^{t_2} = \displaystyle\int_0^L u_{VE}(x)\,|_{t_1}^{t_2}\,dx; \qquad E_{UF}\,|_{t_1}^{t_2} = \int_0^L u_{UF}(x)\,|_{t_1}^{t_2}\,dx \end{array} \tag{14}$$

The defined TEA can be performed for any specific transients to evaluate different energy forms. For example, the energy terms may be assessed at any arbitrary moment t when the limits of the definite time integration in equations are set to $t_1 = 0$ and $t_2 = t$.

Energy Relations Verification and Numerical Applications

Before numerical applications, the derived energy forms and proposed measures are first verified for elastic and viscoelastic systems under idealized system and flow conditions. The results allow for the comparison and investigation of different influential factors.

System specifications for the verification

In the verification, the code performance is verified through traditional numerical models and systems, including elastic and viscoelastic pipe systems with the same configuration and initial conditions. The investigated RPV system consists of a 300 m elastic/viscoelastic pipe with D = 0.06 m and e = 0.006 m, where the reservoir head is maintained at about 20 m during the transient. The initial discharge rate (Q_0) is 1.12 L/s which corresponds to the Reynolds number of $R_0 = 2.7\times10^{4,}$ which can cause a significant pressure surge in the pipeline. A step input generates the transient, that is $Q(L,0+) = 0$ L/s. For such a transient event, no energy flows in or out of the system from the downstream boundary so that the energy in the system is dissipated by the work at the upstream boundary, the frictional effect, and the viscoelastic effect. It is convenient to evaluate each energy form and energy conservation of the numerical calculation in such a system. The pressure head and flow rate of different energy forms are extracted from the Method of Characteristics (MOC) solver (Chaudhry, 2014; Duan et al., 2020). In the MOC model, the time interval (Δt) is set to 0.005 s, which is quite small to ensure the accuracy of numerical simulation. The wave speed of the elastic pipeline is 1000 m/s, while that of the viscoelastic pipeline is 385 m/s. A two-element K-V model is applied to mimic the retarded responses of the viscoelastic pipe behavior, whose fixed parameters are J_1 = 6 GPa^{-1} , J_2 = 16 GPa^{-1}, ϑ_2 = 0.06 s and ϑ_1 = 0.4 s.

Investigation of energy relations

The effectiveness of the derived equations and corresponding computations are verified here. The variations of different energy forms (M, E_p, and E_k) in elastic and viscoelastic systems are shown in Fig. 2. In each scenario, three situations are simulated: (i) frictionless, (ii) steady friction, and (iii) both steady and unsteady friction. The energies are normalized by initial total net energy ($\tilde{M}_0$), and the time is normalized by the fundamental wave period ($4L/a$).

The results of Fig. 2 show that the energy dissipation has different patterns for systems with different influential factors. In the elastic pipeline (either frictionless or with friction), it is known that the flow will be nearly uniform along the pipeline at two specific time moments (namely, L/a and $3L/a$) within any period ($4L/a$) (Wylie et al., 1993). As a result, the value of

E_k will be minimum while $\tilde{E}_p$ will peak at L/a and $3L/a$ s in a period. This result can also be reflected in Fig. 2(a-c), thus validating the calculation. However, Figs. 2(d-f) indicate a significant creep behavior ("shifting") on the kinetic and elastic energy oscillations in the polymeric pipes characterized by the convolution integrals so that the time moments when E_k or $\tilde{E}_p$ peaks in a wave period are skewed. This notion is also referred to as the expansion effect seen in several previous studies (e.g., Covas et al. 2005; Ben Iffa and Triki, 2019).

The case of Fig. 2(f) is taken to inspect the total energy variation during a transient event. Specifically, the results of the first 25 periods are used in the TEA to roughly present the whole transient process (i.e., from the initial steady-state to the final new "steady" state). The results are shown in Fig. 3, in which the solid line indicates the normalized energy change with time due to the four factors (energy supplied by the upstream boundary, steady friction, unsteady friction, and viscoelasticity), and the dashed line refers to the normalized total energy difference between initial steady and final "steady" states (i.e., the dissipated energy during the entire process). In particular, the "negative energy dissipation" at the initial state is mainly due to the energy supplied from the upstream reservoir. Thereafter, the energy dissipation oscillates with time due to the energy exchange mechanisms, i.e., dissipation, storage, and release (Duan et al. 2010b and 2017b). It finally converges to the total dissipated energy of the system. These results qualitatively confirm the validity of the derived energy relations and computations.

Settings for numerical tests

In the context of the TEA for elastic pipes, the energy phase diagram is helpful to analyze and summarize the system state and behavior. In the referred studies (e.g., Duan et al., 2010b; Karney, 1990; Kung and Yang, 1993; Meniconi et al., 2014), a finite time for the valve maneuver is adopted to excite the system and generate transients. In such a case, different paths are achieved corresponding to different closure durations. Suppose a resonating excitation (e.g., with the fundamental water hammer frequency) is applied at the valve boundary, then the resulting flow transients will be oscillatory, which produces circular energy diagrams, as shown in former studies (Lee 2013; Ranginkaman et al. 2019). Although such an oscillatory valve maneuver does not contain as many frequencies as finite-time valve maneuvers, Lee (2013) has pointed out that the fundamental frequency is enough to characterize any system. Thus, an oscillatory valve maneuver is adopted herein for the system characterization via the TEA.

The transient system under consideration is a RPV system (as shown in Fig. 1), that is excited by a sinusoidal change to the dimensionless valve opening coefficient (τ) of the downstream valve for producing oscillatory perturbations:

$$\tau = \tau_0 + \Delta\tau \sin(\omega_f t) \tag{16}$$

in which τ = dimensionless valve opening coefficient; τ_0 = initial dimensionless valve opening coefficient; $\Delta\tau$ = dimensionless magnitude of the valve oscillation; ω_f = oscillatory frequency. Different magnitudes of $\Delta\tau$ generate transients of different intensities at a specific frequency. The system response at the fundamental frequency (the wavenumber $n^f = 1$) and other resonant frequencies (n^f =3, 5, 7, …) are investigated for elastic and viscoelastic pipeline systems with the same configuration (Table 1). The flow rate is Q_0 = 0.56 L/s for all tested systems, and the valve loss coefficients are $K = (2g\Delta H_V A^2)/Q^2$, in which the ΔH_V is the head difference across the valve. The loss coefficient of the valve K = 9900 is applied for all systems meaning that the tested systems are valve-dominated (Lee, 2013) so that over 98% of the head is lost across the valve. The main difference between elastic and viscoelastic pipes is their elastic modulus and response time, leading to different wave speeds. From practical applications, the wave speed of elastic pipes is about three to four times higher than that of viscoelastic pipes (say about 900-1200 m/s in elastic pipes versus 250-400 m/s in viscoelastic pipes, Chaudhry, 2014). Two different viscoelastic materials, namely PVC-O and HDPE, are applied as the pipe wall in the investigation. An example of these two pipeline systems in the Water Engineering Laboratory, University of Perugia, Italy is shown in Fig. 4. The retardation times and creep coefficients of the two materials are provided in the figure based on the results of previous works (e.g., Ferrante, 2021, Ferrante and Capponi, 2018); the wave speed of the elastic pipe is 1000 m/s.

Application Results and Discussion

The numerical tests are conducted for the illustrated settings, and the corresponding energy analysis results are presented in this section.

Energy phase diagram of elastic and viscoelastic systems

The energy analysis is conducted by changing the valve opening coefficient τ with different magnitudes (τ) at the fundamental water hammer frequency (= the first resonant frequency) for the three referred pipe systems. The fundamental frequency of the viscoelastic pipe system is the first resonant frequency of the system, i.e., the frequency corresponding to the first peak of the frequency response diagram. In each system, three cases, including frictionless (quantities without subscript), only steady friction (quantities with subscript "SF"), and both steady and unsteady friction (quantities with subscript "*F*"), are investigated. The pressure head and discharge oscillations are used in Eqs. (4) and (6) for kinetic and elastic energy calculations. Figs. 5(a-c) compare the variations of the dimensionless kinetic and elastic energy under different conditions, where $E_p^* = E_p - E_{p0}$, and $E_k^* = E_k - E_{k0}$ (the subscript "0" stands for the values at the steady-state). From Fig. 5(a), the results of the elastic pipe for small valve perturbations ($\Delta\tau$ = 0.1) are elliptical, while those for relatively large $\Delta\tau$ tend to deform significantly. Similar results for the PVC-O and HDPE pipes are shown in Figs. 5(b-c), respectively. It is worth noting here that the results of Fig. 5 suggest that under the same flow and system conditions, the kinetic energy variation (≈ flow rate change in the pipeline) in elastic systems is smaller than that in viscoelastic systems, so the influence of the frictional effect is unapparent compared with the studied viscoelastic systems.

Furthermore, the results of different effects (elastic and viscoelastic effects, steady and unsteady frictional effects) in Fig.5 show that the steady friction, unsteady friction, and pipe wall viscoelasticity mainly affect the size of the energy phase diagram, while the shape of the diagram is primarily influenced by the amplitude of the excitation at a specific frequency. More specifically, the size of an energy phase diagram reflects the total energy of a system. Once the analysis includes frictional or viscoelastic effects, less energy will remain in the system, so that the size of the energy phase diagram will decrease from the original frictionless case.

On the other hand, the shape of an energy phase diagram reflects the flow state/rate along the pipeline. In a relatively small-amplitude oscillation case (e.g., $\Delta\tau = 0.1$ in the study), the oscillation only changes the magnitude of the flow rate, and flow direction along the pipeline does not change. In this condition, the kinetic and elastic energy will oscillate periodically like a trigonometric function with the same angular frequency (as shown in Fig. 6), thereby forming a closed circular/elliptical shape at the steady oscillatory condition. However, the flow direction near the upstream boundary tends to reverse while the flow keeps flowing out at the downstream valve at large perturbation conditions (e.g., $\Delta\tau > 0.4$ in the study). Thus, the kinetic energy will increase rather than decrease at valleys in the energy curve (as shown in Figs. 6(d) and (f)). This is the reason why the large perturbation can shape the energy phase diagram in Fig. 5. A similar phenomenon is also found in publications (Lee, 2013; Ranginkaman et al., 2019).

Energy exchange inside the pipeline and at boundaries

The previous section revealed that the energy diagram can be affected by different factors in a system. This section serves to provide the manifestations of various factors (including the viscoelastic behavior of the pipe wall, the steady and unsteady friction, and energy transfer through boundaries) on the energy content. To this end, Eqs. (7)-(10) are utilized to evaluate the energy dissipation of these influential factors and demonstrate their relative significance during transients. For a fair comparison, all the energy results are normalized by E_{k0}.

It has been evidenced in the literature that the contribution of viscoelasticity to the energy exchange and dissipation mainly depends on the type of the material and pressure head variations (see Eq. (10)), whereas the frictional energy leans on the flow characteristics (e.g., Duan et al., 2010a and 2010b). For the steady friction, the flow rate is a influential factor and for unsteady friction (e.g. in the WFB model), the history of the flow acceleration determines its contribution level as seen in the corresponding terms in Eq. (9). Accordingly, since the flow rate is perturbed by the valve, one can predict that in the case of low-intensity transients which correspond to small variations in pressure head and flow rate, the dominant effect in absorbing and dissipating the energy is caused by steady friction. Examples of this are shown in Fig. 7 in which the energy dissipated by steady friction is significantly larger than other factors. Thus, a too-small perturbation may not well represent the relations between different energy forms as observed in practice. To better demonstrate and compare each energy form, examples with a medium perturbation ($\Delta\tau = 0.4$) are selected and their energy variations are drawn in Fig. 8.

Fig. 8 clearly shows that the various energy forms have increasing or decreasing trends, and on this basis, they can be further classified into two categories. One involves the energy forms that eventually dissipate the energy like E_{SF}, E_{UF}, and E_{VE}^{p}, and the other like E_{inout} contributes to supply or exhaust the energy through boundaries.

In the simulation, the transient and energy transfer in the pipeline is caused by the change of the valve opening coefficient, and no energy/flow flows into the system from the valve in the steady oscillatory condition. The only boundary through which the energy is supplied is the reservoir. Depending upon the fundamental water hammer period, the upstream reservoir supplies or absorbs energy periodically leading to a quite fluctuating curve compared with other energy forms as seen in Fig. 8. Under the oscillatory flow condition, the transient wave propagates from the downstream to the upstream, causing $E_{\mathrm{inout}}/E_{k0}$ to fluctuate, as seen in Fig.8. Among all the tested cases, the frictionless elastic case (i.e., Fig. 8(a)) is a special one as there are no factors dissipating energy in it. Thus, the fluctuation of $E_{\mathrm{inout}}/E_{k0}$ is stable after achieving a steady oscillatory condition as the energy from the upstream reservoir will compensate for the energy that flows out from the downstream valve. In the remaining cases, because of the energy dissipation, $E_{\mathrm{inout}}/E_{k0}$ shows a decreasing trend revealing that the energy flowing into the system from the upstream boundary can compensate for the dissipated energy. Besides, it is notable that the opposite trend of the initial stages of the E_{inout} for the elastic and viscoelastic systems is due to the different wave speeds in these two kinds of systems.

For the remaining energy forms (e.g., E_{SF}/E_{k0}, E_{UF}/E_{k0}, and E_{VE}^{p}/E_{k0}), they all show an increasing trend with time, revealing that they all dissipate energy. Although the magnitude of $\Delta\tau$ attains 0.4, the energy dissipated by steady friction is still dominant in these cases. Compared with the oscillations of other energy forms, E_{SF}/E_{k0} shows a stair-like pattern suggesting that steady friction only dissipates energy which can also be evidenced by Eq. (9). This is different from the effect of unsteady friction and viscoelasticity in the system, as they not only dissipate energy but also exchange energy via fluid acceleration (inertia) or fluid-pipe interactions, as deduced via the changing rates of E_{SF}/E_{k0}, E_{UF}/E_{k0}, and E_{VE}^{p}/E_{k0} with time in Fig. 9. The results reveal that the dissipation rate of steady friction is always positive, distinguishing the different nature of skin friction from unsteady friction and viscoelasticity.

The unsteady friction-induced energy storage mechanisms may be physically interpreted by vorticities generated due to varying velocity profiles which can affect the mean velocity and hence transform to other energy forms. The significance of this phenomenon can be quantified by the ratio of radial diffusion timescale to the pressure wave timescale (Duan et al. 2010). In another perspective, the “transient” process can be divided into the accelerating and decelerating flow stages. The unsteady friction hinders the flow deceleration in the decelerating stage, thereby maintaining the original flow state. In this circumstance, a negative dissipation rate is caused, which can be regarded as energy storage by unsteady friction. After that, the preserved energy will be dissipated/released into the accelerating stage, meaning that the total energy dissipation depends on the integral effect of both flow stages. Meanwhile, a negative dissipation rate of unsteady friction during the deceleration stage of the transient (as confirmed in Duan et al., 2017b) is also found here, which is almost opposite to that of viscoelasticity (as indicated in Duan et al., 2010b). As the flow accelerates and decelerates periodically, the dissipation rates of unsteady friction and viscoelasticity will show a periodical energy transfer behavior between the pipe wall and the contained fluid, which is consistent with the findings of previous studies (Duan et al., 2010b; Duan et al., 2017b).

Relative importance of different influential factors

Although the results of Figs. 7 and 8 show that the contribution of the steady friction is dominant, the influence of different energy forms highly depends on the magnitude of the transient waves. Furthermore, the unsteady friction and pipe wall viscoelasticity have significant frequency-dependent behavior (Duan, et al., 2012; Gong, et al., 2018a; Louati, et al. 2020; Lee, 2005). This section will discuss the impact of the valve perturbation magnitude and frequency on the energy dissipation caused by frictional effect and viscoelasticity. The magnitude of $\Delta\tau$ varies from 0.02 to 0.8, and the 1st to 7th resonant peak frequencies (which is represented by the wavenumber "n^f" in the following figures) are used to excite the viscoelastic systems. The duration of the energy calculation ($t_2 - t_1$) is $60L/a$ starting from (t_1 =) $24L/a$ as the tested systems have achieved a steady oscillatory condition in this interval.

Fig. 10 reveals that steady friction dissipates a considerable amount of energy in all cases, although its influence decreases with the transient intensity and excitation frequencies. In particular, over 80% of the energy is attenuated by steady friction at relatively small fluctuations (e.g., $\Delta\tau$ <0.06), suggesting that the influence of unsteady friction and viscoelasticity is negligible for weak transients (with relatively small transient intensity). By contrast, the impact of unsteady friction and viscoelasticity increases with the oscillating amplitude ($\Delta\tau$). However, because of different material properties, the consequence of unsteady friction or viscoelasticity in the consideration is different. Specifically, as the PVC-O pipeline is more rigid than the HDPE pipeline (shown in Fig. 5), the influence of unsteady friction in the PVC-O pipe is comparable to that of viscoelasticity. This can be evidenced by the fact that the maximum γ_{UF} can exceed 40%, which is slightly smaller than that of viscoelasticity in the PVC-O system. By contrast, the maximum γ_{UF} is less than 20%, while γ_{VE} can reach up to more than 50% in the HDPE pipeline cases.

Another critical issue investigated here is the similarity of the viscoelastic property and unsteady friction and possible coverage of one by the other in simulations as noted in the literature (Brunone et al., 2011; Covas et al., 2005; Duan et al., 2010b; Keramat et al., 2019). The flaw of such an approach can be understood by comparing Figs. 10 (b,c), as the viscoelasticity and unsteady friction have different trends subject to different loading patterns, thereby indicating that a similar set of fitting coefficients cannot capture the two at the same time. To further clarify this fact, the energy ratio of these two properties (γ_{VE}/γ_{UF}) is plotted in Fig. 11 for the two types of pipe materials. The results reveal that this ratio is strongly frequency-dependent, so that a set of creep coefficients fitted based on one specific pipe length may significantly differ for a system with a different pipe length (Mitosek and Chorzelski, 2003; Pezzinga et al., 2016) if a proper and reliable unsteady friction model is not adopted.

Besides, a couple of conclusions can be drawn from the results of Fig.11 as follows:

(1) The ratio of γ_{VE}/γ_{UF} is not sensitive to the change of the transient intensity, as it is almost a horizontal line with the change of $\Delta\tau$. This means that the variation of E_{UF} with $\Delta\tau$ is proportional to the change of E_{VE}^{p} at the same perturbation frequency;

(2) The oscillatory frequency can significantly affect γ_{VE}/γ_{UF}, and the effect of viscoelasticity increases with rising the excitation frequency in a specific system (Duan, et al., 2010b, Gong, et al., 2018a). Specifically, more energy is dissipated by the viscoelastic effect than by the unsteady frictional effect when $n^f \geq 11$ in the

PVC-O system and the pipe wall viscoelasticity is always more important than the unsteady friction in energy dissipation for all the tested cases in the HDPE system;

(3) The influence of unsteady friction plays a more important role in a relatively rigid pipeline system. For example, at the fundamental frequency, the energy dissipated by the unsteady friction is about nine times higher than that by pipe wall viscoelasticity (corresponding to γ_{VE}/γ_{UF} ~ 0.11) in the studied PVC-O pipe system (with a more rigid pipe wall), while E_{UF} is always less than E_{VE} in the HDPE pipeline (with higher flexibility of pipe wall deformation) under the same condition.

For further and comprehensive study of energy transfer and dissipation in water-filled viscoelastic pipelines, more results of TEA along the pipeline in both single and branched viscoelastic pipe systems are provided in the supplementary material attached with this paper.

Conclusions

The transient energy analysis (TEA) in this study offers a tool capable of indicating the energy content at any moment or any location in a pipeline. Different energy forms are identified, investigated, and discussed to recognize the energy transfer during transients. The established oscillatory flow reveals the variation patterns of the kinetic and elastic energies, forming a closed curve in the energy phase diagram. The analysis of the results under different conditions suggests that the energy dissipation amount alters the size of the curve while the intensity of the transient decides the shape of the diagram. Moreover, the analysis of different energy forms reveals that steady friction only attenuates energy, while unsteady friction and pipe wall viscoelasticity both preserve and dissipate energy, demonstrating their bidirectional energy transmission during a transient event.

Extensive numerical tests reveal that the effect of steady friction is dominant in damping energy at small oscillations, while the proportions of energy dissipated by unsteady friction and viscoelasticity increase with the increase of the oscillating amplitudes. Further analysis shows that the relative importance (ratio) of viscoelasticity to unsteady friction is not so sensitive to the change of the oscillation amplitude but very sensitive to the frequency of the imposed oscillation, thus revealing that the damping effect of viscoelasticity increases with rising excitation frequency. This gives a practical implication that the oscillatory frequency should be low enough so that there is enough time for the viscoelastic creeping and emerging its dissipating property if a viscoelastic pipe is used as an energy dissipator. The results also indicate that the relative importance of viscoelasticity to unsteady friction depends largely on pipe material properties.

Furthermore, the spatial behavior of the energy dissipation in the single pipe system has been investigated and showed that the energy dissipation by the frictional effect decreases from the upstream boundary to the downstream end, which is opposite to that of viscoelasticity. Finally, the energy analysis in a branched system showed that both location and wave reflections of the connecting junction contribute to the energy dissipation along the pipeline.

Data Availability Statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

Acknowledgments

This research work was supported by the Hong Kong Research Grants Council (RGC) under the project no. 15200719.

List of Abbreviations

F: Frictional Effects including Steady and Unsteady Effects

FRF: Frequency Response Function

HDPE: High-Density Polyethylene

IAB: Instantaneous Acceleration-Based model

K-V model; : the Kelvin-Voigt model

MOC: Method of Characteristics

PVC-O: Oriented Polyvinyl Chloride

RPV: Reservoir-Pipeline-Valve system

SF: Steady Friction

TBADMs: Transient-Based Anomaly Detection Methods

TEA: Transient Energy Analysis

TFRMs: Transient Frequency Response Models

UF: Unsteady Friction

VE: Viscoelasticity

VVMs: virtual valves methods

WFB: weighting function-based model

References

Ben Iffa, R., and Triki, A. (2019). "Assessment of inline technique-based water hammer control strategy in water supply systems." *Journal of Water Supply: Research and Technology-AQUA*, 68(7), 562-572.

Brunone, B., Golia, U. M., and Greco, M. (1995). "Effects of two-dimensionality on pipe transients modelling." *Journal of Hydraulic Engineering*, 10.1061/(ASCE)0733-9429(1995)121:12(906), 906–912.

Brunone, B., and Golia, U.M. (2008). Discussion of "Systematic evaluation of one-dimensional unsteady friction models in simple pipelines" by J.P. Vitkovsky, A. Bergant, A.R. Simpson, and M. F. Lambert. *Journal of Hydraulic Engineering*, 134(2), 282-284.

Brunone, B., and Berni, A. (2010). Wall shear stress in transient turbulent pipe flow by local velocity measurement. *Journal of Hydraulic Engineering*, 136(10), 716-726.

Brunone, B., Cacciamani, M., and Meniconi, S. (2011). "Unsteady friction and visco-elasticity in pipe fluid transients." *Journal of Hydraulic Research*, 49(3), 402-403.

Capponi, C., Meniconi, S., Lee, P. J., Brunone, B., and Cifrodelli, M. (2020). "Time-domain Analysis of Laboratory Experiments on the Transient Pressure Damping in a Leaky Polymeric Pipe." *Water Resources Management*, 34(2), 501-514.

Chaudhry M. H. (2014). *Applied Hydraulic Transients*, Springer-Verlag, New York, USA.

Che, T. C.., Duan, H. F., and Lee, P. J. (2021). "Transient wave-based methods for anomaly detection in fluid pipes: A review." *Mechanical Systems and Signal Processing*, 160, 107874

Che, T. C., Duan, H. F., Pan, B., Lee, P. J., and Ghidaoui, M. (2019). "Energy analysis of the resonant frequency shift pattern induced by nonuniform blockages in pressurized water pipes." *Journal of Hydraulic Engineering*, 145(7), 04019027.

Covas, D., Stoianov, I., Ramos, H., Graham, N., and Maksimovic, C. (2004). "The dynamic effect of pipe-wall viscoelasticity in hydraulic transients. Part I—experimental analysis and creep characterization." *Journal of Hydraulic Research*, 42(5), 517-532.

Covas, D., Stoianov, I., Mano, J. F., Ramos, H., Graham, N., and Maksimovic, C. (2005). "The dynamic effect of pipe-wall viscoelasticity in hydraulic transients. Part II—model development, calibration and verification." *Journal of Hydraulic Research*, 43(1), 56-70.

Duan, H. F. (2016). "Sensitivity analysis of transient based frequency domain method for extended blockage detection in water pipeline systems." *Journal of Water Resources Planning and Management* , 142(4), 04015073

Duan, H. F. (2018). "Accuracy and sensitivity evaluation of TFR method for leak detection in multiple-pipeline water supply systems." *Water Resources Management*, 32(6), 2147-2164.

Duan, H .F., Che, T. C., Lee, P. J., and Ghidaoui, M. S. (2018). “Influence of nonlinear turbulent friction on the system frequency response in transient pipe flow modelling and analysis.” *Journal of Hydraulic Research* – IAHR, 56(4), 451-463.

Duan, H. F., Ghidaoui, M., Lee, P. J., and Tung, Y. K. (2010a). “Unsteady friction and visco-elasticity in pipe fluid transients.” *Journal of Hydraulic Research*, 48(3), 354-362.

Duan, H. F., Ghidaoui, M. S., and Tung, Y. K. (2010b). “Energy analysis of viscoelasticity effect in pipe fluid transients.” *Journal of applied mechanics*, 77(4).

Duan, H. F., and Lee, P. J. (2016). “Transient-based frequency domain method for dead-end side branch detection in reservoir-pipeline-valve systems”, *Journal of Hydraulic Engineering*, 142(2), 04015042

Duan, H. F., Lee, P. J., Ghidaoui, M. S., and Tung, Y.-K. (2012). “System response function–based leak detection in viscoelastic pipelines.” *Journal of Hydraulic Engineering*, 138(2), 143-153.

Duan, H. F., Lee, P. J., Che, T. C., Ghidaoui, M. S., Karney, B. W., and Kolyshkin, A. A. (2017a). “The Influence of Non-uniform Blockages on Transient Wave Behavior and Blockage Detection in Pressurized Water Pipelines.” *Journal of Hydro-environment Research*, 17, 1-7.

Duan, H. F., Meniconi, S., Lee, P., Brunone, B., and Ghidaoui, M. S. (2017b). “Local and integral energy-based evaluation for the unsteady friction relevance in transient pipe flows.” Journal of Hydraulic Engineering, 143(7), 04017015.

Duan, H. F., Pan, B., Wang, M., Chen, L., Zheng, F., and Zhang, Y. (2020). “State-of-the-art review on the transient flow modeling and utilization for urban water supply system (UWSS) management.” *Journal of Water Supply: Research and Technology—AQUA*, 69(8), 858-893.

Ferrante, M., and Capponi, C. (2018). “Comparison of viscoelastic models with a different number of parameters for transient simulations." *Journal of Hydroinformatics*, 20(1), 1-17.

Ferrante, M. (2021). "Transients in a series of two polymeric pipes of different materials." *Journal of Hydraulic Research*, 1-10.

Gong, J., Stephens, M. L., and Lambert, M. F. (2018a) "Analysis of the frequency-dependent attenuation of transient pressure waves in plastic pipes." *Proc., WDSA/CCWI Joint Conference Proceedings*.

Gong, J., Stephens, M. L., Lambert, M. F., Zecchin, A. C., and Simpson, A. R. (2018b). "Pressure surge suppression using a metallic-plastic-metallic pipe configuration." *Journal of Hydraulic Engineering*, 144(6), 04018025.

Karney, B. W. (1990). "Energy relations in transient closed-conduit flow." *Journal of Hydraulic Engineering*, 116(10), 1180-1196.

Karney, B, Malekpour, A, & Nault, J. (2014). "An Energy Approach to Studying Pipe Network Transients". *Procedia Engineering*, 89(C), 1298-1305.

Keramat, A., and Haghighi, A. (2014). "Straightforward Transient-Based Approach for the Creep Function Determination in Viscoelastic Pipes." *Journal of Hydraulic Engineering*, 140(12).

Keramat, A., Wang, X., Louati, M., Meniconi, S., Brunone, B., and Ghidaoui, M. S. (2019). "Objective functions for transient-based pipeline leakage detection in a noisy environment: least square and matched-filter." *Journal of water resources planning and management*, 145(10), 04019042.

Kim, S. H. (2017). "Multiple leakage function for a simple pipeline system." *Water Resources Management*, 31(9), 2659-2673.

Kung, C.-S., and Yang, X.-L. (1993). "Energy interpretation of hydraulic transients in power plant with surge tank." Journal of Hydraulic Research, 31(6), 825-840.

Lee, P. J. (2005). "Using system response functions of liquid pipelines for leak and blockage detection." *PhD Dissertation*, University of Adalaide, 2005

Lee, P. J. (2013). "Energy analysis for the illustration of inaccuracies in the linear modeling of pipe fluid transients." *Journal of Hydraulic Research*, 51(2), 133-144.

Liggett, J. A., and Chen, L.-C. (1994). "Inverse transient analysis in pipe networks." *Journal of Hydraulic Engineering*, 120(8), 934-955.

Louati, M., Ghidaoui, M. S., Tekitek, M. M., and Joseph Lee, P. (2020). "Wave-leak interaction in a simple pipe system." *Journal of Hydraulic Engineering*, 146(4), 04020013.

Meniconi, S., Brunone, B., Ferrante, M., and Massari, C. (2012). "Transient hydrodynamics of in-line valves in viscoelastic pressurized pipes: long-period analysis." *Experiments in Fluids*, 53(1), 265-275.

Meniconi, S., Duan, H. F., Lee, P. J., Brunone, B., Ghidaoui, M. S., and Ferrante, M. (2013). "Experimental Investigation of Coupled Frequency and Time-Domain Transient Test–Based Techniques for Partial Blockage Detection in Pipelines." *Journal of Hydraulic Engineering*, 139(10), 1033-1040.

Meniconi, S., Brunone, B., Ferrante, M., and Massari, C. (2014). "Energy dissipation and pressure decay during transients in viscoelastic pipes with an in-line valve." *Journal of Fluids and Structures*, 45, 235-249.

Meniconi, S., Brunone, B., Ferrante, M., and Capponi, C. (2016). "Mechanism of interaction of pressure waves at a discrete partial blockage." *Journal of Fluids and Structures*, 62, 33-45.

Meniconi, S., Capponi, C., Frisinghelli, M., and Brunone, B. (2021). "Leak detection in a real transmission main through transient tests: deeds and misdeeds." *Water resources research*, e2020WR027838.

Mitosek, M., and Chorzelski, M. (2003). "Influence of visco-elasticity on pressure wave velocity in polyethylene MDPE pipe." *Arch. Hydro-Eng. Environ. Mech.*, 50(2), 127–140.

Pan, B., Duan, H.F., Meniconi, S., and Brunone, B. (2021). "FRF-based transient wave analysis for the viscoelastic parameters identification and leak detection in water-filled plastic pipes." *Mechanical Systems and Signal Processing*, 146, 107056.

Pan, B., Duan, H. F. , Meniconi, S., Urbanowicz, K., Che, T., and Brunone, B. (2020). "Multistage Frequency-Domain Transient-Based Method for the Analysis of Viscoelastic Parameters of Plastic Pipes." *Journal of Hydraulic Engineering*, 146(3), 04019068.

Pezzinga, G., Brunone, B., Cannizzaro, D., Ferrante, M., Meniconi, S., and Berni, A. (2014). "Two-dimensional features of viscoelastic models of pipe transients." *Journal of*

Hydraulic Engineering, 140(8), 04014036.

Pezzinga, G., Brunone, B., and Meniconi, S. (2016). On the relevance of pipe period on Kelvin-Voigt viscoelastic parameters: 1-D and 2-D inverse transient analysis. *Journal of Hydraulic Engineering*, 142(12), 04016063.

Ranginkaman, M. H., Haghighi, A., and Lee, P. J. (2019). “Frequency domain modelling of pipe transient flow with the virtual valves method to reduce linearization errors.” *Mechanical Systems and Signal Processing*, 131, 486-504.

Roberts, A. (1998). “Standard Handbook of Environmental Engineering.” McGraw-Hill, New York.

Sun, J. L., Wang, R., and Duan, H. F. (2016). “Multiple-fault detection in water pipelines using transient time-frequency analysis.” *Journal of Hydroinformatics – IWA*, 18(6), 975-989.

Vardy, A. E., and Brown, J. M. B. (1995). “Transient, turbulent, smooth pipe friction.” *Journal of Hydraulic Research*, 33(4), 435–456.

Vardy, A. E., and Brown, J. M. B. (2003). “Transient turbulent friction in smooth pipe flows.” *Journal of Sound Vibration*, 259(5), 1011–1036.

Vardy, A. E., and Brown, J. M. B. (2004). “Transient turbulent friction in fully rough pipe flows.” *Journal of Sound Vibration*, 270(1–2), 233–257.

Wineman, A. S., and Rajagopal, K. R. (2000). *Mechanical response of polymers: an introduction*, Cambridge university press.

Wang, X., and Ghidaoui, M. S. (2018). “Pipeline leak detection using the matched-field processing method.” *Journal of Hydraulic Engineering*, 144(6), 04018030.

Wylie E. B., Streeter V. L., & Suo L. (1993). *Fluid Transients in Systems*. Prentice Hall Englewood Cliffs, NJ.