This is the accepted manuscript of the following article: Huan-Feng Duan, Bin Pan, Manli Wang, Lu Chen, Feifei Zheng, Ying Zhang; 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 1 December 2020; 69 (8): 858–893, which has been published in final form at https://doi.org/10.2166/aqua.2020.048.

State-of-the-Art Review on the Transient Flow Modelling and Utilization for Urban Water Supply System (UWSS) Management

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Abstract

In the context of smart city development and rapid urbanization worldwide, urban water supply system (UWSS) has been of vital importance to this process. This paper presents a comprehensive review on the transient flow research for the UWSS management. This review consists of two aspects as follows. The first aspect is about the development and progress of current transient theory, including transient flow models, unsteady friction and turbulence models, and numerical simulation methods. The other aspect is about the utilization and application of transient-based methods for effective UWSS diagnosis and management, including leakage, discrete and extended partial blockages, unknown branch, and other defects in water pipeline. A total of 228 publications have been reviewed and analyzed in this paper. In addition to the state-of-the-art progress and achievement of the research on transients, the advances and recommendations of future work in this field are also discussed for the development and management of next-generation Smart UWSS in the paper.

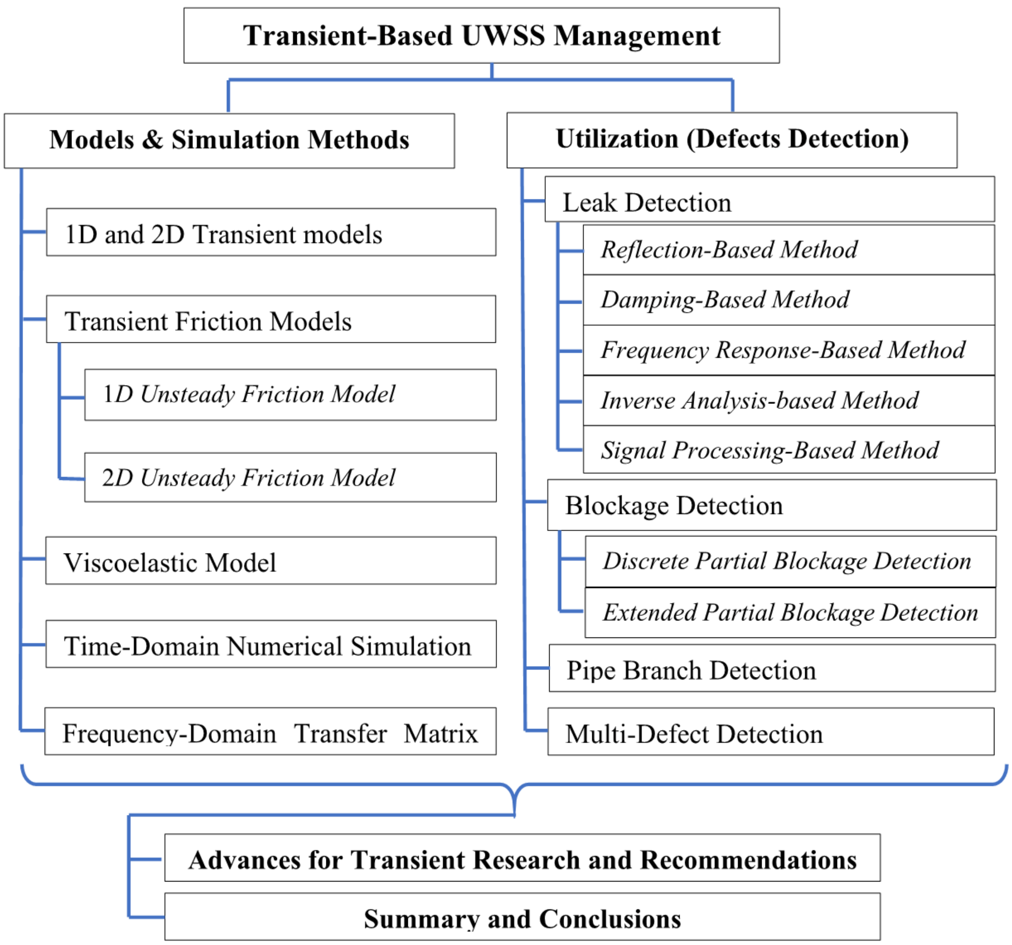
Keywords

Smart City; Smart Water; Transient Modelling and Analysis; Transient-Based Defect Detection (TBDD); Urban Water Supply System (UWSS)

Highlights

- The development and progress of current transient theory and modelling methods have been reviewed
- The transient-based utilization methods for different pipe defects detection have been summarized
- The achievement and implications of transient research for UWSS management have been discussed

Graphical Abstract



Introduction

Water supply is a basic need for society and its security and efficiency are of paramount importance to human health and economic development. At present, the urban water supply system (UWSS) is the lifeline of over 4 billion people globally, the facilitator of urban economic activities, and the pillar of modern urban civilization. However, a substantial portion of these vital systems are decades old and are plagued with deficiencies and inefficiencies (Fig. 1). For instance, pipelines in UWSS usually encounter many different problems that may affect the effectiveness of the system function and operation, such as leakage, partial blockage, ill-junction, corrosion, biofilm, deformation, cavitation, air-pocket, detachment, and so on, which are termed as pipe anomalies in this paper.

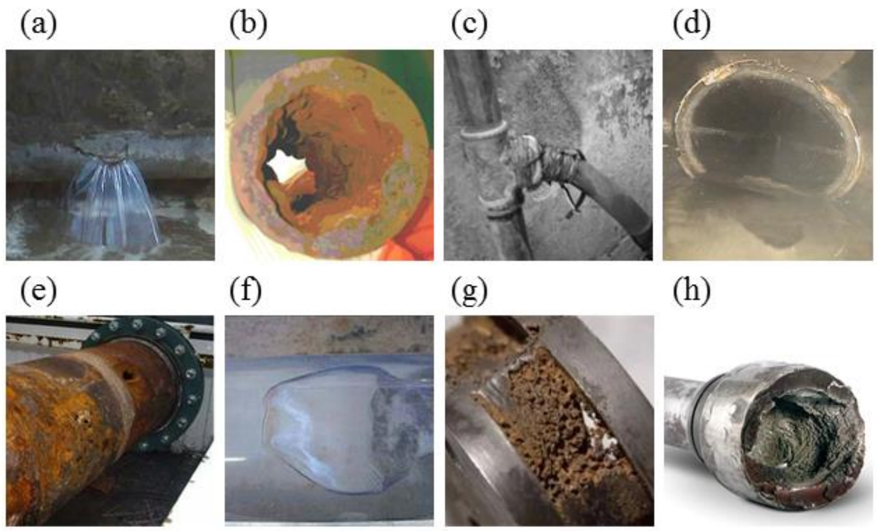


Figure 1. Different types of pipe deficiencies in UWSS: (a) leakage; (b) partial blockage; (c) ill-junction; (d) deformation; (e) corrosion; (f) air-pocket; (g) cavitation; (h) detachment

The formation and existence of pipe anomalies may result in serious problems, including (but not limited to) the reduction of flow capacity, increase of energy loss and deterioration of water quality. As a result, it has been estimated that the water loss attains to over 30% on average in the UWSSs around the world, with typical cases shown in Fig. 2 (Lai et al., 2017; Samir et al., 2017; AL-Washali et al., 2019; Liemberger & Wyatt, 2019). Moreover, the cost of energy required for pumping and supplying water in public systems is also increased significantly due to the extra water volume and energy loss from leakages and partial blockages as leakages in the pipeline cause a decrease in water pressure head to consumers and partial blockages can increase the flow velocity and head loss (Colombo & Karney, 2002). From this point of view, it is urgent to develop more advanced technologies and innovative methodologies to effectively manage and diagnose the UWSS, so as to minimize the resultant problems and wastage.

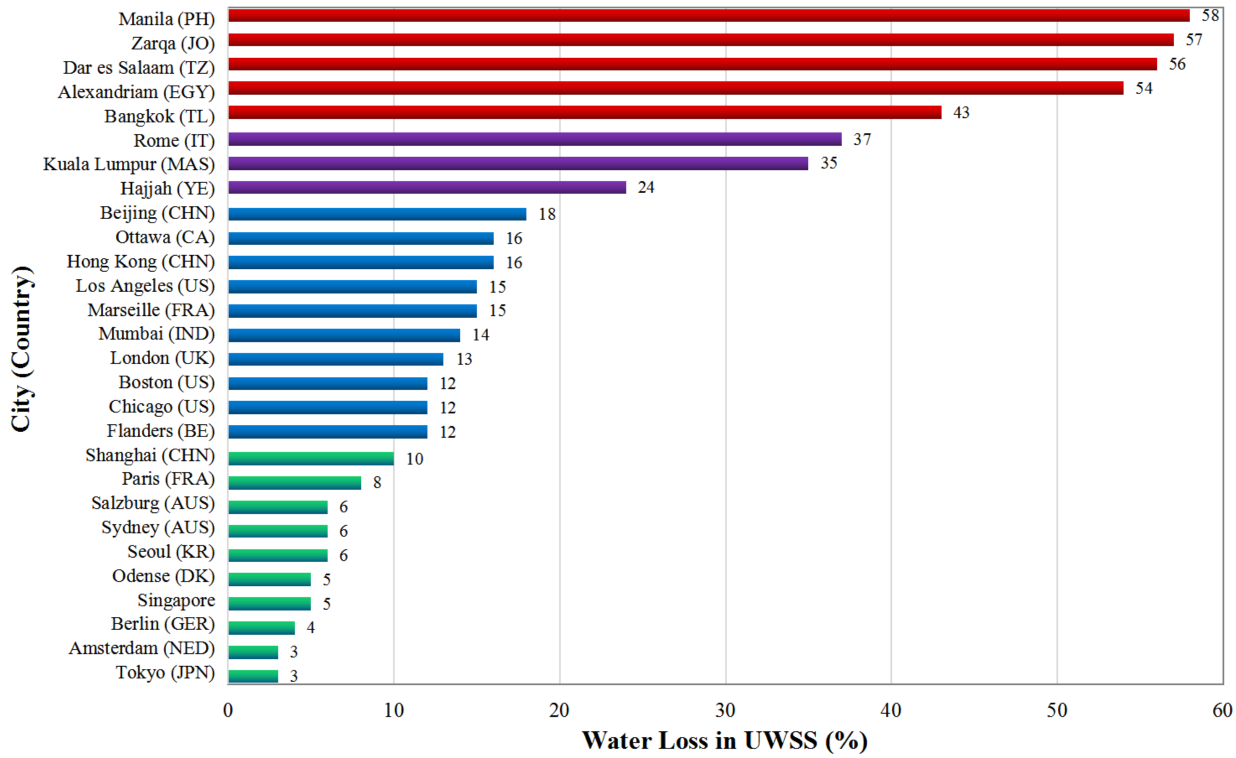


Figure 2. Water loss situation of typical UWSSs in the world

Based on various theoretical development and practical application experiences in the literature, hydraulic models and models have been found to be one of the reliable and cost-effective ways to address the current adverse situations in UWSS. To this end, this paper aims to conduct a comprehensive review on the hydraulic models for describing the highly unsteady flows (i.e., transient) that are commonly used for the effective design and management of UWSS, as well as the innovative transient-based technologies that are widely developed in recent years for the UWSS diagnosis and management. For clarity, the structure of this paper is shown in Fig. 3. The paper content starts with the introduction and illustration on the importance of transients in UWSS, followed by the two aspects of this review (modelling and utilization). Thereafter, the advances and limitations of current transient models and methods are discussed with a perspective of smart UWSS development. Finally, the key contents and findings as well as recommendations on future work are summarized in the conclusion.

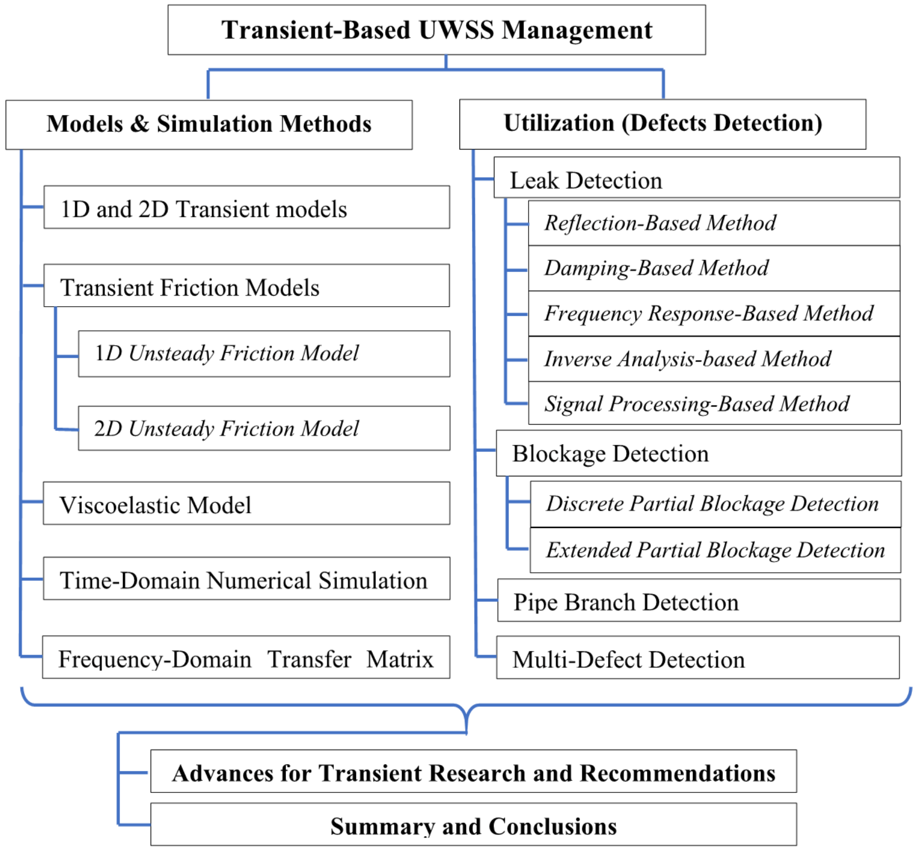


Figure 3. Structure of the review content

Importance of Transient Phenomena and Information in UWSS

The transient state of flows is variously termed waterhammer, fast transients, hydraulic transients, fluid transients, or pressure surges in the literature (Chaudhry, 2014; Wylie *et al.*, 1993). In engineering practice across a multitude of fluids systems and applications, transient flows exert decisive influences on practical aspects of engineering design and operation of pipeline systems. As a result, transient waves are formed during the transient flow states in UWSS. Transient waves are fast moving elastic shocks that travel at relatively high velocities in pipeline systems (e.g., about 1000 m/s in metallic pipes and around 400 m/s in polymeric pipes). They are generally triggered by planned or accidental events in pipe fluid systems that result in rapid changes in the pipe flow. Transient events may be caused by operations of valves, starting and stopping of pumps, variations in the supply or demand of the system fluid, and many other situations. These sudden changes in system flow require the imposition of large forces to accelerate or decelerate the fluid, and consequently are capable of inducing severe or even catastrophic pressures in the pipeline. For example, a waterhammer accident caused the hydro disaster in the Russia's biggest hydroelectric plant in 2009 (RT, 2009).

Hydraulic transients affect the structural integrity of pipelines, and this accounts for their importance in the minds and practice of design engineers. However, because they can move rapidly throughout a system, and their waveforms are modified by their propagation and reflection interactions with the pipe and its component devices, they can also be used as a potentially inexpensive and diverse source of information in integrity management applications. Transient pressure monitoring and analysis appears to hold considerable promise for estimating the state or condition of the pipeline system as it changes over time. Recently developed techniques for leak detection in water pipeline systems are utilizing the information associated with the transient damping and reflections (Colombo *et al.*, 2009; Ayati *et al.*, 2019).

In addition to the traditional water loss identification technology – leak listening that is still widely used nowadays, other commercially available technologies used for UWSS diagnosis mainly include two types from their implementation ways in UWSS: (i) intrusive methods, e.g., CCTV camera, gas tracer, infrared thermography, Smart Ball and robot (El-Zahab and Zayed, 2019); and (ii) non-intrusive methods, e.g., moisture sensor, ground penetrating radar, acoustic correlator and noise logger (Lee, 2005). Despite of the successful applications of these methods in various UWSSs, these methods are also found to be either intrusive & time consuming (e.g., the type (i) methods above) or short ranged & expensive (e.g., the type (ii) methods above) (Gupta & Kulat, 2018; Ali & Choi, 2019). Moreover, the critical situation in current UWSSs (over 30% water loss in the world) demonstrates clearly the inadequacy and inefficiency of using these methods only (Stephens, 2008; Puust et al., 2010).

Utilization of transient data for leak detection could have great practical significance since pipe leakage is a common, costly and serious water conservation and health issue worldwide. Despite that the implementation of a comprehensive pipe replacement scheme with a price tag of more than US$3.0 billion during 2000-2015 in Hong Kong (Burn *et al.*, 1999), the water loss (leakage) in its UWSS still remained at about 16% in 2016, which costs over US$1.0 billion/year (source water price and treatment expenses). Moreover, the leakage situation has presented a bounce back trend in the UWSS after the pipeline replacement according to the data information in recent years. This indicates that, from a long-term perspective, it is necessary to develop and apply a more sustainable way for solving the critical leakage situation in UWSS.

Since points of leakage also represent potential locations for contaminant intrusion, identification and control of leak locations are doubly important. Consequently, an improved understanding of transient flows in pipes is important to advancing the practical utilization of transients as a source of information and, at the same time, minimizing their damaging impacts on the physical infrastructure (Chaudhry, 2014; Wylie *et al.*, 1993; Ghidaoui *et al.*, 2005).

Transient Models and Simulation Methods

In the field of transients or waterhammer, substantial efforts have been made by various researchers and engineers for developing transient theories and models for better design, analysis and management of UWSS (Ghidaoui *et al.*, 2005). The one-dimensional (1D) models are widely investigated and commonly used for the transient system design and analysis for their advantages of efficient computation and easy implementation in practice (e.g., Chaudhry, 2014; Wylie *et al.*, 1993; Duan *et al.*, 2010a; Duan *et al.*, 2010b), while recently two-dimensional (2D) or quasi-2D models that allow to include different type of turbulence models have also been explored and applied for modelling transient pipe flows (e.g., Vardy & Hwang, 1991; Silva-Araya & Chaudhry, 1997; Pezzinga, 1999; Zhao & Ghidaoui, 2006; Duan *et al.*, 2009; Korbar *et al.*, 2014). To replicate the transient pressure attenuation due to friction damping under transient state, many types of unsteady friction (or turbulence) models in 1D and 2D forms have been developed and discussed in the transient/waterhammer literature in the past decades (e.g., Ghidaoui, 2004; Ghidaoui *et al.*, 2005; Lee *et al.*, 2013a; Meniconi *et al.*, 2014; Vardy *et al.*, 2015). These developed models and simulation schemes have been widely verified and validated through various experimental data from both laboratory and field tests. Furthermore, to extend the applicability and improve the accuracy of current transient models and methods, more complex factors in practical UWSS have been gradually investigated and included in the transient models by many researchers in this field. For example, the plastic pipe-wall deformation effect has been successfully incorporated in 1D and 2D transient models using analogous viscoelastic components, such as Kelvin-Voigt (K-V) model (e.g., Franke, 1983; Güney, 1983; Pezzinga, 1999; Covas *et al.*, 2005a; Duan *et al.*, 2010c).

For the purpose of a review, the development progress and achievement of the transient models and simulation methods commonly used for the UWSS are summarized as follows.

1D and 2D Transient Models

In pressurized water supply pipelines, the axisymmetry assumption is usually made for investigating transient pipe flows (Fig. 4), since the velocity component (momentum flux) in azimuthal direction of the pipe cross-sectional area is relatively small (Pezzinga, 1999). Therefore, in this study, the derivation of transient model starts with the 2D Navier-Stokes equations in cylindrical coordinates for compressible pipe flows (Newtonian flow) as follows (Potter & Wiggert, 1997):

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(\rho r v)}{\partial r}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=-\frac{1}{\rho}\frac{\partial P}{\partial x}-\frac{1}{\rho}\frac{\partial \sigma_x}{\partial x}-\frac{1}{\rho r}\frac{\partial(r\tau)}{\partial r} \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial r}=-\frac{1}{\rho}\frac{\partial P}{\partial r}-\frac{1}{\rho}\frac{\partial \tau}{\partial x}-\frac{1}{\rho r}\frac{\partial(r\sigma_r)}{\partial r}+\frac{\sigma_\theta}{\rho r} \tag{3}$$

where P = pressure, ρ = fluid density, σ_x, σ_r, σ_θ = normal stress excluding the pressure stress in longitudinal, transverse and angular directions, respectively, x = spatial coordinate along the pipeline, r = radial distance from pipe center, t = time, g = gravitational acceleration, u = longitudinal velocity, v = transverse velocity, and τ = shear stress.

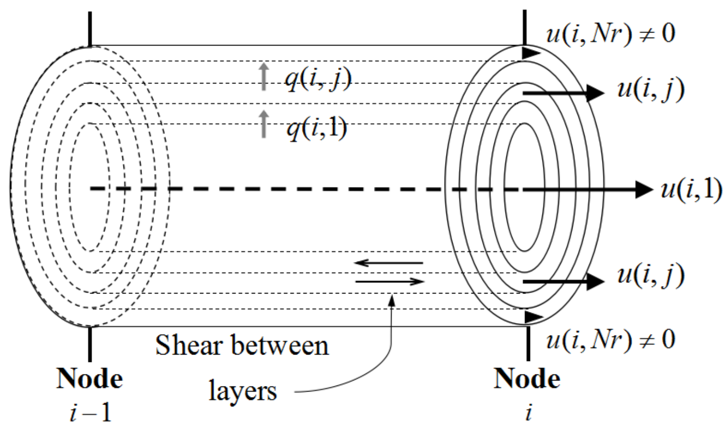


Figure 4. Sketch of axisymmetric flows in a pipe section (i = axial node number, j = radial node number, Nr = number of radial nodes; q = unit radial flow; u = axial velocity)

For simplicity, the external normal stress forces ($\sigma_x, \sigma_r, \sigma_\theta$), except the pressure force, are excluded in the following study regarding water supply pipeline problems (e.g., Pezzinga, 1999; Ghidaoui et al., 2005). Meanwhile, the wave speed during transient pipe flows can be defined as (Wylie *et al.*, 1993; Chaudhry, 2014),

$$a = \sqrt{\frac{\mathrm{d}\rho}{\mathrm{d}P} + \frac{\rho}{A}\frac{\mathrm{d}A}{\mathrm{d}P}} \tag{4}$$

By considering the relations of $A = \pi r^2$ and $P = \rho g H$ in the pipeline, Eq. (1) - Eq. (3) can be re-written as,

$$\frac{\partial H}{\partial t} + u\frac{\partial H}{\partial x} + \frac{a^2}{g}\frac{\partial u}{\partial x} + \frac{a^2}{g}\frac{1}{r}\frac{\partial (rv)}{\partial r} = 0 \tag{5}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial r}\right) = -\rho g\frac{\partial H}{\partial x} - \frac{1}{r}\frac{\partial (r\tau_l)}{\partial r} \tag{6}$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial r}\right) = -\rho g\frac{\partial H}{\partial r} - \frac{\partial \tau_l}{\partial x} \tag{7}$$

To efficiently solve momentum equations under turbulent condition by using the Reynolds-averaged method (RANS), the density-weighted-averaging (*Favre* averaging) and the ensemble-averaging are considered, respectively, as (Zhang 2002):

$$\chi = \overline{\chi} + \chi' \quad \text{and} \quad \overline{\chi} = \frac{\langle \rho\chi \rangle}{\langle \rho \rangle} \tag{8}$$

in which $\chi = H, \rho, \tau_l, u, v$ represents the variable whose quantity is to be solved; $\overline{\chi}$ = the density-weighted-averaging quantities; χ' = density-weighted-averaging pulsation quantities; and $\langle\ \rangle$= the ensemble-averaging quantity. Therefore, for different variables in waterhammer flows,

$$\langle \phi \rangle = \overline{\phi}; \langle \phi' \rangle = 0; \langle \rho\varphi \rangle = \langle \rho\overline{\varphi} \rangle = \overline{\varphi}\langle \rho \rangle; \langle \rho\varphi' \rangle = 0 \tag{9}$$

in which $\phi = u, v, H, \rho, \tau_l$; and $\varphi = u, v, H$. By taking the ensemble-averaging for Eqs. (6) and (7), and applying the relations in Eqs. (8) and (9), the following results are obtained:

$$\langle \rho \rangle\left(\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial r}\right) + \frac{1}{r}\frac{\partial\left(r\langle \rho u'v' \rangle\right)}{\partial r} = \left\langle -\rho g\frac{\partial H}{\partial x} - \frac{1}{r}\frac{\partial (r\tau_l)}{\partial r}\right\rangle \tag{10}$$

$$\langle \rho \rangle\left(\frac{\partial \overline{v}}{\partial t} + \overline{u}\frac{\partial \overline{v}}{\partial x} + \overline{v}\frac{\partial \overline{v}}{\partial r}\right) + \frac{\partial \langle \rho u'v' \rangle}{\partial x} = \left\langle -\rho g\frac{\partial H}{\partial r} - \frac{\partial \tau_l}{\partial x}\right\rangle \tag{11}$$

where τ_l is laminar component of shear stress. By incorporating Boussinesq assumption, and after rearranging terms, the results become,

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial r} = -g\frac{\partial \langle H \rangle}{\partial x} - \frac{1}{\langle \rho \rangle}\frac{1}{r}\frac{\partial\left(r\langle \tau \rangle\right)}{\partial r} \tag{12}$$

$$\frac{\partial \overline{v}}{\partial t}+\overline{u}\frac{\partial \overline{v}}{\partial x}+\overline{v}\frac{\partial \overline{v}}{\partial r}=-g\frac{\partial\langle H\rangle}{\partial r}-\frac{1}{\langle\rho\rangle}\frac{\partial\langle\tau\rangle}{\partial x} \tag{13}$$

in which $\tau = \tau_l + \tau_t$ is total shear stress; and τ_t is turbulent component of shear stress.

Considering the following scales of the quantities in typical transient pipe flows (Duan *et al.*, 2012a),

$$\begin{gathered} u=u^{*}U;v=v^{*}V;H=H^{*}H_{J};\rho=\rho^{*}\rho_{0}; \\ \tau=\tau^{*}\tau_{0};x=x^{*}L;t=t^{*}(L/a);r=r^{*}\delta \end{gathered} \tag{14}$$

where U, V, H_J, τ_0, ρ_0, L, L/a, δ = scaling orders of variables u, v, H, τ, ρ, x, t, r, with δ = unsteady boundary layer thickness; and $u^*, v^*, H^*, \tau^*, \rho^*, x^*, t^*, r^*$ = dimensionless variables. By substituting Eq. (14) into Eqs. (5), (12) and (13), it gives,

$$\frac{\partial H^{*}}{\partial t^{*}}+\frac{U}{a}u^{*}\frac{\partial H^{*}}{\partial x^{*}}+\frac{\partial u^{*}}{\partial x^{*}}+\frac{VL}{U\delta}\frac{1}{r^{*}}\frac{\partial(r^{*}v^{*})}{\partial r^{*}}=0 \tag{15}$$

$$\frac{\partial u^{*}}{\partial t^{*}}+\frac{U}{a}u^{*}\frac{\partial u^{*}}{\partial x^{*}}+\frac{VL}{a\delta}v^{*}\frac{\partial u^{*}}{\partial r^{*}}=-\frac{\partial H^{*}}{\partial x^{*}}-\frac{L\tau_{0}}{\rho_{0}Ua\delta}\frac{1}{\rho^{*}r^{*}}\frac{\partial(r^{*}\tau^{*})}{\partial r^{*}} \tag{16}$$

$$\frac{\delta V}{LU}\frac{\partial v^{*}}{\partial t^{*}}+\frac{\delta V}{La}u^{*}\frac{\partial v^{*}}{\partial x^{*}}+\frac{VV}{aU}v^{*}\frac{\partial v^{*}}{\partial r^{*}}=-\frac{\partial\langle H^{*}\rangle}{\partial r^{*}}-\frac{\delta\tau_{0}}{\rho_{0}UaL}\frac{1}{\rho^{*}}\frac{\partial\langle\tau^{*}\rangle}{\partial x^{*}} \tag{17}$$

Since U/a <<1 in typical water supply pipeline systems, the second term in both Eqs. (15) and (16) can be neglected. Note that in the transient pipe flow, the mass flux fluctuation in axial direction has to be balanced by that in radial direction and the mass storage of fluid compressibility, such that,

Axial mass influx = Radial mass outflux + Mass storage due to fluid compressibility

that is,

$$\frac{U}{L}\geq\frac{V}{\delta}\quad\text{or}\quad\frac{VL}{U\delta}\leq 1 \tag{18}$$

Therefore, the 4th term in Eq. (15) may be important in the transient pipe flows. Furthermore, it can be obtained in Eq. (16),

$$\frac{VL}{a\delta}=\frac{VL}{U\delta}\frac{U}{a}<<1 \tag{19}$$

which indicates the 3rd term in Eq. (16) can also be negligible. For the shear stress in momentum equations, considering $\tau_0 \sim k_d \rho D \frac{\partial u}{\partial t}$ yields (Ghidaoui *et al.*, 2005),

$$\frac{L\tau_0}{\rho Ua\delta} \sim k_d .$$

Previous experimental results in the literature have shown that the coefficient k_d value varies with different transient flows and waterhammer problems under investigation and has a wide range of 0.01~0.62 (Daily *et al.*, 1955; Shuy & Apelt, 1983). This indicates that the turbulent shear stress in the axial momentum Eq. (16) might be important to the transient pipe flow events. However, in radial momentum Eq. (17), it has,

$$\frac{\delta\tau_0}{\rho_0 UaL} = \frac{L\tau_0}{\rho_0 Ua\delta}\frac{\delta^2}{L^2} << 1 \tag{20}$$

Moreover, since $\delta << L$ and $V << U << a$ in pipe flows (Vardy & Hwang, 1991), one has

$$\frac{\delta V}{LU} << 1;\ \frac{\delta V}{La} << 1;\ \frac{VV}{aU} << 1$$

Therefore, the terms of inertia, convection, and shear stress in the radial momentum equation (17) can be negligible during the transient/waterhammer process. As a result, the governing equations, Eqs. (15)-(17), can be simplified as,

$$\frac{\partial H^*}{\partial t^*} + \frac{Ua}{Hg}\frac{\partial u^*}{\partial x^*} + \frac{VL}{U\delta}\frac{1}{r^*}\frac{\partial\left(r^* v^*\right)}{\partial r^*} = 0 \tag{21}$$

$$\frac{\partial u^*}{\partial t^*} = -\frac{gH}{Ua}\frac{\partial H^*}{\partial x^*} - \frac{L\tau_0}{\rho Ua\delta}\frac{1}{\rho^* r^*}\frac{\partial\left(r^*\tau^*\right)}{\partial r^*} \tag{22}$$

$$0 = -\frac{\partial\langle H^*\rangle}{\partial r^*} \tag{23}$$

Returning to the original equation forms of Eqs. (1)-(3) provides:

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial u}{\partial x} = -\frac{a^2}{g}\frac{1}{r}\frac{\partial(rv)}{\partial r} \tag{24}$$

$$\frac{\partial u}{\partial t} + g\frac{\partial H}{\partial x} = -\frac{1}{\rho r}\frac{\partial(r\tau)}{\partial r} \tag{25}$$

$$\frac{\partial H}{\partial r} = 0 \tag{26}$$

These actually are the commonly used quasi-2D transient flow models in the literature (e.g., Vardy & Hwang, 1991; Pezzinga, 1999; Zhao & Ghidaoui, 2006; Duan *et al.*, 2010d).

Furthermore, integrating Eqs. (24) – (26) throughout the cross-sectional area of pipeline, and considering the deformation of pipe-wall, provides the 1D form of transient flow model as follows:

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial U}{\partial x}+\frac{2a^2}{gR}v_R=0 \tag{27}$$

$$\frac{\partial U}{\partial t}+g\frac{\partial H}{\partial x}+\frac{\tau_w \pi D}{\rho A}=0 \tag{28}$$

where H = piezometric head; U = cross-sectional average velocity; A = pipe cross-sectional area; D = pipe diameter; τ_w = wall shear stress; v_R = radial velocity at pipe-wall due to deformation. For the 3rd term in Eq. (27), the relationship between radial velocity and pipe radial expansion is (Güney, 1983; Covas *et al.*, 2005b; Duan *et al.*, 2010d)

$$v_R(x,t)=\frac{1}{2}\frac{\partial D}{\partial t} \quad \text{and} \quad \frac{1}{D}\frac{\partial D}{\partial t}=\frac{\partial \varepsilon}{\partial t} \tag{29}$$

where ε = viscoelastic retarded strain of pipe-wall, and it equals to zero for elastic pipes.

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial U}{\partial x}+\frac{2a^2}{g}\frac{\partial \varepsilon}{\partial t}=0 \tag{30}$$

This 1D form of transient flow model in Eqs. (28) and (30) has been widely used in the study of transient flows for both viscoelastic and elastic pipelines due to the convenience of numerical implementation and the efficiency of the solution process (Wylie *et al.*, 1993; Ghidaoui *et al.*, 2005; Chaudhry, 2014).

Transient Friction Models

The expression of shear stress in the momentum Eqs. (25) or (28) is needed to close the transient models (1D or 2D). In the literature, a 1D quasi-steady wall shear stress model represented by the Darcy-Weisbach formula is commonly used in 1D models for its explicit expression and efficient calculation (Chaudhry, 2014; Wylie *et al.*, 1993)

$$\tau_w(t)=\frac{\rho f(t)|U(t)|U(t)}{8} \tag{31}$$

where *f* is the Darcy-Weisbach friction factor of pipeline.

However, when the transient flow is generated in the system, the pressure wave will distort the velocity profile and even create an inverse flow near the pipe wall, which is significantly different from steady flow. Therefore, the energy dissipation caused by shear stress is different and the results from experimental tests show that the quasi-steady friction model cannot capture the total friction damping because of the unsteadiness of transient flows. Therefore, the shear stress of transient flows along the radial direction (r) is artificially divided into two components in that one represents the quasi-steady part (τ_s) and the other the unsteady part (τ_u), as (Ghidaoui *et al.*, 2005)

$$\tau(r) = \tau_s(r) + \tau_u(r) \tag{32}$$

Many types of unsteady friction model have been proposed to account for the unsteady shear stress during transient flows. For example, the discrepancy between the results of pressure head traces with and without steady/unsteady friction models can be clearly found in Fig. 5. The results indicate that an accurate friction model can greatly improve the accuracy of the numerical prediction with reference to the observed data. Moreover, many previous studies have already shown that the friction or turbulence behavior had a great influence on the water quality problems in pipe systems (Taylor, 1953; Fernandes & Karney, 2004; Naser & Karney, 2008), which supports the argument for the necessity of the friction/turbulence models.

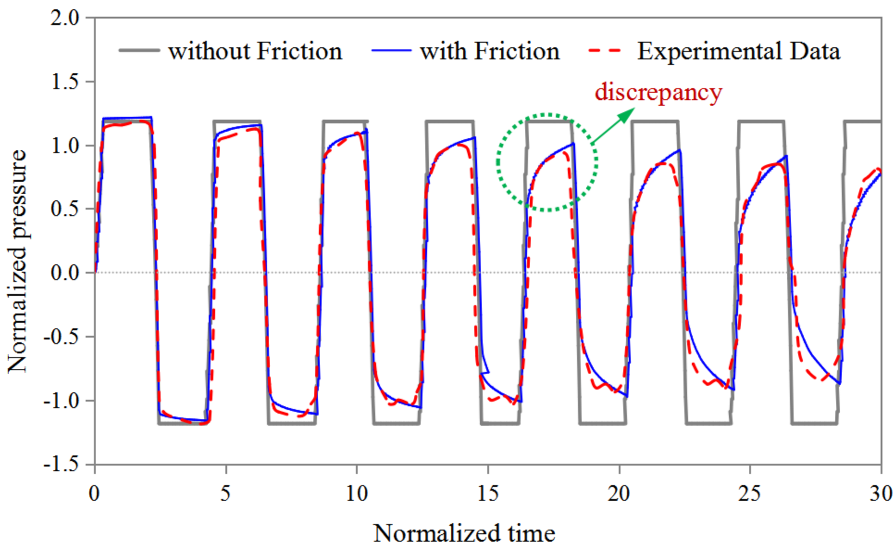


Figure 5. Pressure head traces by numerical model with and without transient friction effect and experimental data (Bergant *et al.*, 1994)

1D Unsteady Friction Model

According to Eq. (32), the 1D wall shear stress can be divided into two components as,

$$\tau_w = \tau_{ws} + \tau_{wu} \tag{33}$$

in which τ_{ws} and τ_{wu} are, respectively, quasi-steady and unsteady components of wall shear stress. In the waterhammer literature, the quasi-steady shear stress is usually represented by the Darcy-Weisbach friction (Chaudhry, 2014; Wylie *et al.*, 1993), while many other unsteady friction models have been proposed to simulate the unsteady wall shear stress component to account for the discrepancy between the instantaneous wall shear stress (τ_w) and quasi-steady component (τ_{ws}). From the previous studies, the existing 1D unsteady friction models can be summarized and classified as the followings:

(1) Instantaneous local acceleration-based (ILAB) formulas (e.g., Daily *et al.*, 1955; Carstens & Roller, 1959; Shuy & Apelt, 1983):

$$\tau_{wu}(t) = \frac{k_1 \rho D}{4} \frac{\partial U}{\partial t} \tag{34}$$

where k_1 is an empirical coefficient from laboratory experiments, which was found to have different values for accelerating and decelerating flows.

(2) Instantaneous material acceleration-based (IMAB) models (Eq. 35a) (e.g., Brunone *et al.*, 1991; Bughazem & Anderson, 1996; Bergant *et al.*, 2001) and its modified counterpart (Eq. 35b) (Pezzinga, 2000; Vítkovský, 2006), which are capable for both accelerating and decelerating flows, respectively:

$$\tau_{wu}(t) = \frac{k_3 \rho D}{4}\left(\frac{\partial U}{\partial t} - a\frac{\partial U}{\partial x}\right) \tag{35-a}$$

$$\tau_{wu}(t) = \frac{k_3 \rho D}{4}\left(\frac{\partial U}{\partial t} + \text{sign}(U)a\left|\frac{\partial U}{\partial x}\right|\right) \tag{35-b}$$

where k_3 is a coefficient, which can be calibrated from experimental data or simulation data by accurate 2D/3D models.

(3) Weighting function-based (WFB) models (e.g., Zielke, 1968; Trikha, 1975; Vardy & Brown, 1995).

$$\tau_{wu}(t) = \frac{4\nu_k \rho}{D}\int_0^t W(t-t')\frac{\partial U}{\partial t'}\,dt' \tag{36}$$

where t' = a dummy variable representing the instantaneous time in the time history; ν_k = kinematic viscosity of the fluid; $W(\cdot)$ = weighting function, and, $W(t) = \alpha\exp(-\beta t)/\sqrt{\pi t}$; $\alpha = D/4\sqrt{\nu_k}$; $\beta = 0.54\nu_k (R_e)^k / D^2$; $k = \log\left(14.3/(R_e)^{0.05}\right)$; and R_e = the Reynolds number.

2D Unsteady Friction Model

Based on the Boussinesq assumption, the total shear stress in Eq. (32) for the quasi-2D and 2D models can be expressed as,

$$\tau = -\rho(\nu_k + \nu_t)\frac{\partial u}{\partial r} = -\rho \nu_T \frac{\partial u}{\partial r} \tag{37}$$

where $\nu_T = \nu_k + \nu_t$ = total viscosity; and ν_t = turbulent eddy viscosity. The commonly used 2D turbulence models in transient pipe flows mainly include the follows.

(1) Quasi-steady algebraic (QSA) models, which are based on the instantaneous velocity distribution (e.g., Wood & Funk, 1970; Vardy & Hwang, 1991; Silva-Araya & Chaudhry, 1997; Pezzinga, 1999). The two commonly used 2D turbulence model for transient flows are five-region model and two-layer model (Ghidaoui *et al.*, 2005):

- Five-region turbulence (FRT) model:

  a) Viscous layer: $\frac{\nu_T}{\nu_k} = 1$ for $0 \le y_* \le \frac{1}{a_c}$;

  b) Buffer I layer: $\frac{\nu_T}{\nu_k} = a_c y_*$ for $\frac{1}{a_c} \le y_* \le \frac{a_c}{C_B}$;

  c) Buffer II layer: $\frac{\nu_T}{\nu_k} = C_B y_*^2$ for $\frac{a_c}{C_B} \le y_* \le \frac{\kappa}{C_B + \kappa^2/4C_m R_*}$;

  d) Logarithmic region: $\frac{\nu_T}{\nu_k} = \kappa y_* \left[1 - (\kappa/4C_m)(y_*/R_*)\right]$ for

  $$\frac{\kappa}{C_B + \kappa^2/4C_m R_*} \le y_* \le \frac{2C_m R_*}{\kappa}\left(1 + \sqrt{1 - C_c/C_m}\right);$$

  e) Core region: $\frac{\nu_T}{\nu_k} = C_c R_*$ for $\frac{2C_m R_*}{\kappa}\left(1 + \sqrt{1 - C_c/C_m}\right) \le y_* \le R_*$;

  where $y_* = \frac{U_T y}{\nu_k}$; $R_* = \frac{U_T R}{\nu_k}$; $U_T = \sqrt{\frac{\tau_w}{\rho}}$; $R = \frac{D}{2}$; $y = R - r$; U_T = the initial friction velocity; and $a_c = 0.19$; $C_B = 0.011$; $\kappa_1 = 0.41$; $C_m = 0.077$; $C_c = 0.06$.

- Two-layer turbulence (TLB) model:

  a) Viscous sub-layer: $\nu_t = 0$ for $y_* \le 11.63$;

b) Turbulent region: $\nu_t = l^2 \left|\frac{\partial u}{\partial r}\right|$ for $y_* \geq 11.63$;

where $l =$ the mixing length, and $l = k_1 y e^{-\left(y/R\right)}$; $k_1 = 0.374 + 0.0132\ln\left(1 + \frac{83100}{R_e}\right)$;

and other notations defined previously.

(2) Two equation-based (TEB) models, i.e., kinetic energy and dissipation equations (e.g., Zhao & Ghidaoui, 2006; Riasi *et al.*, 2009; Duan *et al.*, 2010a)

- Liner κ–ε model

$$\nu_t = C_\mu f_\mu \frac{\kappa^2}{\varepsilon} \tag{38}$$

where κ, ε =turbulent kinetic energy and dissipation rate, respectively, which can be expressed by the two equations below:

$$\frac{\partial \kappa}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu_k + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \kappa}{\partial r}\right] + \nu_t\left(\frac{\partial u}{\partial r}\right)^2 - \varepsilon \tag{39}$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu_k + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right] + \nu_t C_{\varepsilon 1} f_1 \frac{\kappa}{\varepsilon}\left(\frac{\partial u}{\partial r}\right)^2 - C_{\varepsilon 2} f_2 \frac{\varepsilon^2}{\kappa} \tag{40}$$

where $f_w = 1.0 - \exp\left\{-\frac{\sqrt{R_y}}{2.30} + \left(\frac{\sqrt{R_y}}{2.30} - \frac{R_y}{8.89}\right)\left[1 - \exp\left(-\frac{R_y}{20}\right)\right]^3\right\}$; $R_y = \frac{y\sqrt{\kappa}}{\nu_k}$;

$f_2 = f_w^2\left\{1.0 - 0.22\exp\left[-\left(\frac{R_t}{6}\right)^2\right]\right\}$; $R_t = \frac{\kappa^2}{\nu_k \varepsilon}$; $C_\mu = 0.09$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$; $C_{\varepsilon 1} = 1.39$;
$f_1 = 1.0$; $C_{\varepsilon 2} = 1.80$; and $y = R - r$.

Many researchers in the field of transients/waterhammer have investigated the linear $k-\varepsilon$ turbulence model in pipe flows, especially for the near pipe-wall region flows, and developed many different representations of coefficient f_μ in Eq. (38) (e.g., Patel *et al.*, 1985; Martinuzzi & Pollard, 1989; Mankbadi & Mobark, 1991; Fan *et al.*, 1993; Rahman & Siikonen, 2002). One typical representation among these $k-\varepsilon$ models was proposed by Fan *et al.* (1993), which is applicable to both low and high Reynolds flows, has been successfully used to describe the eddy viscosity in transient pipe flows (Zhao & Ghidaoui, 2006):

$$f_\mu = 0.4\frac{f_w}{\sqrt{R_t}} + \left(1 - 0.4\frac{f_w}{\sqrt{R_t}}\right)\left[1 - \exp\left(-\frac{R_y}{42.63}\right)\right]^3 \tag{41}$$

Based on the 1D analytical derivations and 2D numerical simulations, Duan *et al.* (2012a) conducted a systematical analysis on the relevance of unsteady friction (turbulence) with system scales (T_w/T_d or L/D with T_w and T_d being timescales of axial wave propagation and radial turbulent diffusion) and initial flow conditions (fRe_0 with Re_0 being initial Reynolds number). The main results are shown in Fig. 6, indicating that the contribution of unsteady friction effect to the damping rate of pressure head peak in practical pipe systems with relatively large time scale ratio (T_w/T_d or L/D) is less important than that is implied by laboratory experiments characterized by relatively small time scale ratio (T_w/T_d or L/D). The findings of that study also imply that the calibrated unsteady friction or turbulence models based on laboratory experimental tests may overestimate the importance and contribution of transient friction effect to transient responses (amplitude damping and peak smoothing) as they are applied to practical pipeline systems. It is concluded from Duan *et al.* (2012a) that it is necessary to perform a full-scale calibration for any unsteady friction or turbulence model when it is first developed and applied to specific pipeline systems.

To address this issue, an effort has been made in Meniconi *et al.* (2014), which is an extension to the former work by Duan, *et al.* (2012a), where the time dependent unsteady viscosity is considered and included in the 1D unsteady friction model. Their application results for different field tests demonstrated the substantial improvement of the unsteady friction simulation for practical pipeline system with relatively large time scale ratios (T_w/T_d or L/D) and initial Reynolds number (Re_0). Thereafter, Duan et al. (2017a) further investigated the mechanisms of different unsteady friction models, including 1D IMAB and WEB models and 2D $\kappa-\varepsilon$ turbulence model, through the local and integral energy analysis. Their results and analysis confirmed again the former conclusion that the importance of unsteady friction effect to the transient envelope attenuation is decreasing with initial flow conditions (Re_0) and pipe scales (L/D). Meanwhile, their results indicated that the relevance of unsteady friction to the system energy dissipation is highly dependent on the unsteady friction model used. Particularly, the 1D unsteady friction models (IMAB and WFB) may underestimate the unsteady friction effect in the low frequency domain, while may overestimate that effect in the relatively high frequency domain. Therefore, a more comprehensive unsteady friction model (e.g., 2D or 3D turbulence model) is required for simulating a long-duration transient pipe flow such as in practical conveyance pipelines.

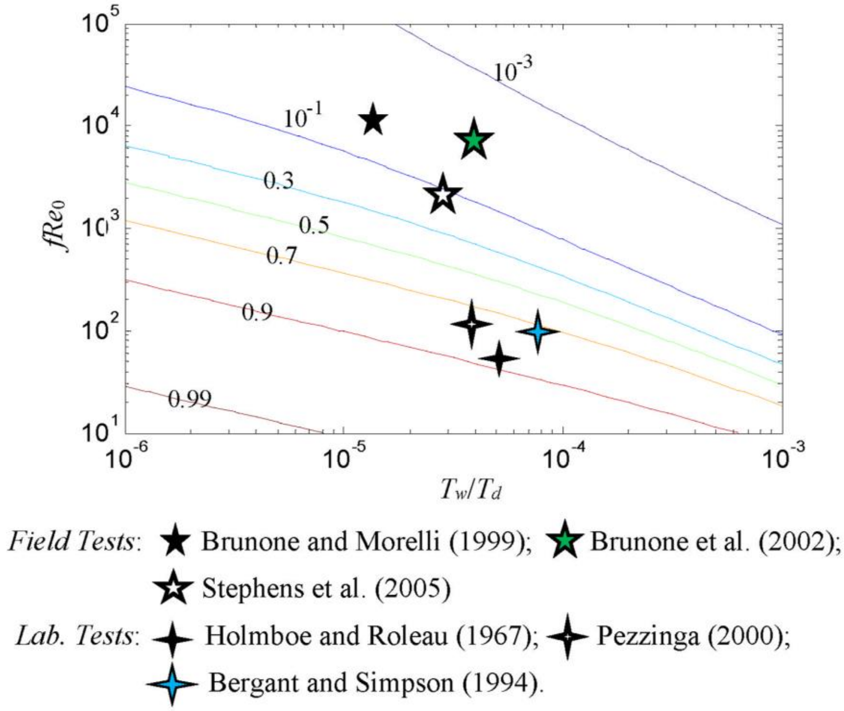


Figure 6. Relevance of unsteady friction with system scales and initial conditions (fRe_0 and T_w/T_d) in water supply pipeline systems

Viscoelastic Model for Plastic Pipelines

While the modelling of unsteady friction effect has been received more and more attention in the study of transient pipe flows, the current transient models coupled solely with those present friction models cannot adequately represent the pressure wave attenuation observed in real-world pipe systems (McInnis & Karney, 1995; Ebacher et al., 2011). In fact, other than the energy dissipation from the pipe skin roughness (τ_w) and turbulent eddy viscosity (ν_t), viscoelasticity due to the pipe-wall deformation is another important factor affecting the energy change and loss in transients, i.e., ε in Eq. (29) and the 3rd term in the continuity Eq. (30). The use of viscoelastic pipes is becoming more and more popular in real-life pipeline installation (Triki, 2018). The commonly used viscoelastic pipe materials today mainly include PVC, PPR, PE, and HDPE. Therefore, the researches on transient flow behaviors in viscoelastic pipeline become essential and important to meet such practical requirements.

Viscoelastic Characteristics of Plastic Pipes

Recently, numerical and experimental studies have been conducted for viscoelastic responses in plastic or polymetric pipelines in laboratory settings to investigate the possibility of using physical properties of such pipes for suppressing transient oscillations (e.g., Franke, 1983; Güney, 1983; Covas *et al.*, 2005b; Covas *et al.*, 2004; Ghilardi & Paoletti, 1986; Ramos *et al.*, 2004; Gong et al., 2018; Triki, 2018; Fersi & Triki 2019; Urbanowicz *et al.*, 2020). It has been shown in these studies that the viscoelastic pipes could reduce the magnitude of unsteady fluid oscillations due to the larger capacity for storing strain energy in comparison with elastic pipes. The general behaviors/response of elastic and viscoelastic pipe materials during the external loading and unloading processes are sketched in Fig. 7 (Meyers & Chawla, 2008).

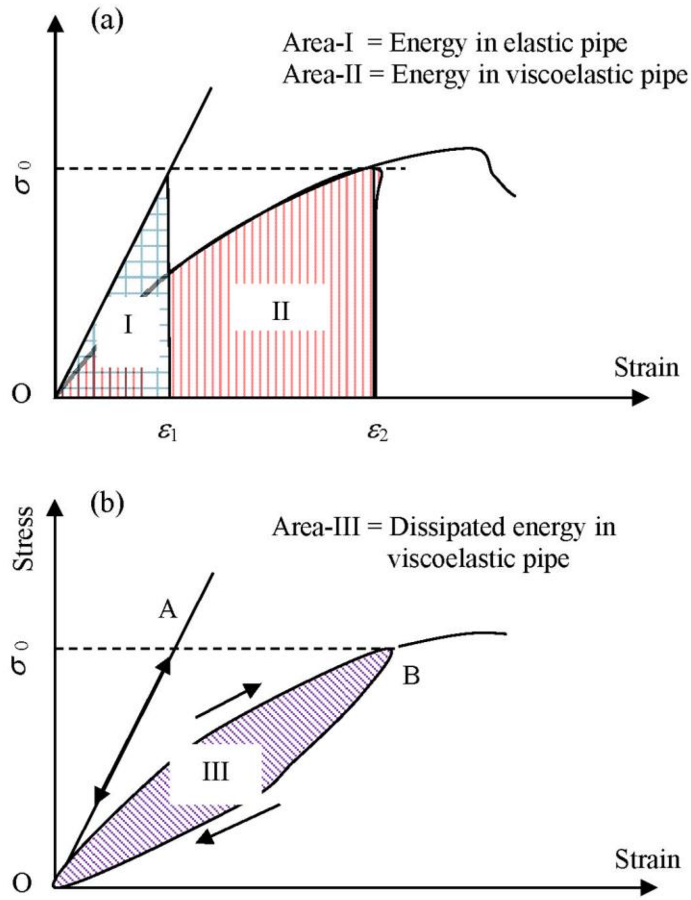


Figure 7. Stress-strain curves for elastic and viscoelastic pipe materials: (a) energy storage capacity; (b) paths of loading and unloading processes

In Fig. 7(a), the energy stored in the elastic material due to external loads can be expressed as Area-I, while that for viscoelastic material is shown as Area-II. Under the same external load, σ_0, the energy area-II of viscoelastic pipeline is much larger than the energy Area-I of elastic pipeline and the deformation of viscoelastic pipes (ε_2) is therefore much larger than that of elastic pipes (ε_1). From Fig. 7(b), the loading path ("O-A") for elastic pipes and the unloading (relaxation) path ("A-O") are nearly on the top of each other with following approximately a linear behavior but in opposite direction. That is, the pressurized state could be recovered immediately once the external load is removed. However, for the viscoelastic material of plastic pipe-wall, the relaxation path ("B-O") is very different from the loading path ("O-B") and both paths behave nonlinearly, forming a "hysteresis" loop with energy dissipation as shown in the energy Area-III of Fig. 7(b) (Meyers & Chawla, 2008; Love, 2013). This kind of material properties will lower the wave speed in viscoelastic pipes. As a result, the viscoelastic pipe would have a longer pipe characteristic time and a slower transient response, so that a given maneuver duration may result in relatively faster operation within the transient response for plastic pipes compared to elastic pipe cases. Meanwhile, the viscoelastic pipes could likely withstand a more serious pressure surge situation than the elastic pipe since the transients can be "smoothed" out and fade away quickly due to the energy storage and dissipation of the viscoelastic materials in plastic pipelines. It is also noted that the response in Fig. 7 is based on an ideal viscoelastic model, and experimental examples may refer to Covas *et al*. (2004).

Modelling of Viscoelastic Behavior in Transients

The K-V model has been commonly adopted to model the material visco-elasticity in pipe fluid transients due to its accurate representation of the creep and retardation effect and its simple form of expression (Güney, 1983; Covas *et al.*, 2005b). The creep function of visco-elastic pipe material can be expressed by:

$$J(t) = J_0 + \sum_{kv=1}^{N}\left[J_{kv}\left(1-e^{-t/\tau_{kv}}\right)\right] \tag{42}$$

in which $J_{kv} = 1/E_{kv}$ = creep compliance of the *kv*-element; E_{kv} = modulus of elasticity of the *kv* -element; $\tau_{kv} = \eta_{kv}/E_{kv}$ = retardation time of the *kv*-element; η_{kv} = viscosity of the *kv*-element; N = total number of K-V elements. By considering the time convolution effect, the retarded strain of pipes in the continuity Eq. (30) can be expressed mathematically by:

$$\varepsilon_r\left(x,t\right) = \int_0^t \left(\sigma\left(x,t-t'\right)\frac{\partial J\left(t'\right)}{\partial t'}\right) dt' \tag{43}$$

in which $\sigma(x,t)$ = normal stress related to pressure head. As a result, a linearized expression of the viscoelastic deformation rate can be obtained as (Güney, 1983):

$$\frac{\partial \varepsilon_r}{\partial t} = \sum_{kv=1}^{N} \left(\frac{J_{kv}}{\tau_{kv}} F_v(x,t) - \frac{\varepsilon_{r_{kv}}(x,t)}{\tau_{kv}} \right) \tag{44}$$

where $F_v(x,t) = C_1 \Delta P(x,t)$; $\Delta P(x,t) = P(x,t) - P_0(x)$, and $P(x,t)$ = instantaneous pressure at time *t*; $P_0(x)$ = initial pressure; $C_1 = \frac{CD}{2e}$, and C = pipe constraint coefficient; e = pipe-wall thickness; $\varepsilon_{r_{kv}}(x,t)$ = retarded strain of *kv*-element, calculated by the following approximation:

$$\begin{aligned} \varepsilon_{r_{kv}}(x,t) &= J_{kv} F_v(x,t) - J_{kv} e^{-\Delta t/\tau_{kv}} F_v(x,t-\Delta t) + e^{-\Delta t/\tau_{kv}} \varepsilon_{r_{kv}}(x,t-\Delta t) \\ &\quad - J_{kv} \tau_{kv} \left(1 - e^{-\Delta t/\tau_{kv}}\right) \frac{F_v(x,t) - F_v(x,t-\Delta t)}{\Delta t} \end{aligned} \tag{45}$$

Therefore, the viscoelastic term in the transient model (continuity equation) can be implemented easily in the discrete scheme, e.g., the Method of Characteristics (MOC), so as to obtain numerically the transient responses in viscoelastic pipes.

The application results of the studies by Covas *et al.* (2005b) and Ramos *et al.* (2004) demonstrated that the viscoelastic effect is much more dominant than the unsteady friction effect on pressure wave peak attenuation. Moreover, in addition to peak attenuation, the viscoelastic effect induces a time-delay or phase-shift in transient responses and this behavior can never be captured by considering only the unsteady friction or turbulence in the transient process. However, extensive numerical simulations conducted in Covas *et al.* (2005b) also indicated that the calibrated creep compliance coefficients for the viscoelastic K-V model are clearly affected by the initial flow conditions (e.g., *Q*, *H*, and Re_0). On this point, Covas *et al.* (2005b) reasoned that these non-physical results are due to inaccurate capture of the unsteady friction effect by 1D quasi-steady models for transient flows in their study.

To address this issue, the study of Duan *et al.* (2010a) developed a quasi-2D model, by coupling the 1D K-V model and 2D κ–ε turbulence model, in order to accurately represent both the unsteady friction (turbulence) and viscoelasticity in plastic pipe transients. Their application results revealed the relatively independence of calibrated viscoelastic parameters in the K-V model on the initial flow conditions in the same system. That is, by using their developed quasi-2D model, a set of unified viscoelastic parameters could be obtained for the same plastic material pipeline system. Meanwhile, the energy analysis performed in Duan *et al.*, (2010b) indicated that the mechanism of pipe-wall viscoelasticity on affecting transient responses (amplitude damping and phase shifting) is totally different from that of unsteady friction. To be specific, the interaction process of transient waves with pipe-wall viscoelasticity is actually an energy transfer process during each wave period, in which part of the stored energy in pipe-wall is dissipated due to the viscoelastic material deformation as shown in Fig. 7(b). That is, the fluid wave energy is initially transferred and stored in the pipe-wall (due to pipe expansion) during the positive wave cycle, which is then returned to fluid waves during the subsequent negative wave cycle (due to pipe contraction). But the returned energy will be smaller than the originally stored amount, which is described as the energy dissipation by the hysteresis shown in Fig. 7(b).

Furthermore, many researchers have focused on the calibration process of viscoelastic parameters in the K-V model for better representing the transient responses of different plastic pipes. For instance, Keramat & Haghighi (2014) proposed a time-domain transient-based straight forward method for the identification of viscoelastic parameters. An FSI model was developed by Zanganeh *et al.* (2015) to represent the interaction of viscoelastic pipe-wall with transient waves. Ferrante & Capponi (2018a) examined the viscoelastic parameter calibration for a branched plastic pipeline system based on the time-domain analysis method, followed by another study on the influence of the number of K-V elements on the model accuracy (Ferrante & Capponi, 2018b). Gong *et al.* (2016) developed a frequency shift-based method for determining the viscoelastic pipe parameter. Frey *et al.* (2019) presented a phase and amplitude-based characterization method in the frequency domain for calibrating the viscoelastic parameters and their influences on transient responses. Recently, Pan *et al.* (2020) proposed an efficient multi-stage frequency domain method for simultaneously determining both the number and values of the viscoelastic parameters. All these calibration methods have been validated through different experimental tests in the literature.

In addition to the K-V model, some other viscoelastic models have been examined for the modelling of transient flows in plastic pipes. For example, Ferrante & Capponi (2017) investigated three types of viscoelastic models (i.e., Maxwell model, standard linear solid model and generalized Maxwell model) for both HDPE and PVC-O pipe systems. Their results revealed that each of these models may present different advantages and limitations in terms of accuracy and efficiency for different pipeline systems. Based on these developed viscoelastic models and calibration methods, the transient theory and model have been successfully extended and applied to plastic pipelines, and thereby the development of transient-based methods for viscoelastic pipeline diagnosis in UWSS, which will be further introduced later in this paper.

Time-Domain Numerical Simulation

In the time domain, due to the non-linear property of the shear stress (friction) in momentum equation (25) or (28) and the complex boundary conditions in UWSS, it is impossible to directly obtain the general analytical solutions for the governing equations of transient pipe flows. To this end, different numerical schemes have been commonly developed used to obtain approximate solutions, such as finite difference, finite volume, finite element and others (e.g., Joukowsky, 1904; Angus, 1935; Amein & Chu, 1975; Chaudhry & Hussaini, 1985,; Katopodes & Wylie, 1984; Rachford Jr & Ramsey, 1977; Suo & Wylie, 1989). Among these methods, the MOC is one of the commonly used schemes for solving 1D or 2D transient models in the literature (Lister, 1960; Wiggert & Sundquist, 1977; Wylie *et al.*, 1993; Ghidaoui & Karney, 1994; Kayney & Ghidaoui, 1997; Ghidaoui *et al.*, 1998; Chaudhry 2014; Nault *et al.*, 2018). For the review purpose, the implementation of MOC for 1D and 2D models are summarized as follows.

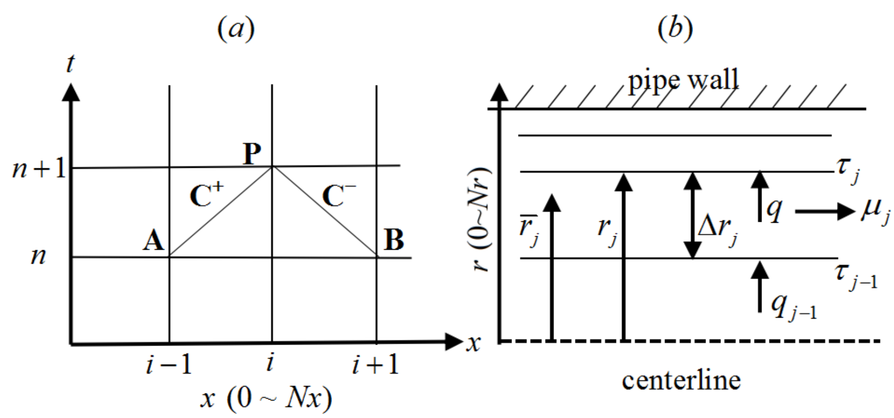


Figure 8. Schematic for MOC Scheme: (a) axial direction; (b) radial direction

The principle of the MOC is to convert original partial differential equations (PDEs) into the ordinary forms (ODEs). In 1D models, the MOC scheme introduces two characteristic lines (lines ***A-P*** and ***B-P***) as shown in Fig. 8(a) and the unknowns at point ***P*** are calculated from the known quantities at points ***A*** and ***B*** obtained from the previous time step. Mathematically, the converted ODEs are shown as follows,

$$H_p = C_A - B_A Q_p$$
$$H_p = C_B + B_B Q_p \tag{46}$$

where

$$C_A = H_A + Q_A\left[B - R\left|Q_A\right|(1-\eta)\right]$$
$$B_A = B + \eta R\left|Q_A\right|$$
$$C_B = H_B - Q_B\left[B - R\left|Q_B\right|(1-\eta)\right] \tag{47}$$
$$B_B = B + \eta R\left|Q_B\right|$$

$$B = \frac{a}{gA}, \quad R = \frac{f\Delta x}{2gDA^2} \tag{48}$$

in which η is the weighting coefficient, and η = 0.5 – 1.0 for achieving numerical stability.

Similarly, for the 2D model, the ODE forms are (Vardy & Hwang, 1991):

$$\frac{dH}{dt} \pm \frac{a}{g}\frac{du}{dt} = -\frac{a^2}{g}\frac{1}{r}\frac{\partial q}{\partial r} \pm \frac{a}{g}\frac{1}{r\rho}\frac{\partial(r\tau)}{\partial r},$$

$$\text{along } \frac{dx}{dt} = \pm a \tag{49}$$

where $q = rv$ is the unit flowrate in the radial direction. In 2D model, a matrix form will be formed for the whole pipeline system, and all the unknowns (H, u, q) for each time-step (e.g., Fig. 8(b)) are solved by using the MOC scheme and finite difference (FD) scheme (Wiggert & Sundquist, 1977; Vardy & Hwang, 1991). To improve the computational efficiency of the 2D MOC results, Zhao & Ghidaoui (2003) has developed a decomposed matrix form for the above ordinary differential equations (ODEs) as,

$$\mathbf{BU} = \mathbf{b_u} \tag{50}$$

$$\mathbf{CV} = \mathbf{b_v} \tag{51}$$

in which: $\mathbf{V} = \{H_i^{n+1}, q_{i,1}^{n+1}, \cdots, q_{i,j}^{n+1}, \cdots, q_{i,Nr-1}^{n+1}\}^T$; $\mathbf{U} = \{u_{i,1}^{n+1}, \cdots, u_{i,j}^{n+1}, \cdots, u_{i,Nr}^{n+1}\}^T$; Nr is the total grid in the radial direction; $\mathbf{b_u}$ and $\mathbf{b_v}$ = known vectors which depend on the hydraulic parameters at time level n, and **B** and **C** are $Nr \times Nr$ tri-diagonal matrices depending on the system conditions and results from previous time-steps. From this mathematic manipulation, the Central Processing Unit (CPU) calculation time can be greatly reduced to nearly $1/Nr^2$ of the original calculation time. Thereafter, this efficient model has been further extended in Duan *et al.* (2009) to more complex situations (e.g., multiple-pipe junctions). For example, The matrices for the branched pipe junctions are shown as follows:

$$\mathbf{RH} = \mathbf{S} \tag{52}$$

$$\mathbf{LQ} = \mathbf{W} \tag{53}$$

$$\mathbf{Kq} = \mathbf{J} \tag{54}$$

where: $\mathbf{H} = \{H^{n+1}, \sum_{j=1}^{Nr} Q_j^{n+1}\}^T$; $\mathbf{Q} = \{Q_{p,1}^{n+1,O1}, Q_{p,1}^{n+1,O2}, \cdots, Q_{p,j}^{n+1,O1}, Q_{p,j}^{n+1,O2}, \cdots, Q_{p,Nr}^{n+1,O1}, Q_{p,Nr}^{n+1,O2}\}^T$; **S**, **J**, **W** and **R**, **L**, **K** = the known vectors and matrices based on the system conditions and previous time-step results.

Frequency-Domain Transfer Matrix Analysis (TMA)

The transfer matrix analysis (TMA) of a transient flow system is to derive the linearized frequency-domain equivalents of the original time-domain momentum and continuity equations in Eq. (28) and (30), which describes the transient behavior of the system in the frequency domain. The general form of the transfer matrix for an intact pipe section is (Lee *et al.*, 2006; Duan *et al.*, 2011a, 2012b; Chaudhry, 2014),

$$\begin{Bmatrix} q \\ h \end{Bmatrix}^{n+1} = \begin{bmatrix} \cos(\mu L) & i\frac{1}{Y}\sin(\mu L) \\ iY\sin(\mu L) & \cos(\mu L) \end{bmatrix} \begin{Bmatrix} q \\ h \end{Bmatrix}^{n} \tag{55}$$

where $\mu = \frac{\omega}{a}\sqrt{1 - i\frac{gAR}{\omega}}$; $Y = -\frac{a}{gA}\sqrt{1 - i\frac{gAR}{\omega}}$; $R = \frac{fQ}{gDA^2}$; q, h = discharge (Q) and pressure head (H) in the frequency domain; n = point under consideration; L = pipe section length; ω = frequency; i = imaginary unit. This matrix equation relates the head and discharge perturbations on either ends of a section of intact single pipeline. Similar matrices describing other system elements can be derived and combined with Eq. (55) to produce the overall matrix describing the system. Elements with external forcing will require the matrix to be expanded into a 3×3 matrix and the final system matrix is in the following form (Lee, 2005; Chaudhry, 2014),

$$\begin{Bmatrix} q \\ h \\ 1 \end{Bmatrix}^{n+1} = \begin{bmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{bmatrix} \begin{Bmatrix} q \\ h \\ 1 \end{Bmatrix}^{n} \tag{56}$$

where U_{ij} is the system matrix element.

For illustration, the transient responses of water supply pipeline systems with different configurations (e.g., single, series and branched pipe systems) obtained by the time-domain

MOC scheme and frequency-domain TMA method are plotted in Figs. 9(a) & 9(b) respectively (Duan *et al.*, 2011a; Duan, 2018).

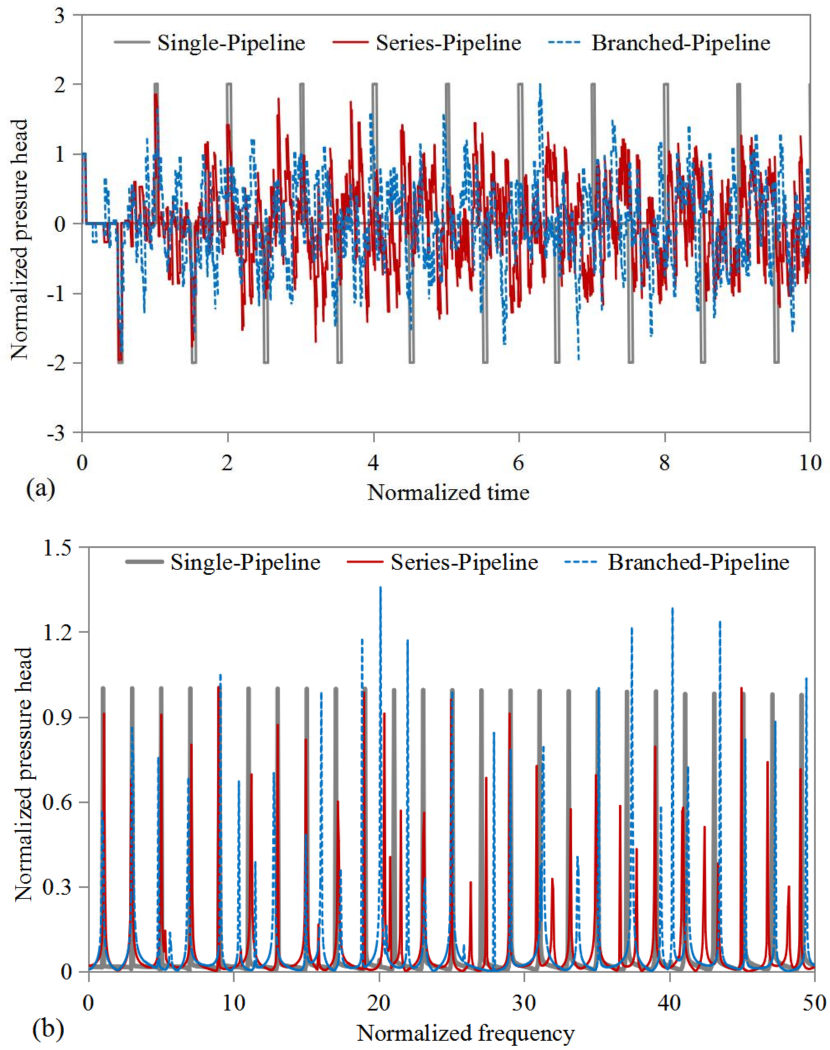


Figure 9. Transient responses of different pipeline systems: (a) time-domain results by MOC; (b) frequency-domain results by TMA

The comparison of different results in Fig. 9 demonstrates that: (i) the significant influences of system complexities (different junctions) on the transient responses in both time and frequency domains (Meniconi *et al.*, 2018); and (ii) the different dependences of transient responses on the system configurations between the time and frequency domain results. Specifically, compared to time-domain results, the influences of pipe junctions to the transient responses by the TMA become relatively simple and independent for different resonant peaks, which have similar impact complexities that are not superimposed or accumulated with frequency as shown in Fig. 9(b).

It is also worthy of noting that, the linearization approximation has been applied in the mathematical derivations to obtain the above transfer matrix, such as nonlinear turbulent friction and external orifice flows in the system. On this point, the influence and error of such linearization have been systematically examined in the literature (e.g., Lee & Vítkovský, 2010; Lee, 2013; Duan *et al.*, 2018). Their results indicated that this linearization approximation becomes valid with acceptable accuracy for transient modelling and analysis, as long as the perturbation of transient flows is relatively small to the initial steady state flows (e.g., $q << Q_0$). Meanwhile, the study by Duan *et al.* (2018) has provided an iterative solution for the transfer matrix analysis, so as to include the nonlinear turbulent friction term (e.g., Eq. (31)).

Due to the explicit and relatively simple dependent relationship of transient responses on the system information (pipeline conditions, devices and system states) in the frequency domain (e.g., Fig. 9(b)), the transfer matrix analysis (TMA) has been widely used for developing the transient-based pipe diagnosis methods in the literature, such as leakage, different junctions partial blockage detection (Lee, 2005; Duan, 2011a, 2017; Lee *et al.*, 2013b; Che, 2019).

Transient-Based Defect Detection (TBDD) Methods

While many practicing engineers think most often about transients referred to their negative or damaging physical effects on a pipe system, or deterioration of potable water quality, etc., there is a positive aspect to transients as an integrity management tool (Wylie et al., 1993; Duan *et al.*, 2010d; Chaudhry, 2014). In fact, transients have the ability to acquire and transmit a significant range and variety of system information along the pipeline while travelling through the system at high speeds. This high-speed transmission of information can be utilized in many practical applications, such as leak and partial blockage detection and pipeline condition monitoring. This is also the underlying physics and principle for developing different transient-based defect detection (TBDD) methods in the literature.

In the past two decades, transient pressure waves have been widely used for the detection of different pipe defects or anomalies (especially for leaks) by many researchers (e.g., Brunone, 1999; Vítkovsky *et al.*, 2003; Covas *et al.*, 2005a; Lee *et al.*, 2006; Stephens, 2008; Covas & Ramos, 2010; Duan *et al.*, 2011a; Duan *et al.*, 2012b; Ghazali *et al.*, 2012; Gong *et al.*, 2013a; Duan *et al.*, 2014a; Duan, 2020; Kim, 2018; Kim, 2020; Xu & Karney 2017; etc.). This transient-based method has been regarded as a promising way for detecting pipe anomalies because it has desirable merits of high efficiency, low cost, and non-intrusion (Gupta & Kulat, 2018). The tenet of the TBDD method is that an injected transient wave propagating in a pipeline is modified by, and thus contains information on, properties and states of the pipeline. Potential pipe anomalies can be detected by actively injecting waves and then measuring and analyzing data at the accessible points in the system (e.g., fire hydrants) (Lee, 2005; Stephens, 2008; Duan, 2011).

In this section, the progress and achievement of the TBDD methods are reviewed and summarized according to their detection contents (different types of pipe defects) and application methods (different utilizations of transient information) in UWSS.

Transient-Based Leak Detection

Although it has been reported that not all of the water loss attributes to pipe leaks and bursts (as shown in Fig. 2), leakage in the pipe system may be one of the main causes according to the reports of the International Water Supply Association (IWSA) (Lambert, 2002). Leakage under pressurized state and the infiltration under unpressurized state from the surrounding environment in the UWSS (e.g., Fig. 1(a)) can damage the surrounding environment (soil washing and foundation scouring) and can also cause potentially increase of public health risks (water contamination and air/solid intrusion) (Burn *et al.*, 1999). These practical problems stimulated the development of many leak detection techniques in the past decades (Wang, 2002). Amongst the various leak detection methods, the transient-based leak detection method has especially attracted the attention of researchers recently (Colombo *et al.*, 2009; Ayati *et al.*, 2019). In the following, five types of transient-based methods are reviewed briefly (Colombo *et al.*, 2009; Duan *et al.*, 2010c), including: transient reflection-based method (TRM), transient damping-based method (TDM), transient frequency response-based method (TFRM), inverse transient analysis-based method (ITAM), and signal processing-based method (SPM).

Transient Reflection-Based Method (TRM)

The transient reflection-based method (TRM) is the easiest to apply among the five types of leak detection method. It evaluates the presence of a leak and locates the leak in the pipeline by utilizing the reflection information of the pressure signal. Brunone (1999) introduced the method with the following equation:

$$x_L^* = \frac{a}{2L}\left(t_2 - t_1\right) \quad (57)$$

where x_L^* = dimensionless leak location that represents the leak distance from the downstream boundary (x_L) normalized by pipe length; L = length of pipe section under investigation; t_1 = time instant at which the pressure wave generated at the end valve arrives at the measurement location; and t_2 = time instant at which the reflected wave at the leak reaches the measurement location. The leakage quantity (leak size) can be evaluated by the orifice equation:

$$Q_L = C_d A_L \sqrt{2g\left(H_L^t - H_{OL}^t\right)} \quad (58)$$

where Q_L = leak discharge; C_d = leak size coefficient; A_L = leak area size; H_L^t = instant internal pressure head at leak location; and H_{OL}^t = instant external pressure head at leak location. Note that the leak size in Eq. (58) can be calculated by combining the numerical MOC for waterhammer governing equations (see details in Brunone, 1999). Brunone & Ferrante (2001) further studied the applicability of the TRM for leak detection and estimation in pressurized single pipes by experimental validation. Their results showed that the leak location can be accurately predicted by measuring the arrival times of the signal reflections.

To better identify the transient reflection information from the measured data traces, different algorithms have been adopted to achieve transient signal analysis in the literature, such as Impulse Response Function (IRF) (Liou, 1998; Kim, 2005; Lee *et al.*, 2007; Nguyen *et al.*, 2018), Wavelet Analysis (Ferrante & Brunone, 2003a, 2003b; Ferrante *et al.*, 2007, 2009a, 2009b), and Cumulative Sum (CUSUM) (Misiunas *et al.*, 2005; Bakker *et al.*, 2014). It has been evidenced from these studies that the use of these algorithms has substantially enhanced the application of the TRM.

Transient Damping-Based Method (TDM)

While the TRM relies solely on the reflection information within transient traces, an alternative method has been developed to work solely on the damping rate of the transient signal (Wang *et al.* 2002, Brunone *et al*. 2019, Capponi *et al*. 2020). The transient damping-based method (TDM) was firstly proposed in Wang *et al.* (2002) that utilizes the relative damping rates of the first two harmonic frequency components in the transient trace to locate the leak. This method was derived analytically from the 1D transient model for a single pipe system. The equation relating the harmonic damping ratios and the leak location is,

$$\frac{R_{n_1L}}{R_{n_2L}} = \frac{\sin^2(n_1\pi x_L^*)}{\sin^2(n_2\pi x_L^*)} \tag{59}$$

$$C_d A_L == \frac{R_{nL} A\sqrt{2gH_{L0}}}{a\sin^2(n\pi x_L^*)} \tag{60}$$

where R_{nL} = the leak-induced damping rate for the n^{th} mode; C_d = leak coefficient; n = any mode of n_i; and n_i = mode number, with i = 1 or 2.

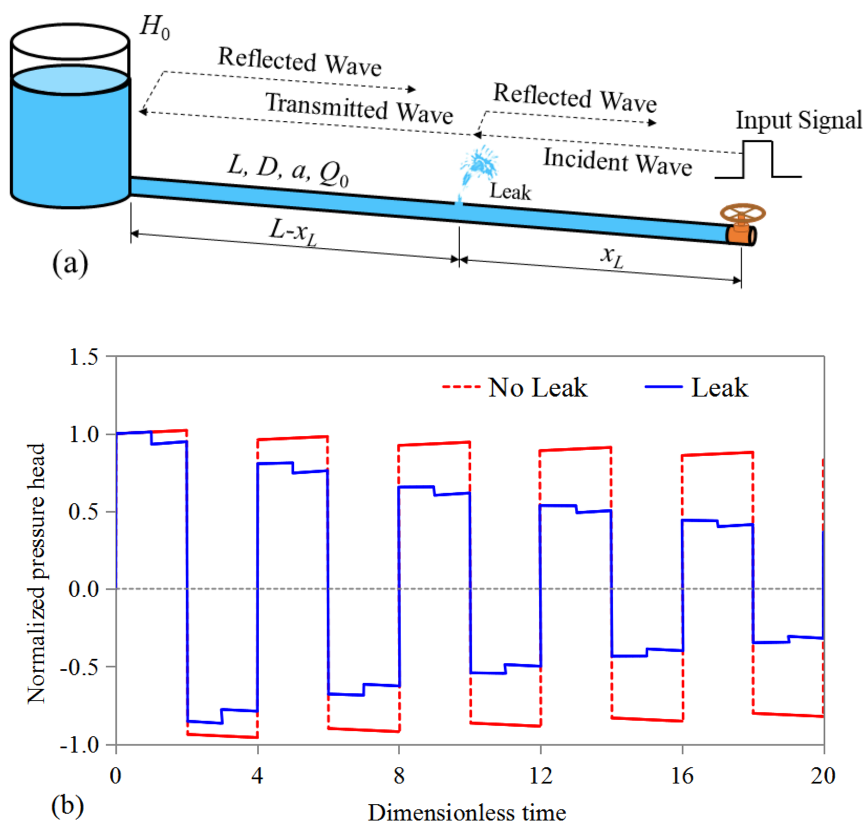


Figure 10. Pipe system for illustration: (a) pipeline with a leak; (b) transient pressure head at downstream valve (1D numerical results)

Based on this method in Eqs. (59) and (60), the leaks can be found through the inspection of the results of different mode amplitude ratios. For example, in the simple pipe system shown in Fig. 10(a), if a small leak (e.g. 10% of pipe discharge) is placed at 60% of the pipe length distance from the upstream tank (i.e., $x_L = 0.4L$), the leak information appears in Fig. 10(b) as the difference between the transient pressure head traces with and without leakage in pipeline. The results show clearly that the damping for the leak case is much faster than that for the no-leak case. By using Wang's method (Wang *et al.*, 2002), the damping rates of different frequency modes for cases with and without leakage are shown in Figs. 11(a) & 11(b) respectively, which finally can provide the prediction of leaks in the system according to Eq. (59) and Eq. (60).

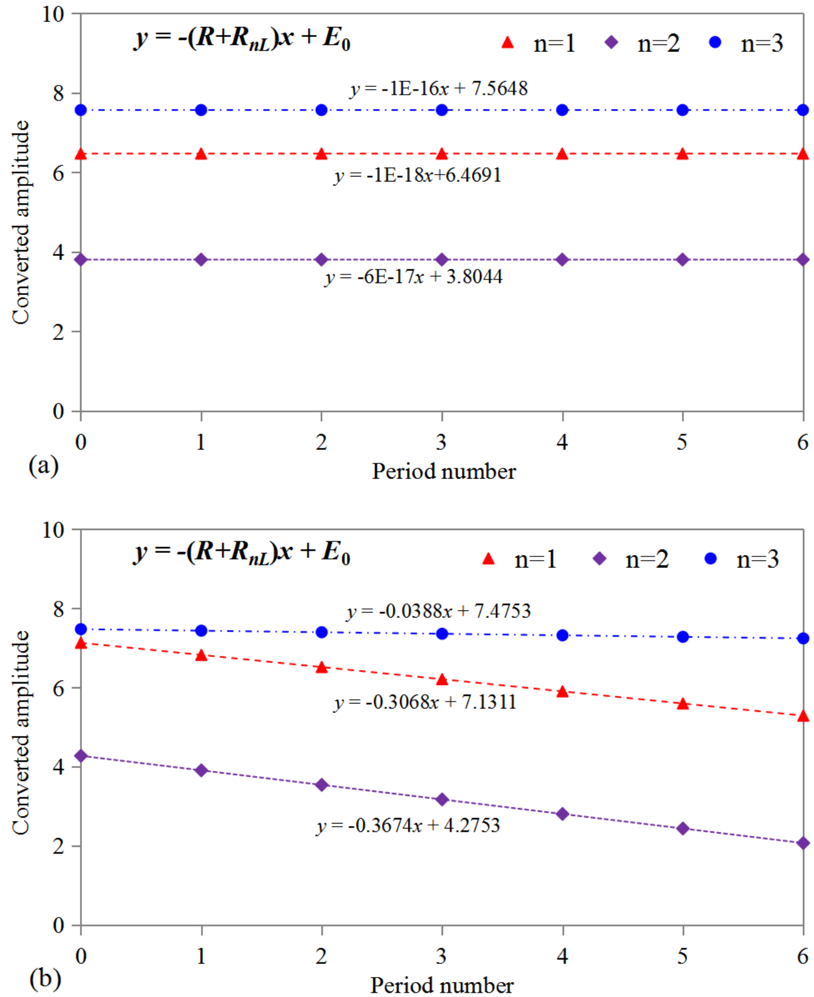


Figure 11. Results of damping rates for different modes: (a) without leak; (b) with leak

To obtain the results of Eqs. (59) and (60) for the TDM in Wang *et al.* (2002), the key assumptions imposed for analytical derivations include (Nixon *et al.*, 2006):

(i) Linearization of turbulent friction term;

(ii) Relatively small amplitude of transient event;

(iii) Relatively small size of leak relative to the main flowrate;

(iv) Single pipeline system configuration.

These assumptions have been discussed and verified in Nixon *et al.* (2006) by using a 2D transient model. Their study showed that the assumptions do not limit the applicability of the TDM developed in Wang *et al.* (2002) model in practice provided that the system is simple and the friction damping effect could be represented correctly in pressure head traces. Because of the last assumption, the TDM is restrictive to multiple-pipeline systems since the complex initial and boundary conditions are still difficult to be incorporated into this method if the studied water distribution system is not simplified (Capponi *et al.* 2020). However, Nixon *et al.* (2006) also pointed out that the TDM in Wang *et al.* (2002) could be applied to practical complex systems by isolating the individual pipelines from the rest of the system.

Meanwhile, to address the influence of transient friction and turbulence, a 2D form of the TDM was successfully derived by Nixon *et al.* (2006). The incorporation of the constant viscosity formula in the 2D transient model provides the feasibility of qualitative evaluation of 2D turbulence (unsteady friction) effect on the transient-based leak detection. The detailed form can be expressed as below:

$$\begin{aligned}&\frac{n\pi R}{L}\sum_{k=1}^{\infty}\left(\frac{u_{nk}(t)}{\alpha^*_k}J_{B1}\left(\alpha^*_k\right)\right)-\frac{gR}{2a^2}\frac{d\tilde{h}_n}{dt}-\frac{gf_{bc}'(t)R}{n\pi a^2}(-1)^{n+1}\\&=\gamma+\frac{2\eta_c}{L^2}f_{bc}(t)x_L\sin\frac{n\pi x_L}{L}+\frac{2\eta_c}{L}\tilde{h}(x_L,t)x_L\sin\frac{n\pi x_L}{L}\end{aligned} \tag{61}$$

or in matrix form,

$$\frac{d\mathbf{u}}{dt}=\mathbf{B_1u}+\mathbf{C_1f} \tag{62}$$

where $J_{B1}(\cdot)$ = the Bessel function; α^*_k = roots of the equation of $J_{B0}\left(\alpha^*_k\right)=0$, and $J_{B0}(\cdot)$ is the Bessel function of the first kind of order zero; $f_{bc}(\cdot)$= boundary conditions in 2D derivation ; R = pipe radius; $\tilde{h}=h-xf(t)/L$ = the auxiliary function; x_L = leak location; γ, η_c = the coefficients of the linearized leak term in model, which can be calculated as

$$\gamma=\frac{C_dA_L\sqrt{2g}}{2\pi R}\sqrt{(H_{L0}-z_L)}$$

$$\eta=\frac{C_dA_L\sqrt{2g}}{2\pi R}\frac{1}{2\sqrt{(H_{L0}-z_L)}}$$

in which H_{L0}, z_L = original head and elevation at leak location; $\mathbf{u}=\left[\tilde{h}_1,\tilde{h}_2,\cdots,\tilde{h}_N,u_{11},u_{12},\cdots u_{NK}\right]$; and $\mathbf{B}$, $\mathbf{C}$ = coefficient matrices. As a result, the real parts of the complex eigenvalues of matrix

B represent the damping rates of the given transient information.

Transient Frequency Response-Based Method (TFRM)

The transient reflection and damping based methods were designed to use only one of the two types of information in the transient signal for detecting and locating leaks. There are other methods, such as the transient frequency response-based method (TFRM) that uses the entire transient signal to detect and locate the leaks. In this type of method, the leak can be identified and located in the system by analyzing the harmonic and impulse modes of pressure wave traces (Ferrante & Brunone, 2003a, b; Covas *et al.*, 2005c; Lee *et al.*, 2006; Lee *et al.*, 2007; Sattar & Chaudhry, 2008; Duan *et al.*, 2011a; Duan *et al.*, 2012c; Gong *et al.*, 2013b; Gong *et al.*, 2014a; Kim, 2016; Duan, 2017). For illustration, the TFRM presented in Lee *et al.* (2006, 2007) and Duan *et al.* (2011a) is introduced herein for the method principle and application procedure.

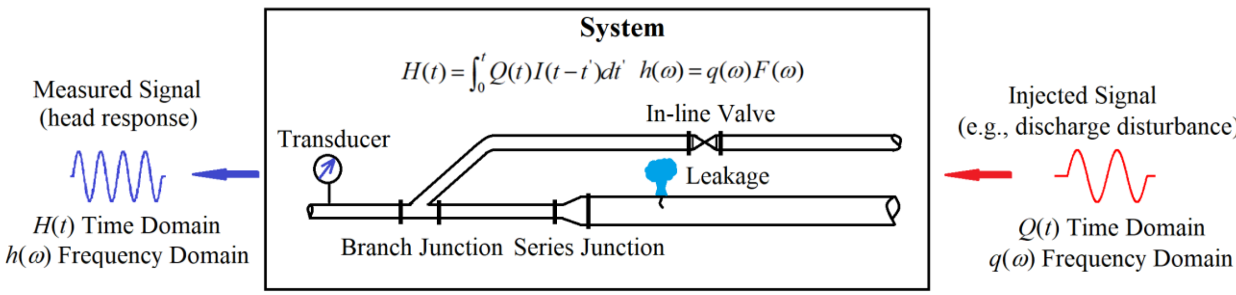


Figure 12. Sketch of transient frequency response analysis for a pipeline system

In any pipeline system, as shown in Fig. 12, a transient signal can be considered as the result of different disturbances imposed on the system, e.g., input $Q(t)$, while the measured system responses are the outputs from the system, $H(t)$. In this way, the behavior of a pipeline system can be described as a transfer function that produces the outputs for given inputs. The relationship between input and output signals in the time domain is given as a convolutional integral (Lee *et al.*, 2007):

$$H(t)=\int_0^t Q(t)I(t-t')dt' \quad (63)$$

where $I(\cdot)$ = the impulse response function (IRF) of the system containing all the information pertaining to the behavior of the system. By applying the Fourier transform technique (Kreyszig *et al.*, 2008), the expression becomes,

$$h(\omega) = q(\omega)F(\omega) \tag{64}$$

where $F(\cdot)$ = the frequency response function (FRF) of the system; ω = wave frequency.

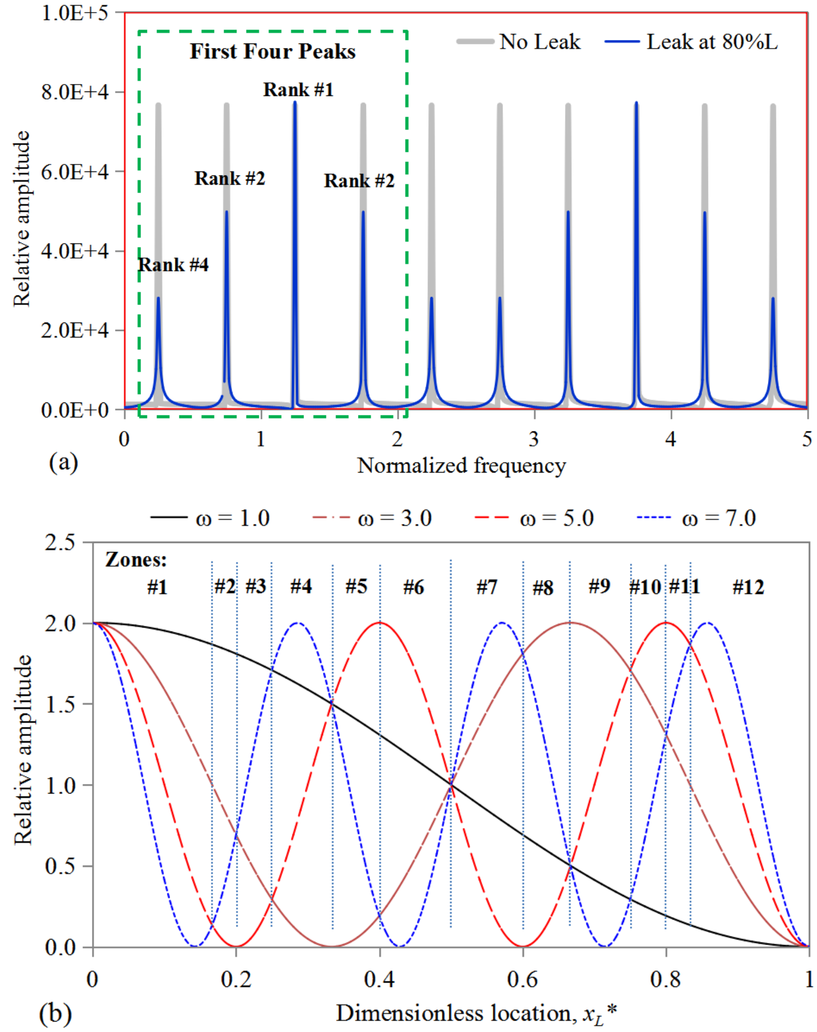


Figure 13. Transient frequency response results (based on 1D numerical results): (a) FRF in the frequency domain; (b) response pattern for different frequency modes

The system response function, either in the time domain as the IRF or in the frequency domain as the FRF, describes the fundamental response of the system from an impulse excitation. A leak in the pipeline results in a change in this system response. Taking again the simple pipe system in Fig. 9(a) for example, the FRF from leaking and non-leaking pipelines are shown in Fig. 13(a). In an intact pipeline the frequency response function consists of a series of uniformly spaced and sized harmonic peaks (thin solid-line in Fig. 13(a)). On the other hand, for a leaking system the size of these peaks varies with frequency (thick solid-line in Fig. 13(a)) and was called the "leak-induced pattern" by Lee *et al.* (2006) and Duan *et al.* (2011a). The responses of the relative amplitude for the first four peak frequency modes with a leak at different locations along the pipeline are shown in Fig. 13(b). Then the entire domain along pipeline can be divided into different zones in which there is unique relation among different frequency peak responses.

This perturbation pattern is the result of leak-induced changes to the transient response and can be used to locate the leaks. Thereafter, the analytical expression for the leak induced pattern has been widely developed and applied for leak detection in both elastic and viscoelastic pipelines (Lee *et al.*, 2006; Duan *et al.*, 2012c) with the following form,

$$\hat{h} = \alpha_s \cos\left(2\pi m x_L^* - \theta\right) + \beta \tag{65}$$

where $\hat{h}$ = inverted FRF magnitude; θ, β = coefficients; and m = peak number. The variables x_L^* and α_s in Eq. (65) are measures of the potential leak location and size in the system.

From Lee *et al.* (2006), the TFRM agrees well with experimental results. As the technique uses the entire transient signal, the TFRM technique utilizes both the reflection and damping information from the leak. But there are several aspects still need more in-depth validations which may include the influences of the transient amplitude, external transient noise, and unsteady friction, among others. It is important to note that this developed TFRM for leak detection does not rely on the system to be driven to resonance by a continuous valve oscillation at the natural system frequency. That is, a continuous valve oscillation at each frequency is not required to build the frequency response function as in Fig. 13(a). Instead the technique observes the response of the harmonic frequency components contained in the initial input signal, which can be any signal with sufficient bandwidth including the signal from a fast valve closure (Lee *et al.*, 2015). The frequency components corresponding to an odd integral multiple of the natural system frequency are reinforced by the system and forms the "frequency peaks" in Fig. 13(a).

The initial form of the TFRM was developed in Lee *et al.* (2006) for single pipeline situation only, which has greatly limited the applicability of this efficiency and economic method. To this end, the study of Duan *et al.* (2011a) has successfully extended this method to multiple pipes in series, in which the analytical expression of leak induced pattern has been derived in multiple pipe systems for leak detection. Thereafter, Duan (2017) has further extended this TFRM to more complex pipe systems including simple branched and looped pipe junctions as shown in Fig. 14. As a result, this TFRM has been greatly enhanced for its applicability and efficiency. Specifically, the derived patterns for the branched and looped pipeline systems are given as follows (Duan, 2017).

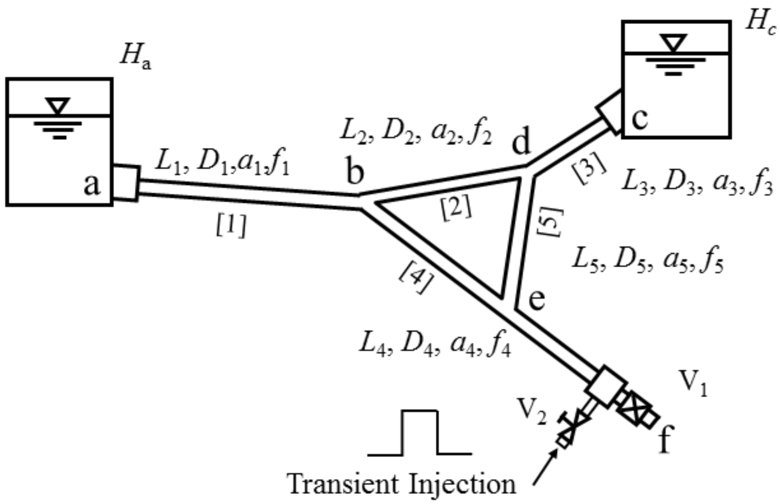


Figure 14. An illustrative pipe network with branched and looped junctions

(1) For branched pipelines:

$$\hat{h}_{Lnp}^{B} = \frac{K_L}{C_{np}^{B}}\left[1-\cos\left(2\mu_{np}x_{Lnp}+\varphi_{np}^{B}\right)\right] \tag{66}$$

where $\hat{h}_{Lnp}$ is the converted TFR based on the difference between the intact and leakage situations in branched pipeline system; *np* is the number of pipe that the potential leakage is located; x_{Lnp} is the distance of leakage location from the upstream end of the pipeline *np*; K_L is the impendence factor for describing the leakage size; the subscript *L* is used for quantity for leaking pipe system; the superscript *B* indicates the quantity for branched pipeline system, and *C*, ϕ are intact system based known coefficients.

(2) For looped pipelines:

$$\hat{h}_{Ln}^{O} = \frac{K_L}{C_n^{O}}\left[R_n^{O}+\sqrt{\left(S_n^{O}\right)^2+\left(T_n^{O}\right)^2}\sin\left(\mu_n l_n-2\mu_n x_{Ln}+\phi_n^{O}\right)\right] \tag{67}$$

where the superscript *O* indicates the quantities obtained for the looped pipeline system; and *C*, *R*, *S*, *T*, ϕ are known coefficients based on intact system; other symbols are the same as in Eq. (66).

This extended TFRM has been validated through different numerical simulations (Duan, 2017), followed by a systematical investigation based on sensitivity analysis in Duan (2018). The application results in Duan (2017) demonstrated the applicability and accuracy of the extended

TFRM method for leakage identification and detection in these multiple-pipeline systems. However, the results also implied that this method is more accurate to locate the pipe leakage than to size the leakage from the applications. Moreover, the results and analysis in Duan (2018) indicated that the uncertainty of the pipe wave speed, diameter and data measurement can contribute dominantly to the variability of the detection results (both leak size and leak location), and the variation of the detection results is more sensitive to the actual leak size than the leak location, which is consistent with the original TFRM for single pipeline systems. From these researches, it can be concluded that a good understanding of the intact pipeline system as well as an accuracy measurement system will be crucial to the application of the TFRM for practical UWSS diagnosis and management.

Inverse Transient Analysis-based Method (ITAM)

The inverse transient analysis-based method (ITAM) is a popular method which uses the entire transient signal by calibrating and matching the outputs from a numerical model to measured data records (e.g., Liggett & Chen, 1994; Vítkovský *et al.*, 2000; Al-Khomairi, 2008; Shamloo & Haghighi, 2009; Covas & Ramos, 2010; Capponi *et al.*, 2017). The predicted response with the leaks in the correct locations results in the closest match with the measured results. Since the ITAM uses the entire transient response trace in the time domain for calibration, this method utilizes both leak induced damping and reflection information. For example, the objective function for the optimization can be expressed as,

$$\max : Z = \frac{C}{1 + \sum_{i=1}^{N} \left[H_i^m - H_i^p \right]^2} \tag{68}$$

where Z is fitness of objective function; H^m is measured pressure head; H^p is predicted pressure head by using numerical models; $i = 1 \ldots N$ is time-step point for comparison; and C is a constant coefficient. To obtain the potential leak information, different mathematical programming and searching methods have been used for optimizing the objective function of Eq. (68), including: Genetic Algorithm (GA) (Liggett & Chen, 1994; Vítkovský *et al.*, 2000; Stephens, 2008); Simulated Annealing (SA) (Huang *et al.*, 2015); Levenberg-Marquardt (LM) (Kapelan *et al.*, 2003), Non-linear Programming (NLP) (Shamloo & Haghighi, 2009, 2010); Least Squares and Match-Filter (LSMF) (Al-Khomairi, 2008; Keramat *et al.*, 2019); Gaussian Function (GF) (Sarkamaryan *et al.*, 2018); and Artificial Neural Networks (ANN) (Bohorquez *et al.*, 2020).

Signal Processing-Based Method (SPM)

In recent years, another type of transient-based method with the aid of different advanced signal processing algorithms, termed as signal processing-based method (SPM) herein, has been developed and used for leak detection in water pipelines. According to the used signal processing methods for transient analysis, the SPM can be divided into several groups as follows:

(1) time-frequency analysis based on the Empirical Mode Decomposition (EMD), coupled with Hilbert Transform (HT) (e.g., Ghazali *et al.*, 2012; Sun *et al.*, 2016) or Cepstrum analysis (e.g., Taghvaei *et al.*, 2006; Taghvaei *et al.*, 2010; Ghazali *et al.*, 2011; Shucksmith *et al.*, 2012; Yusop *et al.*, 2017);

(2) frequency domain variable separation by the Matched-Field Processing (MFP) (e.g., Wang & Ghidaoui, 2018a; Wang *et al.*, 2019; Wang *et al.*, 2020);

(3) statistical analysis through Maximum Likelihood (ML) (e.g., Wang & Ghidaoui, 2018b), or Cross-correlation Analysis (CCA) (e.g., Beck *et al.*, 2005);

(4) time domain signal reconstruction based on the Least Squares Deconvolution (LSD) or Generalized Cross Validation (GCV) (e.g., Nguyen *et al.*, 2018; Wang & Ghidaoui, 2018a; Wang *et al.*, 2020).

Despite that these five types of transient-based methods (TRM, TDM, TFRM, ITAM and SPM) have been developed, validated and applied for different experimental systems (laboratory or field), it is also observed from various applications in these studies that their effectiveness would be highly dependent on the accuracy of transient models implemented in the method as well as the precision and capacity of transient data measured from the system. Meanwhile, all these methods are mainly limited to relatively simple pipeline systems that may include few series and branched and looped junctions (e.g., Kapelan *et al.*, 2003; Duan, 2011; Ghazali *et al.*, 2012; Shucksmith *et al.*, 2012; Duan, 2017), while they are unable to deal with pipe systems with complex configurations as commonly seen in practical UWSS. A relevant literature review by Colombo *et al.* (2009) pointed out that the validations and applications of present transient-based leak detection methods are mainly focused on simple systems and many had not yet involved field situations. Based on their analysis, one of the main reasons is the potential difficulty in dealing with practical factors/complexities affecting the transient damping and reflections such as external fluxes, internal junction connections, elbow connections and other system properties.

Moreover, it is also noted that the appropriate combinations of different transient-based methods (and other technologies if possible) will be greatly beneficial to improve the leak detection results for complex UWSS.

Transient-Based Blockage Detection

Partial blockages in aging pipeline infrastructures can be caused by various reasons, including biofilm and deposition (e.g., Fig. 1(b)), deformation (Fig. 1(d)), corrosion (e.g., Fig. 1(e)) and air pocket accumulation (e.g., Fig. 1(f)). Partial blockages in pipelines could increase operational costs by reducing the flow capacity as well as increasing the energy dissipation throughout the system (Lee *et al.*, 2008a). Unlike leaks, the presence of partial blockages in a pipeline does not result in clear external indicators and the problem often remains undetected until the pipeline is close to fully constricted. Partial blockages are classified based on their physical extent relative to the total length of the system. Localized constrictions that can be considered as point discontinuities are referred to as discrete partial blockages (Lee, 2005). Common examples of this type are partially closed inline valves or orifice plates. In comparison, partial blockages caused by pipe aging are more common and often cover significant stretches of pipe relative to the total pipe length, which are commonly termed as extended partial blockages in this field (Stephens, 2008; Duan *et al.*, 2012b). Since the diagnosis methods developed for these two types of partial blockages are different in principle, they are presented individually as follows.

Discrete Partial Blockage Detection

Several researches recently dealt with the first type of partial blockage detection—discrete partial blockage in pipelines. The methods used for discrete partial blockage detection can be divided into time-domain and frequency-domain approaches. For the time-domain approach, the principle and procedure are similar to the TRM and ITAM that were developed for leak detection as shown in Fig. 10(a), where the location and size of discrete partial blockage can be estimated in the time-domain through the analysis of the interaction of waves with partial blockages (e.g., Stephens *et al.*, 2004; Stephens *et al.*, 2007; Meniconi *et al.*, 2011, 2012; Meniconi *et al.*, 2016). For the frequency-domain approach, the discrete partial blockage induced transient pattern is firstly derived based on analytical analysis for the 1D transient model, which is then used to inversely determine the potential partial blockage information (location and size) (e.g., Wang *et* *al.*, 2005; Mohapatra *et al.*, 2006; Lee *et al.*, 2008a; Sattar & Chaudhry, 2008; Kim, 2018). For example, the FRF result by Lee *et al.* (2008a) is shown as follows:

$$\hat{h}_B = \alpha I_B \cos\left[(2m-1)\pi x_B^*\right] + \beta \tag{69}$$

where $I_B = \Delta H_{B0}/Q_{B0}$ is partial blockage impedance; ΔH_{B0} is steady state head loss across the partial blockage; Q_{B0} is steady state flow across the partial blockage; x_B^* is partial blockage location from the upstream reservoir normalized by the total pipe length; m is peak number; α and β are constant coefficients. Through different experimental applications (laboratory and field) in the literature, it is shown that these developed transient-based techniques are applicable and accurate for locating and sizing partial blockages in water pipelines, provided that the potential partial blockage to be detected can be approximated as a localized discontinuity in the system.

Extended Partial Blockage Detection

The discussion by Brunone *et al.* (2008) has shown that discrete and extended partial blockages have significantly different impacts on the system responses and the techniques for discrete partial blockages in the literature may not be applicable for extended partial blockages. For the time domain analysis, the properties of extended partial blockage can be identified through the wave reflections at the ends of partial blockage section (see Fig. 15), so that the time-domain method for extended partial blockage detection has been proposed and applied for this purpose (e.g., Tuck *et al.*, 2013; Gong *et al.*, 2013a; Gong *et al.*, 2014b; Massari *et al.*, 2014; Massari *et al.*, 2015; Gong *et al.*, 2016; Zhao *et al.*, 2018; Zhang *et al.*, 2018; Keramat & Zanganeh, 2019). The principle of this time-domain extended partial blockage detection method is similar to the TRM above for the leak detection.

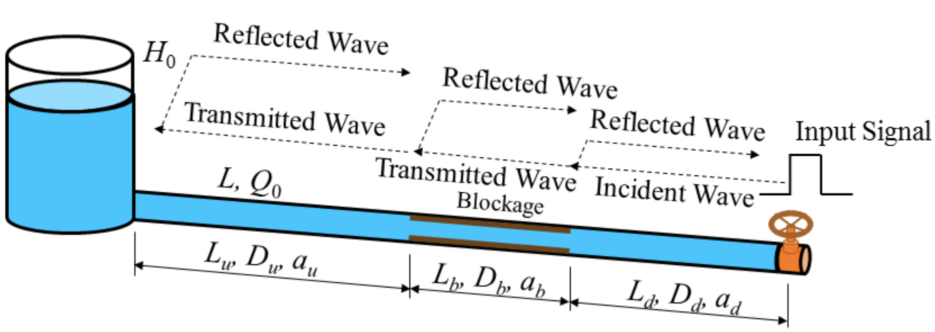


Figure 15. Illustrative pipeline system with an extended partial blockage

For the frequency domain analysis, Duan *et al.* (2012c) firstly developed the transient-based extended partial blockage detection method, which is based on the frequency shift pattern of transient responses that is dependent on partial blockage properties (location, size and length). This method has been verified with theoretical demonstration and sensitivity analysis as well as validated through laboratory experimental tests (Duan *et al.*, 2013, 2014a; Duan, 2016). Specifically, the blockage-induced frequency shift pattern for a single pipeline system with uniform extended partial blockage can be expressed as follows:

$$\begin{bmatrix} (Y_u+Y_b)(Y_b+Y_d)\cos[(\lambda_u+\lambda_b+\lambda_d)\omega_{rfb}] \\ +(Y_u-Y_b)(-Y_b-Y_d)\cos[(\lambda_u-\lambda_b-\lambda_d)\omega_{rfb}] \\ -(Y_u+Y_b)(Y_b-Y_d)\cos[(\lambda_u+\lambda_b-\lambda_d)\omega_{rfb}] \\ -(Y_u-Y_b)(-Y_b+Y_d)\cos[(\lambda_u-\lambda_b+\lambda_d)\omega_{rfb}] \end{bmatrix}=0 \tag{70}$$

where Y is the characteristic impedance of pipeline; λ is wave propagation coefficient; ω_{rfb} = resonant frequencies of the blocked pipe system; the subscripts *u*, *b*, *d* denote pipe sections from upstream to downstream (Fig. 15); $R_f = R_{fs} + R_{fu}$ is friction damping factor, with R_{fs} and R_{fu} representing the steady and unsteady friction components, respectively. The detailed expressions have been given previously in this paper.

For better describing the frequency shift pattern induced by the extended partial blockage in the pipeline, Eq. (70) can be further simplified as follows (Duan *et al.*, 2014a):

$$\Delta\omega^* \approx \frac{2}{\pi}\frac{\varepsilon_A}{2-\varepsilon_A}\left[\sin(2\lambda_u\omega_{rf0})-\sin(2\lambda_d\omega_{rf0})-\frac{\varepsilon_A}{2-\varepsilon_A}\sin(2\varepsilon_L\lambda_0\omega_{rf0})\right] \tag{71}$$

where $\Delta\omega^*$ is the normalized resonant frequency shift induced by the extended partial blockage; ω_{rf0} is the fundamental frequency of intact pipeline system; ε_A and ε_L are the normalized quantities of blocked area and length in the pipeline. Meanwhile, the mechanism of extended partial blockage induced frequency shift has been explained in Duan *et al.* (2014a) based on the analytical analysis of 1D wave equation for pipeline with uniform partial blockage. Specifically, their results evidenced that the wave reflection by extended partial blockage can be governed by:

$$R_w = -\left(1-\mathrm{e}^{-\mathrm{i}2\pi\omega/\omega_b}\right)\xi_s \tag{72}$$

where R_w is wave reflection coefficient; $\omega_b = 2\pi a_b/2L_b$; a_b and L_b are wave speed and length of partial blockage section (e.g., Fig. 15); and ξ_s is the relative change of the characteristic impedance by the partial blockage section along the pipeline. This result reveals clearly the dependence of wave reflection (and thus the transient phase and amplitude changes) on the extended partial blockage properties (length and size). For clarification, the changes of transient wave phase and amplitude imposed by an extended partial blockage are shown in Fig. 16 below, with the results normalized by the incident wave quantities.

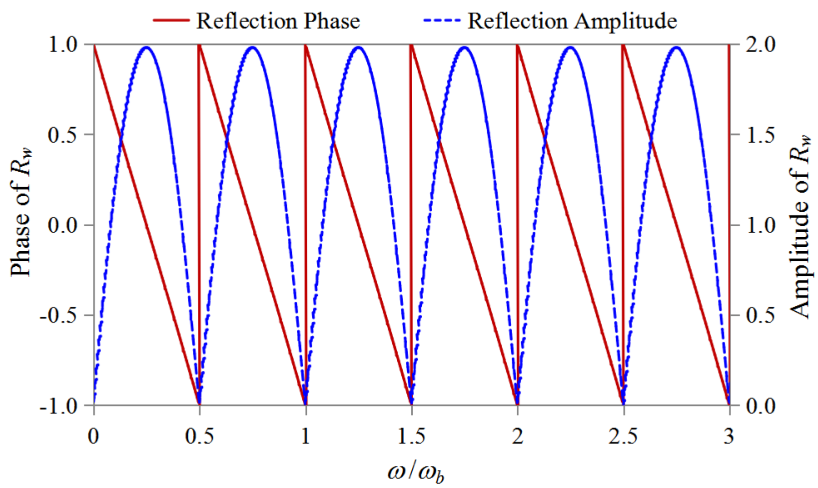


Figure 16. Changes of transient wave phase and amplitude induced by extended partial blockage

To enhance the effectiveness of transient-based methods, the coupled time and frequency domain method was explored in the study by Meniconi *et al.* (2013), and the application results demonstrated the improvement on the accuracy and efficiency of this type of method for extended partial blockage detection in water pipelines. Meanwhile, this method has also been extended for complex pipe systems by introducing advanced searching technology to solve Eq. (70), such as genetic algorithm (GA) (e.g., Datta *et al.*, 2018). Nevertheless, this developed transient-based method by Eq. (70) or Eq. (71) is valid only for uniform partial blockages which have relatively similar severity for each of these blockages (i.e., regular variations), so that the blockage sections could be treated as small uniform pipe sections in these methods. To address this issue, Che *et al.* (2018a) and Che *et al.* (2019) have investigated the interactions of non-uniform partial blockages with transient waves through analytical derivation and energy analysis. The results indicated the non-uniform partial blockage may induce very different modification patterns on both frequency shift and amplitude change of transient waves from the uniform case. To be specific, the resonant frequency shifts induced by non-uniform partial blockages become less evident for higher harmonics of transient waves. The mechanism understanding and derived results from these studies are useful to the application and improvement of current transient-based methods for extended partial blockage detection in UWSS.

Furthermore, the extended partial blockage detection method has also been further developed by advanced mathematical analysis and signal processing techniques for more realistic situations such as rough partial blockages with irregularity. For example, based on the multiple-scale wave perturbation analysis, the effect of wave scattering by rough partial blockages was derived and applied in Duan *et al.* (2011b, 2014b, 2017b). Meanwhile, Jing *et al.* (2018), Blåsten *et al.* (2019) and Zouari *et al.* (2019) have developed the pipe area reconstruction methods for rough partial blockage detection in both single and branched pipeline systems based on mathematical transformation and linear approximation (e.g., Liouville transformation and impulse response function), followed by laboratory experimental validations under different partial blockage conditions in Zouari *et al.* (2020). These studies have provided the possibility of extending current transient-based method to practical pipeline systems.

Transient-Based Pipe Branch Detection

In addition to the two common defects mentioned above (leakage and partial blockage), unknown branch is another important issue that is usually encountered in complex UWSS, such as illegal connections and non-recorded branches (e.g., Fig. 1(c)). Identifying these unknown branches becomes important to the construction, operation, monitoring and maintenance of UWSS. Unfortunately, these unknown branches commonly exist underground in UWSS and are not easy to detect by current commercial tools. For this purpose, transient has become a good choice to solve this problem. In this regard, Duan & Lee (2016) firstly developed the transient-based method for dead-end branch detection (e.g., branch section [3] in Fig. 14). In that study, the frequency domain shift pattern has been derived for the dead-end branched pipe system, which can be inversely used for identifying the properties of potential branches (connecting location, size and length) with the aid of a GA-based optimization procedure. Thereafter, Meniconi *et al.* (2018) proposed a time-domain method using the wave reflections for branch detection based on a Wavelet analysis technique. Their results have been validated through a field test, indicating the acceptable accuracy of branch detection results. Currently, however, all these methods are developed and applicable only for simple pipeline systems that include very few and simple branches with known intact system configurations.

Recently, an inverse transient analysis method based on the ANN framework was developed by Bohorquez *et al.* (2020) for a comprehensive diagnosis of pipe leakage and system topology (which may include unknown branches). But this method requires abundant prior-known data information for ANN training as well as relatively high computation capacity, which is therefore not feasible or practical for complex UWSS at current stage. Based on these preliminary researches, transient-based method has been shown to be a promising approach for pipe branch characterization and detection, but still needs further development and improvement for its applicability range and accuracy in the future.

Transient-Based Multi-Defect Detection

In practical UWSS, the potential problems of different pipe defects and system operations may occur simultaneously in the system (which is actually very common in UWSS), so that the types and numbers of defects are usually not known in advance. As a result, the application of above-mentioned transient-based defect detection (TBDD) methods becomes difficult or even invalid. To this end, preliminary studies in the literature have made efforts on developing more holistic TBDD in order to achieve the capability of multiple-defect detection in pipelines. For instance, Stephens *et al.* (2004) has successfully applied the inverse transient wave analysis for locating the leakage, air-pocket and discrete partial blockage in two field test pipeline systems. Thereafter, Sun *et al.* (2016) developed a time-frequency analysis method based on EMD-HT algorithm, which can be applied to identify different types of defects including leakage, discrete and extended partial blockages, and branched junction. The proposed method and application procedure have been validated through laboratory experimental tests. The results demonstrated that this method could provide good detection accuracy for the types, numbers and locations of multiple defects, but failed to quantify the sizes of all the defects in the system. Meanwhile, Kim (2016) proposed the transient impedance method for the detection of leakage and partial blockage in a branched pipeline system, followed by the recent studies for the multiple partial blockage detection in a single pipeline (Kim 2018) and multiple leaks detection in pipe networks (Kim, 2020).

Recently, Duan (2020) developed a TFRM for the simultaneous detection of leakage and partial blockage in the pipeline. The TMA method was applied to derive the analytical results of FRF in a simple pipeline system with both leakage and discrete partial blockage. The results implied that the leak-induced and partial blockage-induced patterns could be treated approximately to be independent (i.e., linear superposition), as long as the impedance factors of these two defects are much smaller than 1 (so that their product is also much smaller than 1). This finding from that study has been validated through both different numerical and experimental applications.

The development progress and achievement of these TBDD methods have given the promise and confirmation on the feasibility and possibility of this type of innovative method for the pipeline system diagnosis under different conditions, although it also indicates a relatively long distance to make further advances in this field in the future.

Advances for Transient Research and Recommendations for Future Work

Despite the substantial progress and achievement made in the past many years, the developed model and methods still could not cover all the possible situations in practical UWSS. That is, the high complexities in the realistic UWSS may cause the failure or inaccuracy of these models and methods, especially when the transients are utilized more and more for system diagnosis and management rather than for the transient system design purpose only (e.g., system strength and protection devices). Meanwhile, transient flows are common states of UWSS (as common as steady flow states), which may be triggered at anytime and anywhere in the system due to various factors including both regular/normal and unexpected operations of the system, such as (but not limited to) demand variation, valve operation, pipe burst, pump switching and power failure, system construction and maintenance, etc.). In this connection, understanding the very details of transient evolutions in the system becomes important to the system operation and management, which may present relatively high requirements for transient models and methods.

To address these issues and make further advances on the transient research, many researchers and engineers in this field have been involved in different advanced topics on transient modelling and utilization. Through the literature review, some important transient research topics and directions that have been initiated by the researchers in this field can be briefly summarized as follows.

(1) Multi-phase transient flows, including transient air-water interaction and air-pocket analysis in the UWSS (e.g., Wylie *et al.*, 1993; Zhou *et al.*, 2002; Zhou et al., 2011; Zhou et al., 2018; Zhu *et al.*, 2018; Alexander *et al.*, 2019; Alexander *et al.*, 2020);

(2) High-frequency and radial waves in both actively and passively generated transients for system diagnosis (e.g., Mitra and Rouleau 1985; Che and Duan, 2016; Louati & Ghidaoui, 2017a, 2017b, 2019; Che *et al.*, 2018b);

(3) Transient generation (bandwidth and amplitude) for the application of transient-based methods (e.g., Brunone *et al.*, 2008; Lee *et al.*, 2008b; Lee *et al.*, 2015; Lee *et al.*, 2017; Haghighi and Shamloo, 2011; Meniconi et al., 2011);

(4) Transient noise and uncertainty analysis for transient modelling and utilization (e.g., Duan *et al.*, 2010d; Duan *et al.*, 2010e; Dubey *et al.*, 2019; Duan, 2015, 2016);

(5) Transient-based skeletonization and design for complex UWSS (e.g., Huang *et al.*, 2017a, 2017b; Huang *et al.*, 2019, 2020a, 2020b);

(6) Transient data measurement and transfer (e.g., Brunone *et al.*, 2000; Brunone and Berni, 2010; Kashima *et al.*, 2012, 2013; Brito *et al.*, 2014; Leontidis *et al.*, 2018).

In addition, with the rapid development of computational capacity, the efficient multi-dimensional simulations (e.g., CFD-based 2D or 3D modelling) will become gradually feasible for both fundamental research and small-scale application purposes (e.g., Martins *et al.*, 2014; Martins *et al.*, 2016; Martins *et al.*, 2018; Che *et al.*, 2018b). With these advanced research methods and simulation tools, it is expected that the understanding of transient-related phenomena and the application of transient-based methods would be greatly enhanced and thereby effectively utilized for the development and management of Smart UWSS.

Concluding Remarks

This paper presents a state-of-the-art review on the progress and accomplishment in the field of transient research and application in the urban water supply system (UWSS), with providing perspectives for comprehensive understanding and essential dissemination on the necessity and significance of transient research for UWSS.

On one hand, the transient theory and models developed in the literature are revisited in a systematical way for the transient simulations and analysis in UWSS, including the derivations of governing equations in 1D and 2D forms, unsteady friction and turbulence formulas and viscoelastic models. Meanwhile, the common numerical methods for solving the transient models in both time and frequency domains are introduced, such as the method of characteristics (MOC) and the transfer matrix analysis (TMA). Particularly, typical examples are given in the paper for demonstrating the applications of these models and methods. On the other hand, the utilizations of transient flows for pipeline diagnosis, termed as TBDD method, are reviewed for different types of pipe defects with introducing the main principles and application procedures. Particularly, four types of common pipe defects in UWSS are illustrated herein – leakage, discrete partial blockage, extended partial blockage and unknown branch. The advantages and limitations of each developed TBDD method have been elaborated through example demonstrations and/or explanatory analysis.

Based on the literature review, the potential advances and implications as well as recommendations for the future work on transient research are also discussed in the end of the paper, with the aim to better assist in the development and management of Smart UWSS. Finally, despite that a total of over 200 publications have been reviewed and analyzed in this paper, it is very possible that other relevant publications might have been omitted unintentionally during the preparation of current paper.

Acknowledgement

This research work has been supported by the Hong Kong Research Grants Council (RGC) under projects numbers 25200616, 15201017 and 15200719.

Notation:

List of main symbols used in the paper

a = wave speed;

a_c, C_B, κ_1, C_m, C_c, C_μ, σ_k, σ_ε, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, f_1, f_2, f_μ, f_w, R_y, R_t, R_*, y_*, y = coefficients in turbulence models;

$A = \pi r^2$ the cross-sectional area of the pipe;

A_L = leak area size;

$\mathbf{b_u}$, $\mathbf{b_v}$ $\mathbf{B}$, $\mathbf{B_1}$, $\mathbf{C}$, $\mathbf{C_1}$, $\mathbf{S}$, $\mathbf{J}$, $\mathbf{W}$, $\mathbf{R}$, $\mathbf{L}$ and $\mathbf{K}$ = vectors and matrices in 2D model;

C = pipe constraint coefficient;

C_L, C_d = leak and orifice coefficients;

D = pipe diameter;

e = pipe-wall thickness;

E_{kv} = modulus of elasticity in K-V model;

f = the Darcy-Weisbach friction factor of pipeline;

$F(\cdot)$ = the frequency response function (FRF) of the system;

g = gravitational acceleration;

$\hat{h}$ = inverted FRF magnitude;

H = piezometric head;

H_{L0}, Z_L = original head and elevation at leak location;

ΔH_{B0} = steady state head loss across the partial blockage;

i = imaginary unit or counting number;

$I(\cdot)$ = impulse response function (IRF);

I_B = partial blockage impedance;

$J(\cdot)$ = creep compliance;

$J_{B1}(\cdot)$ = the Bessel function;

$J_{kv} = 1/E_{kv}$ = creep compliance of the k-element;

K_L = the leakage impendence factor;

l = the mixing length in turbulence model;

L = pipe section length;

m = peak number;

n = harmonic mode number;

np = leaking pipe number;

N = total number of K-V elements;

Nr = the total grid number in radial direction in 2D model;

P = pressure;

q, h = discharge (Q) and pressure head (H) in the frequency domain;

Q_L= leak discharge;

Q_{B0} = steady state flow across the partial blockage;

r = radial distance from pipe center;

R = radius of pipe;

R_e = Reynolds number;

R_{nL}= the leak-induced damping rate for the nth mode;

R_{fs}, R_{fu}, R_f = steady, unsteady and total friction damping factors, respectively;

R_w = wave reflection coefficient;

t = time;

t' = a dummy time variable;

T_w, T_d = timescales of axial wave propagation and radial turbulent diffusion;

u = longitudinal velocity;

u^*, v^*, H^*, τ^*, ρ^*, x^*, t^*, r^* = dimensionless variables;

U, V, H_J, τ_0, ρ_0, L, L/a, δ = scaling orders of variables u, v, H, t, ρ, x, t, r;

U_T = initial friction velocity;

$W(\cdot)$ = weighting function in unsteady shear stress;

x = spatial coordinate along the pipeline;

x_L, x_L^* = dimensional and dimensionless leak location;

Y = the characteristic impedance of pipeline;

Z = fitness of objective function;

α_k^* = roots of the equation of $J_0(\alpha_k^*) = 0$;

α, β = coefficients;

α_s = the potential leak size in the system;

δ = unsteady boundary layer thickness;

ε_A and ε_L = normalized quantities of blocked area and length in the pipeline

ε_r = total retarded strain of the viscoelastic pipe;

v = transverse velocity;

ν_k = kinematic viscosity of the fluid;

ν_t = turbulent eddy viscosity

$\nu_T = \nu_t + \nu_k$ = total viscosity;

v_R = radial velocity at pipe-wall due to deformation;

ξ_s = relative change of the characteristic impedance by the partial blockage;

ρ = fluid density;

σ = normal stress related to pressure head;

σ_x, σ_r, σ_θ = normal stress in longitudinal, transverse and angular directions, respectively;

η = the weighting coefficient;

η_{kv} = viscosity of the kv-element;

θ, β = coefficients;

κ, ε = turbulent kinetic energy and dissipation rate, respectively;

λ = wave propagation coefficient;

μ = propagation operator;

τ = shear stress;

$\tau_{kv} = \eta_{kv} / E_{kv}$ = retardation time of the *kv*-element;

τ_t = turbulent component of shear stress;

τ_l = laminar component of shear stress;

τ_s, τ_{ws} = quasi-steady part of shear stress and wall shear stress;

τ_u, τ_{wu} = unsteady part of shear stress and wall shear stress;

τ_w = wall shear stress;

ϕ, φ = the variables to be solved;

$\overline{\chi}$ = density-weighted-averaging quantities;

χ' = density-weighted-averaging pulsation quantities;

ω = frequency of wave signal;

$\Delta\omega^*$ = normalized resonant frequency shift;

ω_{rfb} = resonant frequencies of the blocked pipe system;

ω_{rf0} = fundamental frequency of intact pipeline system;

List of main acronyms used in this paper

1D: one-dimensional;

2D: two-dimensional;

ANN: artificial neural networks;

CCA: cross-correlation analysis;

CPU: central processing unit;

CUSUM: cumulative sum;

EMD: empirical mode decomposition;

FD: finite difference;

FRF: frequency response function;

FRT model: five-region turbulence model;

GA: genetic algorithm;

GCV: generalized cross validation;

GF: Gaussian function;

HDPE: high-density polyethylene;

HT: Hilbert transform;

IMAB models: instantaneous material acceleration-based models;

IRF: impulse response function;

ITAM: inverse transient analysis-based method;

IWSA: International Water Supply Association;

K-V model: Kelvin-Voigt model;

LM: Levenberg-Marquardt;

LSD: least squares deconvolution;

LSMF: least squares and match-filter;

MFP: matched-field processing;

ML: maximum likelihood;

MOC: method of characteristics;

NLP: non-linear programming;

ODE: ordinary differential equation;

PE: polyethylene;

PPR: polypropylene;

PVC: polyvinyl Chloride;

QSA models: quasi-steady algebraic models;

RANS: Reynolds-averaged method;

SA: Simulated Annealing;

SPM: signal processing-based method;

TBDD: transient-based defect detection;

TDM: transient damping-based method;

TFRM: transient frequency response-based method;

TLB: two-layer turbulence;

TMA: transfer matrix analysis;

TRM: transient reflection-based method;

UWSS: urban water supply system;

WFB: weighting function-based;

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