Brunone, B., Meniconi, S., and Capponi, C. (2018). Numerical analysis of the transient pressure damping in a single polymeric pipe with a leak. Urban Water Journal, 15(8), 760–768, available at: http://www.tandfonline.com/https://doi.org/10.1080/1573062X.2018.1547772.

Numerical analysis of the transient pressure damping in a single polymeric pipe with a leak.

B. Brunone[a] and S. Meniconi[a] and C. Capponi[a]

[a]Dipartimento di Ingegneria Civile ed Ambientale, The University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy

ABSTRACT

In the last decades transient test-based techniques (TTBTs) are imposing for fault detection in transmission mains. Within TTBTs, the direct transient analysis (DTA) allows identifying the defects directly in the pressure signal. A possible DTA procedure is based on the analysis of the damping of the pressure peaks. In this paper, it is shown that the pressure decay in a polymeric leaky pipe depends exponentially on leak size and location and the pressure at the leak. It is also pointed out that, for a given transient, the same damping of the pressure peaks may result from different pipe systems (e.g., with the leak of a different size in a different location). Such a result merits further insights also by means of experimental tests in different pipe systems.

KEYWORDS

leak detection, pressure damping, transients, transmission mains

1. Introduction

It is more than a century ago that, by the evidence of clear laboratory experiments, Joukowsky (1900) pointed out that in a pressurized pipe transient pressure waves are partially reflected by any change in the physical structure of the pipe. Possible changes are defects like, as an example, a leak, a partial blockage due to the deposition of sediment, and a deterioration of the pipe wall. A change may be also due to a device (e.g., a partially closed in-line valve) or a branch. As a consequence of such a property of the pressure waves, in principle any change in the pipe can be detected by means of transient tests. However, the fault detection procedure may fail if the way how the tests are executed and the methods used for analyzing the results are not appropriate. Notwithstanding the clear evidence of the principle on which they are based, till early nineties of the last century, transient test-based techniques (TTBTs) disappeared into an almost full oblivion surrounded by skepticism. Even in the solitary paper by Babbitt, Amsbary, and Gwinn (1920), after having highlighted the potential of the TTBTs, the Authors clearly show their preference for steady-state tests to detect a leak in a pipe. The true reason of such an attitude of both the Academia and technicians is the unjustified assumption that large — and then potentially dangerous for the pipes — pressure waves must be generated for a reliable fault detection. Only recently, such a

---

CONTACT B. Brunone. Email: bruno.brunone@unipg.it

prejudice has been rebutted on the basis of convincing results of both laboratory and field tests. Specifically, it has been shown that small amplitude pressure waves allow a reliable fault detection (e.g. Meniconi et al. 2011b, 2017).

This said, it is evident that, particularly for transmission mains (TMs), for a number of reasons competitiveness and favorable prospects of TTBTs are undeniable with respect to other methods. As an example, the short duration of the transient tests and the fact that only pressure measurements are needed are certainly in favor of TTBTs with respect to steady-state tests. TTBTs are even more attractive since they allow detecting devious defects (e.g., partial blockages) which do not give rise to any exterior sign (Duan et al. 2011, 2013; Lee et al. 2008; Louati and Ghidaoui 2017; Louati et al. 2017; Zhang et al. 2018). The alternative option, i.e. the in-line type technologies with tethered and free-swimming sensors inserted into the pipelines, is more demanding from both the economic and logistic point of view. In fact such technologies imply the construction of quite expensive as well as stable access points for the insertion and extraction of the sensors. Furthermore, such a need prevents the utilization of the in-line type technologies for executing an extemporary check of the pipe systems which, on the contrary, is possible when TTBTs are used (e.g. Meniconi et al. 2011a).

In the view of the above, with the aim of improving the performance of TTBTs, nowadays attention is focused on refining procedures for executing reliable transient tests and appropriate methods for analyzing the experimental data. With regard to the latter point, in literature several approaches have been proposed to maximize the amount of information which can be extracted from data collected during transient tests. A basic distinction concerns whether or not a numerical model simulating the transient tests is used. If it is, we can speak in terms of Inverse Transient Analysis (ITA) where the characteristics of the defect (e.g., type, location, and severity) are the unknowns of the problem and are obtained within a calibration procedure by minimizing the difference between the measured data and the numerical model results. The success of such a method, proposed by Liggett and Chen (1994), depends strongly on the degree of knowledge of the pipe system feature (e.g., boundary and initial conditions, and geometrical and mechanical characteristics of the pipes). To fulfill such a requirement, the preliminary measurement at several sections of both pressure and discharge and a detailed inspection of the pipe components is needed. Moreover, within ITA a proper balance between using the most appropriate governing equations and minimizing the number of the parameters to be estimated is not an easy task. As an example, the role of the unsteady friction (UF) and viscoelasticity (VE), and then if it is the case of including or not such a term in the momentum and continuity equation respectively, is not known a priori (e.g. Duan et al. 2010a; Nixon and Ghidaoui 2007). In general, it can be said that the more complete the model — and then the better its performance — the more complex the preliminary phase in which it must be assessed before the unknowns of the problems (i.e., the characteristics of the defects) are obtained. The criticality of such constraints are merely suggested when numerical or laboratory experiments are examined but they can exceed the most pessimistic forecast when dealing with real TMs. As an example, in Meniconi, Brunone, and Frisinghelli (2018), field and numerical experiments show the unexpected remarkable effect of the short minor branches, even if inactive, and small defects (e.g., the malfunction of a valve which allows the flow of a small discharge) on the transient response of a TM. Moreover, the evaluation of the actual pressure wave speed — a key parameter within TTBTs — may experience a serious difficulty (e.g. Meniconi et al. 2015).

To the end of surpassing the intrinsic complexity of ITA, instead of simulating accurately the full experimental pressure traces, a Direct Transient Analysis (DTA) can be performed in which the effects of the defects are identified directly in the pressure signal. Within DTA, two possible approaches can be followed (Colombo, Lee, and Karney 2009): the time-domain reflectometry (e.g. Jönsson 1970; Jönsson and Larson 1992; Brunone 1999), and the transient damping method (Wang et al. 2002; Nixon, Ghidaoui, and Kolyshkin 2006). In the first case, the characteristics of the pressure waves reflected by the defect/device are considered whereas in the second case the examined feature is the damping of the Fourier components for each mode of the pressure signal. The relative importance of the damping and reflective effects from the leak has been examined in Duan et al. (2010b).

In literature, the properties of the reflected pressure waves have been quite extensively explored. In fact, laboratory and field tests, as well as numerical experiments both in the time and frequency domain (e.g. Brunone 1999; Covas and Ramos 2010; Lee et al. 2006, 2005; Mpesha, Gassman, and Chaudhry 2001; Mpesha, Chaudhry, and Gassman 2002), have pointed out the main factors influencing the reflected pressure waves. On the contrary, since the identification of the mechanisms governing the damping of the pressure peaks in a pipe with a leak deserved less attention (Wang et al. 2002; Nixon, Ghidaoui, and Kolyshkin 2006), particularly for polymeric pipes, the aim of this paper is to explore in more details the behavior of the pressure peak damping in a high-density polyethylene pipe (HDPE).

As an important premise, it must be noted that after fast closure maneuvers (as those usually executed for fault detection), in an integer single pipe the damping of the pressure peaks — hereafter referred to as intrinsic damping — is mainly due to UF and VE since in such transients the relevance of the steady-state friction is quite negligible. As highlighted by Duan et al. (2010a), UF plays a significant role in elastic pipes whereas VE is noticeable in polymeric ones. In elastic pipes, the presence of a leak changes significantly the transient response of the system (Wiggert 1968) with the importance of UF depending on the percentage of the flow through the leak with respect to the mean flow (Nixon and Ghidaoui 2007). In terms of the pressure signal, the effect of the leak is an additional damping of the pressure peaks with respect to the intrinsic one (e.g. Wang et al. 2002; Colombo, Lee, and Karney 2009). Pressure signals of Fig. 1 indicate that the same applies to HDPE pipes with an additional pressure peak decay quite larger than the intrinsic one (i.e., the damping, due mainly to VE, happening in the integer pipe), according to Duan et al. (2012); in the figure, H = piezometric head (with the subscripts M and 0 indicating the downstream end section of the pipe and the initial steady-state conditions, respectively), $C_\ell A_\ell$ is the leak effective area, C_ℓ and A_ℓ are the leak discharge coefficient and area, respectively, and the subscript ℓ refers quantities to the leak. Precisely these plots show that the larger the leak, the larger the damping of the pressure peaks with respect to the integer pipe. In tests of Fig. 1 — executed at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy — a leak of a different size has been considered at a distance $s_\ell = 60.84$ m from the supply reservoir in a single HDPE pipe (Fig. 2) with a length $L = 166.28$ m, an internal diameter $D = 93.3$ mm and pressure wave speed $a = 377.15$ m/s. In all these transients, the same value of the discharge downstream of the leak, $Q_{0,d}$ (= 4.24 L/s), has been assumed as an initial condition (the subscript d refers to the pipe downstream of the leak). As a consequence, the same Allievi-Joukowsky overpressure, $\Delta H_{AJ} = aV_{0,d}/g$ (= 24 m) has been generated, with V = mean flow velocity, and g = gravitational acceleration.

Having in mind the proposed use of the damping of the pressure peaks as a possible feature for leak detection by means of unsteady-state tests, in this paper attention is focused on the effect of leak size and location for a given pipe in transient conditions.

The behavior of the total (i.e., the sum of the intrinsic and leak-induced damping) pressure peak damping is examined by means of numerical experiments executed by using a 1-D model calibrated on the basis of a huge series of tests carried out at WEL on polymeric pipe systems with different characteristics — e.g., with a leak (Ferrante et al. 2014; Capponi et al. 2017), both an extended (Meniconi, Brunone, and Ferrante 2012) and discrete (Meniconi et al. 2016) partial blockage, branch (Meniconi et al. 2011c), and a partially closed in-live valve (Meniconi et al. 2012). Therefore this paper differentiates significantly from the literature where, within the hypothesis of small amplitude transients, attention has been focused on i) the analytical solutions for leak detection and sizing — corroborated by laboratory tests on a small diameter copper pipe — of the linearized governing equations (Wang et al. 2002), and ii) the range of validity of such a method with an assessment of the effect of transient amplitude and noticeable comments about its applicability to non simple systems and nonuniqueness of the solution (Nixon, Ghidaoui, and Kolyshkin 2006).

2. Materials and Methods

As anticipated above, attention is focused on the total damping of the pressure peaks which happens in a single-diameter polymeric pipe with a leak placed at a distance s_ℓ from a constant head supply reservoir (Fig. 2), hereafter referred to as *leaky pipe*. Transients are generated by the complete closure of the valve installed at the downstream end section of the pipe. For the sake of clarity, firstly transients caused by an instantaneous closure are examined and successively the role of the duration of the maneuver is discussed.

According to literature (e.g. Ramos et al. 2004; Meniconi et al. 2014), as a preliminary step, the time-history of the pressure maxima at the downstream end section of the pipe (section M in Fig. 2), $H_{M,max}$, is assumed as the representative feature of the considered transients; thereafter the whole transient pressure trace will be taken into account.

In dimensionless terms, the pressure local maxima, $h^*_{M,max}$, at the downstream end section of the pipe are defined as:

$$h^*_{M,max}(t^*) = \frac{H_{M,max}(t^*) - H_{F,d}}{\Delta H_{AJ}}, \tag{1}$$

where the subscript F indicates the final steady-state condition and the dimensionless time, t^*, is equal to t/τ, with $t =$ time elapsed since the beginning of the transient, and $\tau = 2L/a$ being the characteristic time of the pipe. The available 1-D model — calibrated, as mentioned, by means of transient tests executed on HDPE pipe systems — has then been used to identify quantities affecting the total pressure peak damping i.e., the time-history of $h^*_{M,max}$. In the executed analysis, $V_{0,d}$, $H_{0,\ell}$, $C_\ell A_\ell$, and s_ℓ have been assumed as possible characteristic quantities for the given pipe material (i.e., high-density polyethylene). In fact, on one side, for the considered maneuver and given pressure wave speed, $V_{0,d}$ is responsible for the value of ΔH_{AJ} which is the pressure wave that, injected into the system, successively will damp because of the presence of the leak, the other boundary conditions, as well as pipe material behavior. On the other side, according to literature (Liou and Tian 1995; Liou 1998; Ferrante et al. 2014), for the given pipe characteristics, $H_{0,\ell}$ and $C_\ell A_\ell$ characterize fully the behavior

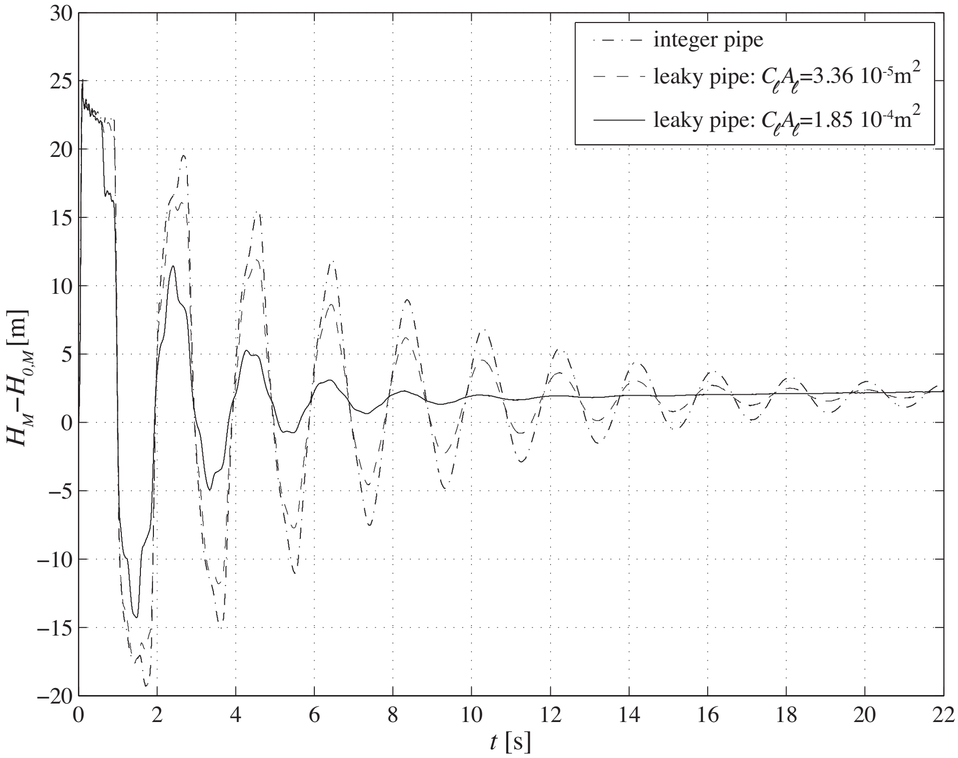

Figure 1.: Experimental pressure signal in an integer pipe vs. those in the same pipe with a leak of different size.

of the leak whereas s_ℓ plays a crucial role in the mechanisms of interaction between the pressure waves and the boundary conditions and then on the pressure damping. In the below numerical experiments, the mentioned laboratory pipe has been considered as reference. Accordingly, in dimensionless terms, the following relationship can then be written:

$$h^*_{M,max} = h^*_{M,max}\left[N_{0,d}, h^*_{0,\ell}, \Sigma^*, \delta\right](t^*), \tag{2}$$

where:

$$N_{0,d} = V_{0,d} D/\nu \tag{3}$$

$$\delta = 1 - s_\ell/L \tag{4}$$

$$\Sigma^* = A/(C_\ell A_\ell) \tag{5}$$

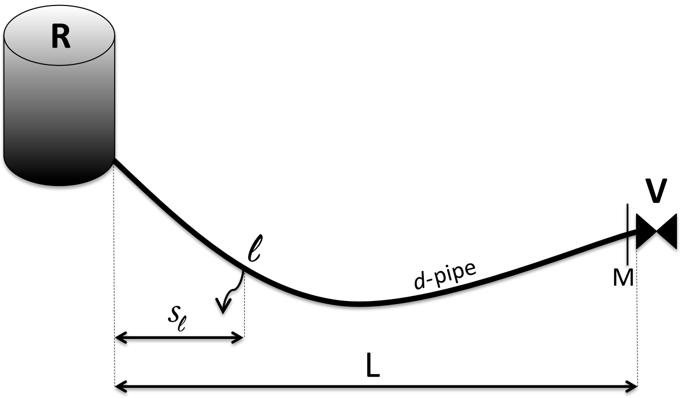

Figure 2.: Sketch of the single-diameter pipe with a leak (R = supply reservoir, L = pipe length, ℓ = leak; s_ℓ = distance between the supply reservoir and the leak; d-pipe = pipe downstream of the leak; M = downstream end section; and V = maneuver valve.)

$$h^*_{0,\ell} = \sqrt{2gH_{0,\ell}}/a \tag{6}$$

with $N_{0,d}$ = initial Reynolds number in the d-pipe, A = pipe area, and ν = kinematic viscosity.

3. The pressure peak damping behavior

According to Covas et al. (2004, 2005) — who examined the case of the integer single pipe — and Wang, Lambert, and Simpson (2005) and Meniconi et al. (2014) — for the case of a pipe with a partially closed in-line valve — a possible formulation of the function of Eq. (2) is in terms of an exponential law:

$$h^*_{M,max}(t^*) = \alpha \mathrm{e}^{-\beta t^*}, \tag{7}$$

where coefficient α takes into account the initial conditions, whereas β, the decay coefficient, reflects both the intrinsic and leak-induced damping (i.e., the total damping). Such an assumption — anticipated in Brunone et al. (2015) — is based on experimental evidence. In fact, for the considered leaky pipe (i.e., for given pipe material, L, D, and a), the behavior of the total pressure damping is clearly of an exponential type (Fig. 3).

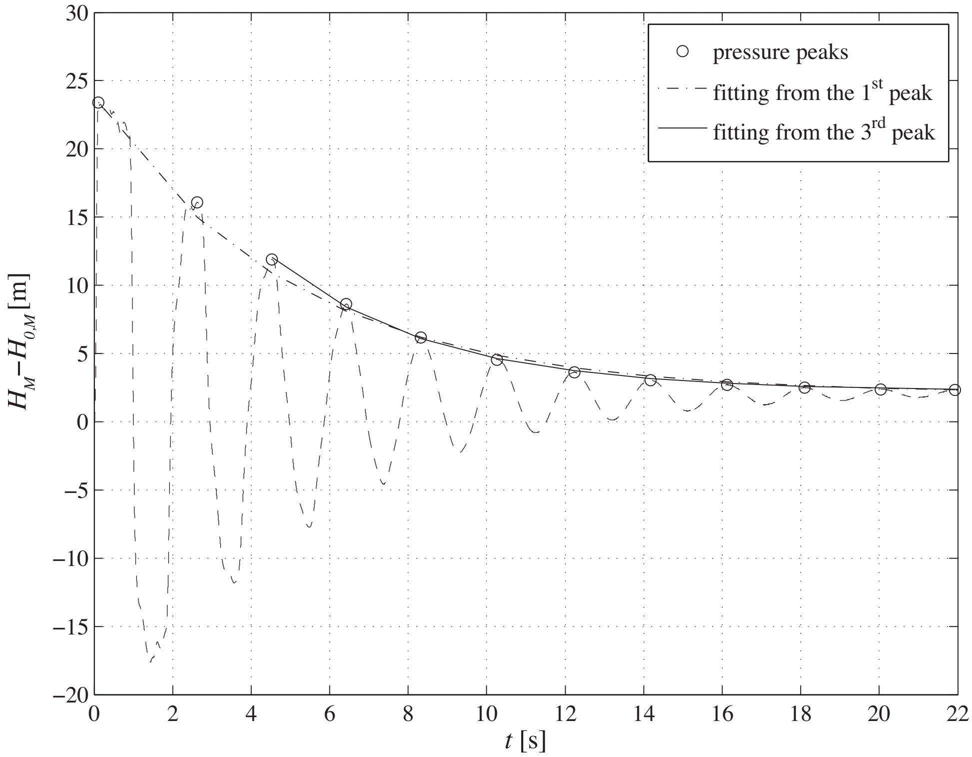

Figure 3.: Fitting of the pressure peaks in a leaky laboratory pipe ($C_\ell A_\ell = 3.36\ 10^{-5}$ m^2).

Within the numerical experiments, by changing the value of the dimensionless parameters $N_{0,d}$, $h^*_{0,\ell}$, Σ^*, and δ, numerical pressure signals have been obtained and for each of them the coefficients α and β have been evaluated. As highlighted in Fig. 3, the quality of the fitting improves if the starting time of the analysis does not include the first characteristic time (Wang et al. 2002). Precisely, the coefficient of determination, R^2, is equal to 0.9945 and 0.9983 for the fitting from the first and the third peak, respectively. This is due to the fact that in the first phases of the transient, the shape of the pressure signal is strongly influenced by the single reflected pressure waves, with a negative effect in terms of periodicity of the pressure signal.

In Fig. 4 coefficients α and β are reported as a function of the dimensionless parameters (3)-(6). These plots of Fig. 4 point out the relevance of $h^*_{0,\ell}$, Σ^*, and δ as well as the much smaller importance of $N_{0,d}$. With regard to the last dependence, the slight decrease of α with $N_{0,d}$ is a direct consequence of Eq. (1), whereas the almost constance of β implies that the entity of the injected pressure wave does not affect significantly the damping of the pressure peaks. The clear dependence of both α and β on $h^*_{0,\ell}$ and Σ^* confirms the experimental results reported in Fig. 1 and literature (e.g. Liou and Tian 1995; Liou 1998). Precisely, the larger $h^*_{0,\ell}$, and then the larger the pressure at the leak, $H_{0,\ell}$, the smaller the leak-induced damping. Moreover, the larger Σ^*, and then the smaller the leak size, $C_\ell A_\ell$, the smaller its effect during the transient. Less straightforward is the role of the leak location on β. According to Fig. 4, the smaller δ, i.e. the closer the leak to the end valve (i.e., the larger s_ℓ) where the pressure wave

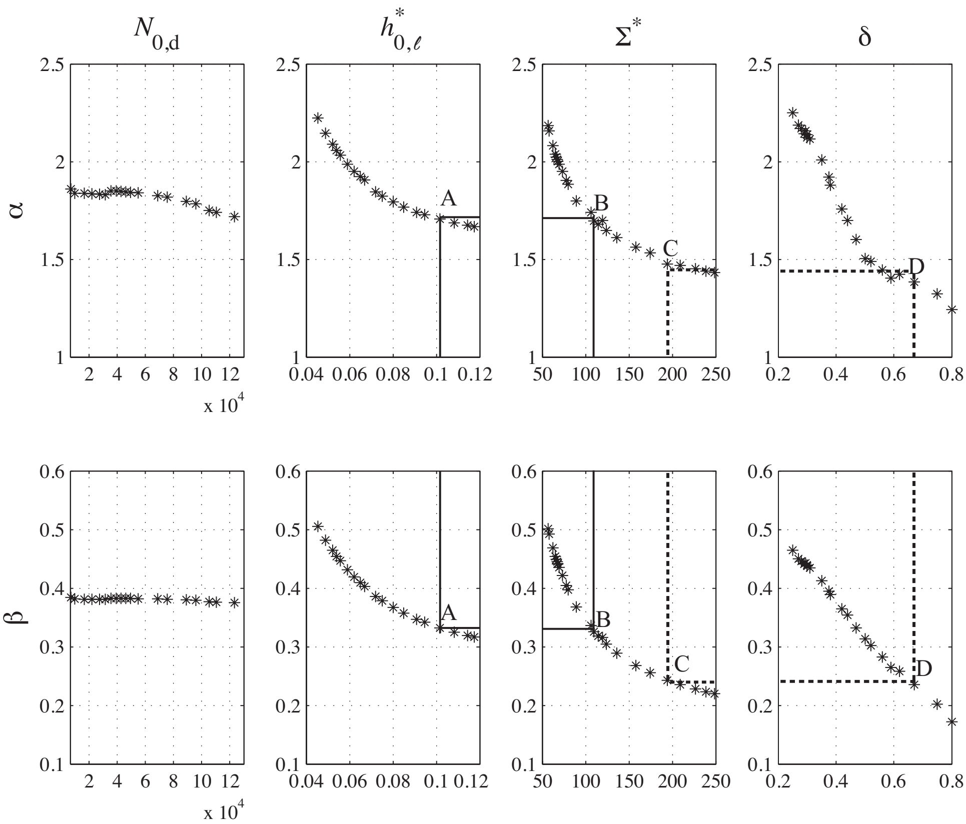

Figure 4.: Initial value coefficient, α, and decay coefficient, β, of Eq. (7), as functions of the dimensionless parameters $N_{0,d}$, $h^*_{0,\ell}$, Σ^*, and δ with selection of cases with the same value of α and β (couples A and B, and C and D).

is generated, the larger β as shown in numerical pressure signals of Fig. 5 where a given leak ($C_\ell A_\ell = 8.0\ 10^{-5}$ m^2) is placed at two different locations (δ equal to 0.30 and 0.85, respectively). In such a behavior, which merits an experimental check, the key role is played by the frequency of the reflections at the leak.

The analysis of Fig. 4 plots suggests that the same value of the coefficients α and β can characterize the damping of the pressure peaks of transients in different pipe systems (i.e., with a leak of a different size in a different location). In Fig. 4, two possible cases are highlighted (couple A and B, and couple C and D, respectively). The first couple of pressure signals with the same coefficients α (= 1.70) and β (= 0.33), labelled as A and B respectively, concerns two quite different leaky pipes. Specifically, for given $N_{0,d}$ (= 4.1 10^4) and δ (= 0.4), i.e., for the same $V_{0,d}$ (= 0.44 m/s) — and then ΔH_{AJ} (= 16.92 m) — and leak location, s_ℓ (= 99.77 m), in case A, Σ^* = 85.46 ($C_\ell A_\ell = 8.0\ 10^{-5}$ m^2) and $h^*_{0,\ell} = 0.102$ ($H_{0,\ell} = 75$ m) whereas in case B, it is Σ^* = 106.25 ($C_\ell A_\ell = 6.4\ 10^{-5}$ m^2) and $h^*_{0,\ell} = 0.074$ ($H_{0,\ell} = 40$ m). This means that two leaks with a different size and initial pressure cause the same pressure peak damping. The differences between cases C and D ($\alpha = 1.44$ and $\beta = 0.24$) are leak location (δ equal to 0.4 and 0.67, respectively) and size ($C_\ell A_\ell$ equal to 5.0 10^{-5} m^2 and 8.0 10^{-5} m^2, respectively). In other words, even if the leak location and size change significantly — the difference in the location is about the 27% of the total length — the pressure

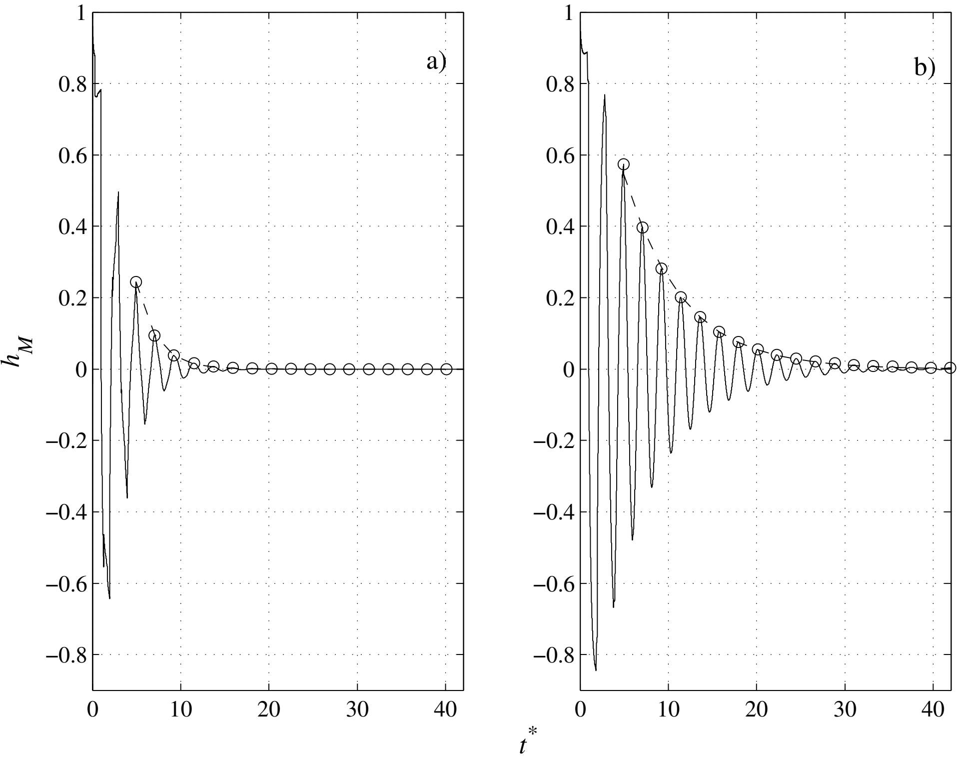

Figure 5.: Numerical pressure signals in a pipe with a given leak ($C_\ell A_\ell = 8.0\ 10^{-5}$ m^2) at a different location: a) $\delta = 0.30$ ($s_\ell = 116.40$ m), b) $\delta = 0.85$ ($s_\ell = 24.94$ m).

damping at the end section of the pipe is the same. It is worthy of noting that the damping of the pressure peaks is not the only common feature between cases A and B, and C and D, respectively. In fact, as shown in Figs. 6 and 7, the whole pressure signals, both in dimensionless (h^*_M) and dimensional (H_M) terms, are almost indistinguishable with the exception of the first characteristic time. In fact, as shown in Fig. 8, for the pressure signals of Figs. 6b and 7b, the leak effect (i.e., a pressure drop) is evident in the first phases of the pressure signals.

Having in mind that in real pipe systems it may be quite difficult to execute fast maneuvers — unless a proper device is used (e.g. Brunone, Ferrante, and Meniconi 2008; Taghvaei, Beck, and Boxall 2010) or a small-diameter side valve is installed (Stephens et al. 2011) — the effect of the duration of the closing maneuver, T, on the transient response has been explored. Moreover the interest for slower maneuvers derives from the fact that for complex systems the damping of the pressure peaks is easier to evaluate with respect to single pressure waves reflected in the first characteristic time as within the time domain reflectometry. Specifically, for cases C and D, as an example, different values of Θ ($= T/\tau$) have been considered ($\Theta = 0.5$; 1; 5; and 10). As clearly shown in Fig. 9, the pressure signals for cases C and D are almost indistinguishable for all the considered values of Θ.

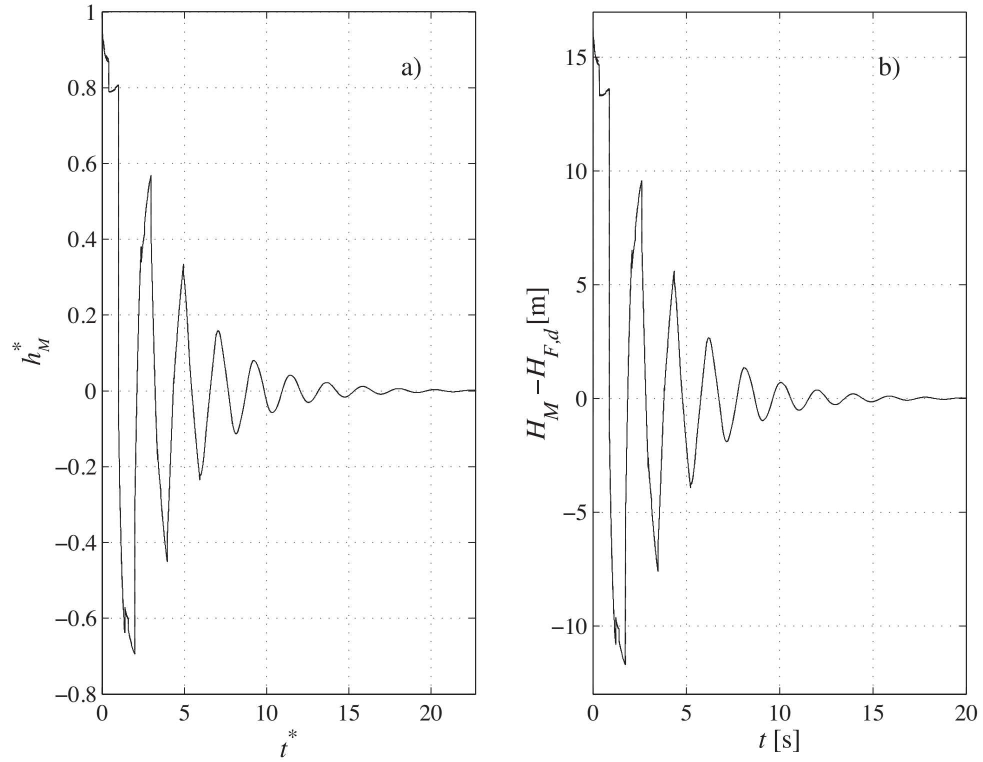

Figure 6.: Transients with the same value of the coefficients α and β of Eq. (7) for couple A (solid lines) and B (dashed lines) of Fig. 4: a) dimensionless pressure signals; b) dimensional pressure signals.

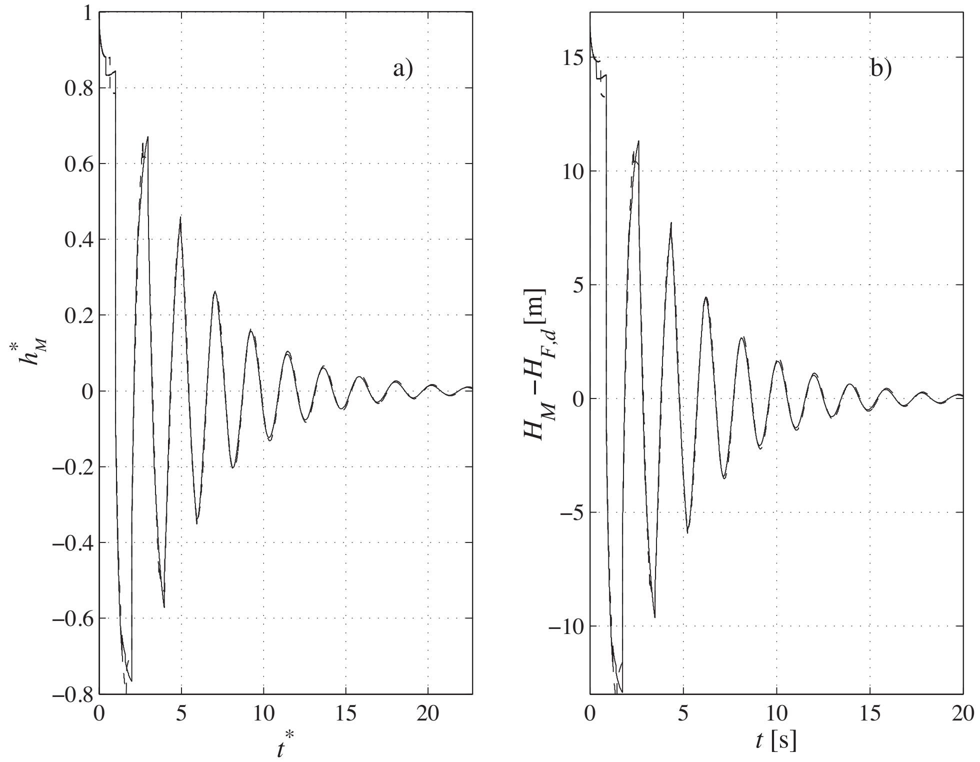

Figure 7.: Transients with the same value of the coefficients α and β of Eq. (7) for couple C (solid lines) and D (dashed lines) of Fig. 4: a) dimensionless pressure signals; b) dimensional pressure signals.

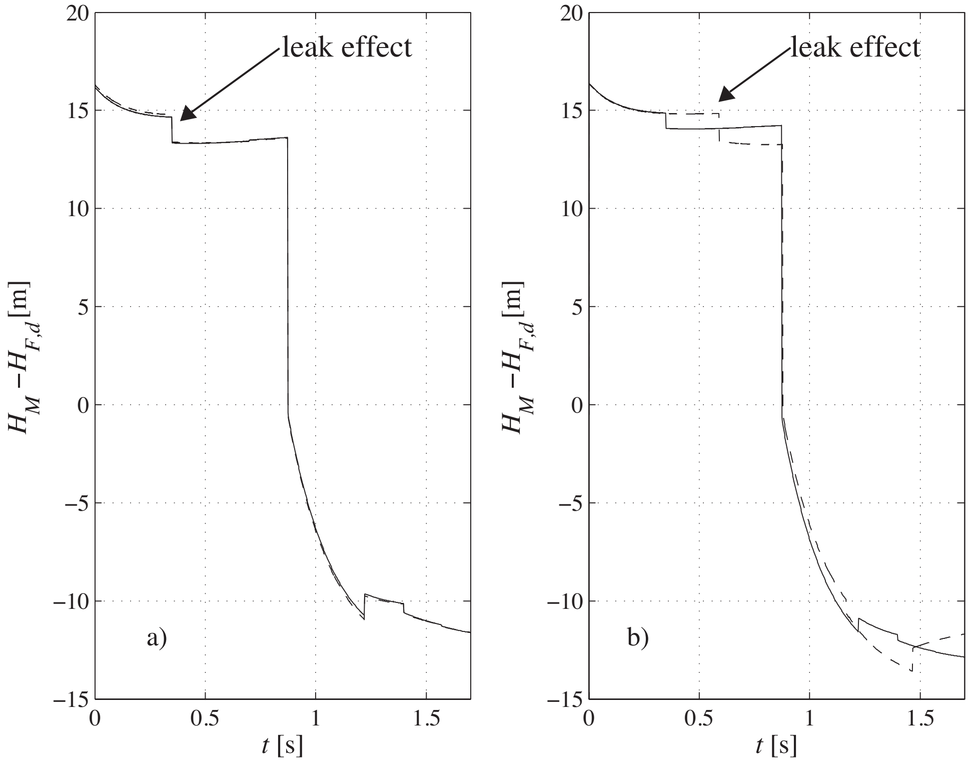

Figure 8.: Magnified vision of the first phase of transients of Figs. 6b and 7b with the effect of the leak in the pressure signal pointed out: a) couple A and B, b) couple C and D.

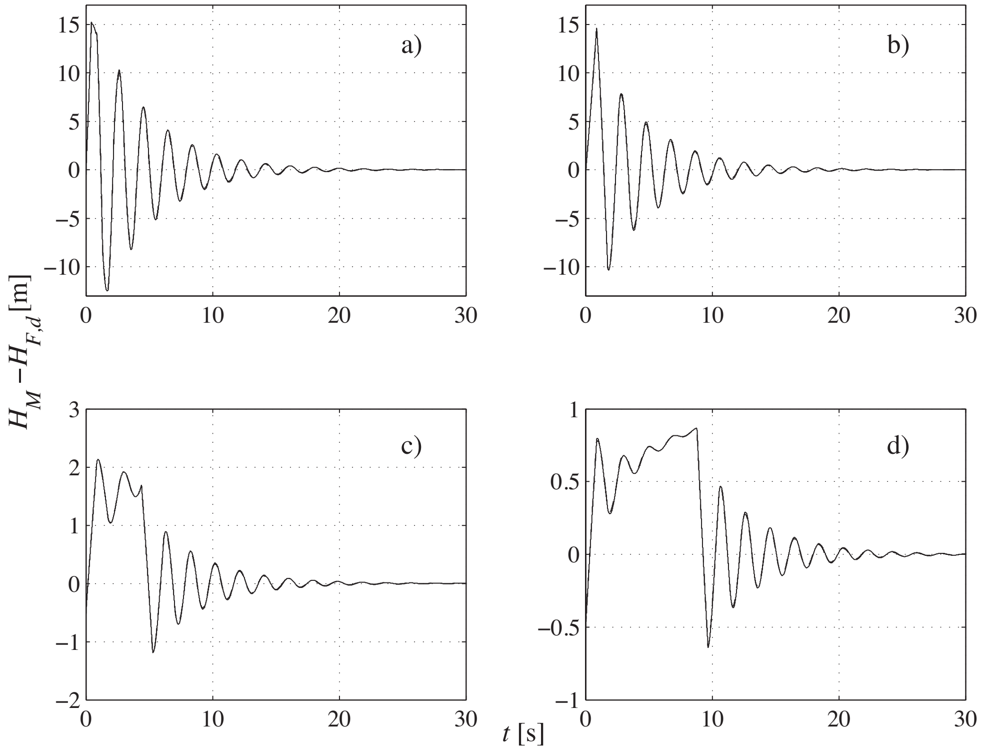

Figure 9.: Dimensional pressure signals for cases C and D of Fig. 4 for different values of the duration of the closing maneuver: a) $\Theta = 0.5$; b) $\Theta = 1$; c) $\Theta = 5$; d) $\Theta = 10$.

4. Conclusions and implications for real pipe systems

Because of the short duration of the tests and cheapness of the probes that are used (i.e., only pressure transducers), transient test-based techniques (TTBTs) apply for an important role within the management of pressurized pipe systems. This justifies the interest for an in-depth check of the most appropriate methods for the analysis of the results of the transient tests.

In this paper, the transient response of a single pipe with a leak (*leaky pipe*) has been examined with the specific aim of evaluating the mechanisms governing the total damping of the pressure peaks after the completion of the maneuver. In fact, since in a leaky pipe the total damping of the pressure peaks is much larger than the one in an integer pipe (i.e., the intrinsic damping), in principle such a feature could be assumed as a sort of marker of the leak in the pressure signals acquired during the transient tests (Wang et al. 2002; Nixon, Ghidaoui, and Kolyshkin 2006).

The results of the numerical tests, executed by means of a 1-D model calibrated on the basis of a huge series of laboratory tests and analyzed in the time-domain, show that the damping of the pressure peaks depends, as characteristic quantities, on the size and location of the leak and the initial pressure at the leak. On the contrary, the role of the initial mean velocity in the pipe downstream of the leak is quite negligible.

Moreover, the numerical experiments confirm that an exponential law to simulate the behavior in time of the pressure peak damping can be assumed according to the case of the single integer pipe (Covas et al. 2004, 2005) and the pipe with a partially closed in-line valve (Meniconi et al. 2014).

The inspection of the charts where the coefficients of the exponential law are reported as a function of the mentioned characteristic quantities highlights that the same pressure peak damping may occur in pipe systems which differ in terms of leak size and location. Moreover, it is shown that, for a given duration of the maneuver, if the pressure peak damping is the same, negligible differences occur in the whole pressure signal, with the exception of the first characteristic time.
In terms of the non-uniqueness of the correspondence between the total pressure peak damping and the characteristics of the pipe system for a given transient, the obtained results suggest that a more in-depth analysis of such a feature is needed. Therefore, in future work different pipe materials (e.g., metallic) and more complex pipe systems will be examined from both the numerical and experimental point of view.

Acknowledgments. This research has been funded by the Hong Kong (HK) Research Grant Council Theme-Based Research Scheme and the HK University of Science and Technology (HKUST) under the project *Smart Urban Water Supply System (Smart UWSS)*. Support from Italian MIUR and University of Perugia is acknowledged within the program *Dipartimenti di Eccellenza 2018-2022*.

References

Babbitt, HE, FC Amsbary, and DR Gwinn. 1920. “The detection of leaks in underground pipes.” *Journal of the American Water Works Association, AWWA* 7 (4): 589–595.

Brunone, B. 1999. “A transient test-based technique for leak detection in outfall pipes.” *J. of Water Resources Planning and Management, ASCE* 125 (5): 302–306.

Brunone, B, M Ferrante, and S Meniconi. 2008. “Portable pressure wave-maker for leak detection and pipe system characterization.” *J. of American Water Works Association, AWWA* 100 (4): 108–116.

Brunone, B, S Meniconi, C Capponi, and M Ferrante. 2015. “Leak-induced pressure decay during transients in viscoelastic pipes. Preliminary results.” *Procedia Engineering, Elsevier* 117: 243–252.

Capponi, C, M Ferrante, AC Zecchin, and J Gong. 2017. “Leak detection in a branched system by inverse transient analysis with the admittance matrix method.” *Water Resources Management* 31 (13): 4075–4089.

Colombo, AF, PJ Lee, and BW Karney. 2009. “A selective literature review of transient-based leak detection methods.” *Journal of Hydro-Environment Research* 2 (4): 212–227.

Covas, D, and H Ramos. 2010. “Case studies of leak detection and location in water pipe systems by inverse transient analysis.” *J. of Water Resources Planning and Management, ASCE* 136 (2): 248–257.

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

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

Duan, HF, MS Ghidaoui, PJ Lee, and YK Tung. 2010a. “Unsteady friction and visco-elasticity in pipe fluid transients.” *Journal of Hydraulic Research, IAHR* 48 (3): 354–362.

Duan, HF, PJ Lee, MS Ghidaoui, and YK Tung. 2010b. “Essential system response information for transient-based leak detection methods.” *Journal of Hydraulic Research* 48 (5): 650–657.

Duan, HF, PJ Lee, MS Ghidaoui, and YK Tung. 2011. “Extended blockage detection in pipelines by using the system frequency response analysis.” *Journal of Water Resources*

Planning and Management, ASCE 138 (1): 55–62.

Duan, HF, PJ Lee, MS Ghidaoui, and YK Tung. 2012. "System response function–based leak detection in viscoelastic pipelines." *Journal of Hydraulic Engineering* 138 (2): 143–153.

Duan, HF, PJ Lee, A Kashima, J Lu, MS Ghidaoui, and YK Tung. 2013. "Extended blockage detection in pipes using the system frequency response: Analytical analysis and experimental verification." *Journal of Hydraulic Engineering, ASCE* 139 (7): 763–771.

Ferrante, M, B Brunone, S Meniconi, BW Karney, and C Massari. 2014. "Leak size, detectability and test conditions in pressurized pipe systems." *Water Resources Management* 28 (13): 4583–4598.

Jönsson, L. 1970. "Leak detection in pipelines using hydraulic transients." *WIT Transactions on Ecology and the Environment* 7: 343–352.

Jönsson, L, and M Larson. 1992. "Leak detection through hydraulic transient analysis." In *Pipeline systems*, 273–286. Springer.

Joukowsky, N. 1900. "Über den hydraulischen Stoss in Wasserleitungsröhren" ("On the hydraulic hammer in water supply pipes") (in German)." *Mèmoires de l'Acadèmie Impèriale des Sciences de St.-Pétersbourg* 9 (5): 1–71.

Lee, PJ, MF Lambert, AR Simpson, JP Vitkovsky, and J Liggett. 2006. "Experimental verification of the frequency response method for pipeline leak detection." *J. of Hydraulic Research, IAHR* 44 (5): 693–707.

Lee, PJ, JP Vitkovsky, MF Lambert, AR Simpson, and JA Liggett. 2005. "Frequency domain analysis for detecting pipeline leaks." *J. of Hydraulic Engineering, ASCE* 131 (7): 596–604.

Lee, PJ, JP Vítkovskỳ, MF Lambert, AR Simpson, and JA Liggett. 2008. "Discrete blockage detection in pipelines using the frequency response diagram: numerical study." *Journal of Hydraulic Engineering, ASCE* 134 (5): 658–663.

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

Liou, CP. 1998. "Pipeline leak detection by impulse response extraction." *J. of Fluids Engineering, ASME* 120: 833–838.

Liou, JCP, and J Tian. 1995. "Leak detection - Transient flow simulation approaches." *J. of Energy Resources Technology* 117: 243–248.

Louati, M, and MS Ghidaoui. 2017. "High-frequency acoustic wave properties in a water-filled pipe. Part 1: dispersion and multi-path behaviour." *Journal of Hydraulic Research, IAHR* 55 (5): 613–631.

Louati, M, S Meniconi, MS Ghidaoui, and B Brunone. 2017. "Experimental study of the eigenfrequency shift mechanism in a blocked pipe system." *Journal of Hydraulic Engineering, ASCE* 143 (10): 04017044.

Meniconi, S, B Brunone, and M Ferrante. 2012. "Water hammer pressure waves at cross-section changes in series in viscoelastic pipes." *Journal of Fluids and Structures* 33: 44–58.

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

Meniconi, S, B Brunone, M Ferrante, C Capponi, CA Carrettini, C Chiesa, D Segalini, and EA Lanfranchi. 2015. "Anomaly pre-localization in distribution-transmission mains. Preliminary field tests in the Milan pipe system." *J. of Hydroinformatics, IWA* 17 (3): 377–389.

Meniconi, S, B Brunone, M Ferrante, and C Massari. 2011a. "Potential of transient tests to diagnose real supply pipe systems: what can be done with a single extemporary test." *Journal of Water Resources Planning and Management, ASCE* 137 (2): 238–241.

Meniconi, S, B Brunone, M Ferrante, and C Massari. 2011b. "Small amplitude sharp pressure waves to diagnose pipe systems." *Water Resources Management* 25 (1): 79–96.

Meniconi, S, B Brunone, M Ferrante, and C Massari. 2011c. "Transient tests for locating and sizing illegal branches in pipe systems." *Journal of Hydroinformatics, IWA* 13 (3): 334–345.

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

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

Meniconi, S, B Brunone, and M Frisinghelli. 2018. "On the role of minor branches, energy dissipation, and small defects in the transient response of transmission mains." *Water* 10 (2): 187.

Meniconi, S, B Brunone, M Frisinghelli, E Mazzetti, M Larentis, and C Costisella. 2017. "Safe transients for pipe survey in a real transmission main by means of a portable device: the case study of the Trento (I) supply system." *Procedia Engineering, Elsevier* 186: 228–235.

Mpesha, W, MH Chaudhry, and SL Gassman. 2002. "Leak detection in pipes by frequency response method using a step excitation." *Journal of Hydraulic Research, IAHR* 40 (1): 55–62.

Mpesha, W, SL Gassman, and MH Chaudhry. 2001. "Leak detection in pipes by frequency response method." *Journal of Hydraulic Engineering, ASCE* 127 (2): 134–147.

Nixon, W, and MS Ghidaoui. 2007. "Numerical sensitivity study of unsteady friction in simple systems with external flow." *Journal of Hydraulic Engineering, ASCE* 133 (7): 736–749.

Nixon, W, MS Ghidaoui, and AA Kolyshkin. 2006. "Range of validity of the transient damping leakage detection method." *Journal of Hydraulic Engineering, ASCE* 132 (9): 944–957.

Ramos, H, D Covas, A Borga, and D Loureiro. 2004. "Surge damping analysis in pipe systems: modelling and experiments." *Journal of Hydraulic Research, IAHR* 42 (4): 413–425.

Stephens, ML, MF Lambert, AR Simpson, and JP Vitkovsky. 2011. "Calibrating the water-hammer response of a field pipe network by using a mechanical damping model." *Journal of Hydraulic Engineering, ASCE* 137 (10): 1225–1237.

Taghvaei, M, SBM Beck, and J Boxall. 2010. "Leak detection in pipes using induced water hammer pulses." *Int. J. of COMADEM* 13 (1): 19–25.

Wang, X-J, MF Lambert, and AR Simpson. 2005. "Detection and location of a partial blockage in a pipeline using damping of fluid transients." *Journal of Water Resources, Planning and Management, ASCE* 131 (3): 244–249.

Wang, X-J, MF Lambert, AR Simpson, JA Liggett, and JP Vitkovsky. 2002. "Leak detection in pipelines using the damping of fluid transients." *J. of Hydraulic Engineering, ASCE* 128 (7): 697–711.

Wiggert, DC. 1968. "Unsteady flows in lines with distributed leakage." *Journal of the Hydraulics Division, ASCE* 94 (1): 143–162.

Zhang, C, AC Zecchin, MF Lambert, J Gong, and AR Simpson. 2018. "Multi-stage parameter-constraining inverse transient analysis for pipeline condition assessment." *Journal of Hydroinformatics, IWA* 20 (2): 281–300.