CONTROLLED TRANSIENTS ARE RELIABLE FOR FAULT DETECTION

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In the last decades, transient test-based techniques (TTBTs) have been proposed for fault detection in pressurized pipe systems. Such techniques, where pressure waves are injected in pipes "to explore" the system, are competitive with respect to other methods (e.g. inline techniques using sensors inserted into the pipelines). This article discusses the reliability of TTBTs for some real systems based on the results of case studies that fully confirm those of numerical and laboratory experiments.

Transmission mains (TMs) lose an average of 40% worldwide of the transported water in part because of limitations of current leak detections methods. Water losses in conveyance systems cost money and energy, and represent an effective reduction in the available water resources putting more stress on aquatic ecosystems in addition to the climate change impacts. Moreover, leaks could reduce system reliability, lead to infrastructure failures, and allow water contamination thereby decreasing water quality and threatening public health. In recent decades, controlled transient waves in pipes have been shown to be efficient and promising tools for overall system diagnosis.

This article discusses the ability of the TTBTs to detect in TMs not only leaks, but any type of faults (e.g., partial blockages, negligently partially closed in-line valves, damaged pipe sections due to corrosion, and illegal branches). Moreover, they minimize the interference with the regular functioning, without breaking ground or making particular changes in the pipe asset. Like any other technique, TTBTs require a preliminary survey of the system to identify the layout, the geometric and mechanical characteristics of the pipes (to set, for example, a preliminary value of the pressure wave speed), and the location and behavior of known boundary conditions (e.g., reservoirs, and pumps). During a transient test, a pressure wave is injected into the system at a selected location through a rapid change in flow or in pressure; the pressure response is recorded at one or more measurement sections. The transient wave, while travelling along the pipeline at a high speed, interacts with any pipe boundary or defect, being partially or totally reflected. The arrival of these reflected waves at the measurement sections is detected as a sudden change in the pressure signal. The arrival times of the waves, combined with the knowledge of the system topology, allow determining the actual value of the wave speed, the unknown functioning of boundary conditions, and the defect location. The performance of this approach is surely noteworthy in systems with a simple topology. In complex networks, such as water distribution systems, the complicated pattern of wave transmission and reflection makes the analysis of the pressure signal quite difficult, but possible [1]. The difficulties are mainly related to the limited number of measurement locations and they can be resolved by monitoring pressure at the system boundaries regardless of the network [2]. A numerical model (e.g. a Lagrangian model, a model based on the Method of Characteristics or the Transfer Matrix Method) based on the solution of the partial differential equations governing transients, may help in detecting the instances that the pressure waves are expected to pass through the measurement section based on the topology of the system. Such instances are compared – possibly by using an optimization procedure, such as a genetic algorithm or match-field processing [3] – with those detected in the pressure signal to exclude expected wave reflections from system boundaries and junctions and to point out singularities from defects. Recently, the use of TTBTs is increasing, because of the simplicity and time-efficiency of the tests, as well as the modest cost of the necessary instruments (in fact only pressure must be measured). For these reasons, TTBTs are undoubtedly competitive with the invasive techniques that involve the insertion of probes in the pipelines, or the realization of "listening points" for the leak a few hundred meters away from each other. In addition, TTBTs are found to be very efficient at detecting leaks at low pressure whereas the

Figure 1. High-density polyethylene pipe system: anomaly effect in the pressure signal during the first characteristic time of the pipe: (a) leak (or branch); (b) partially closed in-line valve; (c) partial blockage.

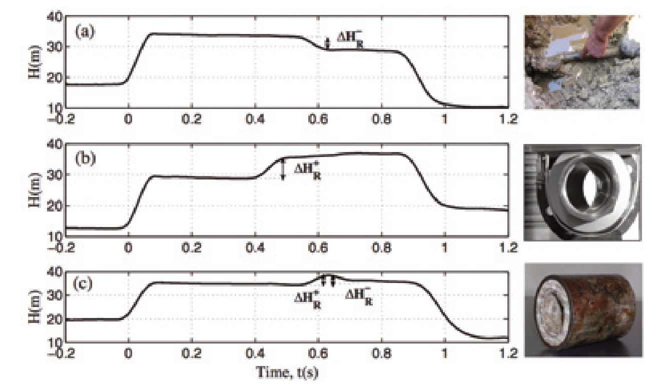


Figure 2. The Water Engineering Laboratory (WEL) of the University of Perugia, Italy.

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accuracy and the competence of steady state-based leak detection methods are mainly dependent on high pressures [4].

In literature, the results of numerical and laboratory/field experiments show that the transient response of leaks [5], [6], [7], [8], partially closed in-line valves and partial blockages [9], [10], internal wall conditions [11] and illegal branches [12] allows their detection. As an example, in Figure 1, the effect (positive or negative reflected pressure waves) of some of these faults in the pressure signals acquired in the Water Engineering Laboratory (WEL) of the University of Perugia is highlighted. In general, a transient test provides the transient-system response (TSR) which represents a transient imprint characterizing the system. A system with defects modifies the intact TSR and each defect type has a specific signature on the TSR.

WEL (for more details see: https://welabpg.wordpress.com), active in this field since 1997, has been recently renovated (Figure 2) with the addition of a pipe network with two loops simulating a Pressure Management Area, and two parallel external straight lines (one buried and one unburied, to evaluate the soil effect), thanks to the support of the Italian Ministry of Education, University and Research (in Italian: Ministero dell'Istruzione, dell'Università e della Ricerca, or MIUR) and the University of Perugia within the program Dipartimenti di Eccellenza 2018-2022, and the Hong Kong (HK) Research Grant Council T21-602/15R Theme-Based Research Scheme and the HK University of Science and Technology (HKUST) under the project Smart Urban Water Supply System (Smart UWSS: http://suwss-dev.ust.hk/).

A crucial role in TTBTs is played by the method used to analyze the pressure signals to improve the detection accuracy: time-domain, frequency-domain, coupled time- and frequency-domain and wavelet analysis methods. Inter alia, within this topic a permanent special session "Transients in Pipes", organized by two of the authors – at the 37th IAHR World Congress in Kuala Lumpur (Malaysia) in 2017, in collaboration with P. Lee (University of Canterbury), A.S. Leon (Oregon State University), and S. Kim (Pusan National University) and at 38th IAHR World Congress in Panama City (Panama) in 2019 – has highlighted interesting fundamental development and practical applications in the fluid transient field. Moreover, a working group on "Transient flows" has just been created to provide a framework to the transient group community within IAHR.

The following sections present examples where transient analyses are used in real pipeline systems for the accurate location of faults: the quite simple transmission main in Trento (Italy) and the more complex Milan (Italy) water distribution-transmission system.

The Trento transmission main, managed by NovaReti SpA, is an iron pipe with DN 500 mm and length 1.3 km, connecting the "Spini" well-field to the "10000" reservoir which supplies the city of Trento (Figure 3a). The pipeline has few minor branches, quite short and certified by the system manager as inactive (i.e., connecting the main pipe to a dead-end or with a closed valve at about the inlet). The diameter and the length of such minor branches range between DN 80 mm and DN 500 mm, and 0.7 m and 18.5 m, respectively. All branches are steel, except one (marked as E in Figure 3a), which is a high-density polyethylene (HDPE) pipe and consists of two reaches of 3 m and 15.5 m long, respectively. The end nodes of these reaches are the red valve shown in Figure 3a, certified as fully closed, and the inactive San Lazzaro well [13]. The transient is generated by a change of pressure, which is an alternative to the change of the flow rate, the most frequent cause of pressure wave generation (i.e., pump switching off or valve closing). Precisely, such a perturbation is generated by the Portable Pressure Wave Maker (PPWM) device refined at the WEL, which is a vessel filled with water and air. The PPWM has been installed immediately upstream of the "10000" reservoir and connected to the main pipe by a short connection pipe (about 1 m long) and 1/2'' valve. Just before the transient test started, the pressure at the PPWM was set at a value larger than that in the pipe (about 5 bar of difference), and the pipeline was isolated by closing the valve just upstream of the "10000" reservoir and stopping pumping at the well-field. Precisely, all the pumps were shut down one by one, waiting enough time to damp the transient effects. The manual and fast opening of such a valve allowed injecting a quite sharp pressure wave into the system measured by a pressure transducer installed immediately upstream of the connection valve. It is worth nothing that such a pressure wave injected at 0 s is very small (about 0.85 m) (Figure 3b). The wavelet transform allowed denoising the signal, and pointing out discontinuities. Specifically, the one happening at about 2.51 s after the injection maneuver could be ascribed to the "10000" reservoir and could be used to evaluate the wave speed as equal to 1055.88 m/s. The clear reduction of pressure at 1.52 s was due to the wave reflected by the junction of the E branch and the successive clear increase at 1,62 s could be associated with the San Lazzaro well. A further interview with the water utility technicians revealed that the red valve was not closed as expected. Furthermore, a more detailed analysis [14] pointed out that a small leak of 1 to 2 L/s had occurred at the San Lazzaro well.

The analyzed system in the city of Milan (Italy) is the steel pipe supplied by the Novara pumping station managed by Metropolitana Milanese SpA. As clearly shown in Figure 4d, the topology of the system approaches that of a water distribution network because of the presence of several branches immediately downstream of the pumping station. In the figure, the main pipe, 6.3 km long, and with a nominal diameter DN 800 mm, is highlighted by a bold line; the main connections, as well as the pumping station node, are numbered. The transient was generated by a pump trip. Figure 4a shows the pressure signal at the section immediately downstream of the check valve. The pressure signal was analyzed by the Wavelet Transform (WT) (Figure 4b). The first clear singularity after the pump trip occured at time 9.607 s. Such a wave can presumably be ascribed to junction 8. By associating the discontinuity of the pressure signal with junction 8, the resulting value of the pressure wave speed of the main pipe is equal to 954.26 m/s, which is compatible with its mechanical characteristics. In order to evaluate the other pressure wave speeds, firstly the network was skeletonized and, then, an optimization procedure based on a genetic algorithm was carried out by coupling the WT and the Lagrangian Model (LM). The obtained values of the pressure wave speeds were used in the LM, which integrates analytically the water hammer equations and allows evaluating the causes of the discontinuities. In such a way the defects of the network could be localized more reliably. Because of the complexity of the system and the subsequent inability of knowing the functioning of all terminals, in Figure 4c the impulse response function of the LM is shown for the case that all terminals are closed to emphasize the response of the system to the transients. By comparing the WT and the LM it is possible to evidence a chain of extreme values of the WT, at 10.4 s, that could not be associated with any known boundary condition (i.e. a modification of the TSR). Because of its characteristics, such a discontinuity could be due to an unknown increase in pipe diameter or a change of pipe material, a junction, or a leak. According to the pipe system characteristics, the possible locations of the anomaly pointed out by circles are six in the area highlighted in Figure 4d. It is worth noting that, for a given

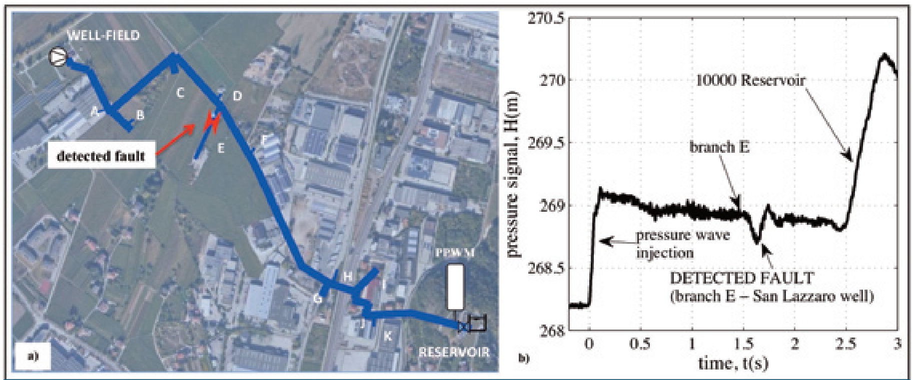

Figure 3. (a) Schematic representation of the Trento supply pipe system (note that letters indicate the branches and a different length scale has been used for the main pipe and minor branches); (b) pressure signal at the section immediately upstream of the connection valve between the main pipe and the PPWM (modified from [14]).

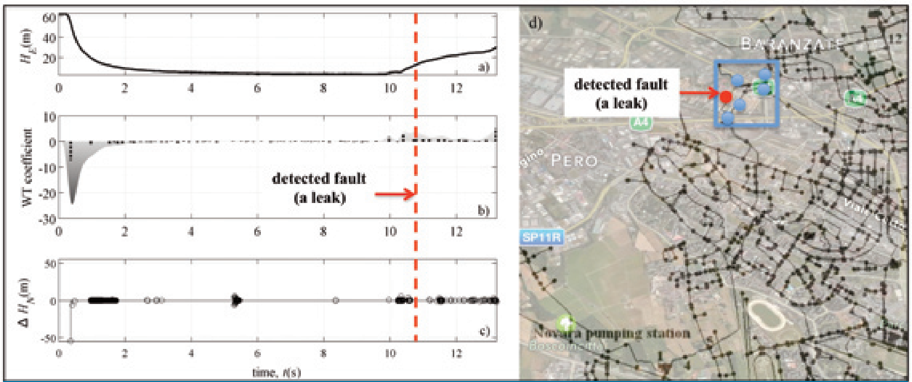

Figure 4. A part of the Milan water distribution system supplied mainly by the Novara pumping station: a) pressure signal, b) time history of the corresponding WT, c) impulse response function is given by the Lagrangian model, and d) schematic of the system [1].

arrival time of a pressure wave at a measurement section, several paths can be assumed, and then the uniqueness of the solution – in terms of defect pre-localization – is not ensured unless further measurement sections are activated. As a consequence, a fault area was identified with some possible leak locations highlighted inside. The reliability of this procedure has been confirmed since a leak was repaired in the detected area.

Successful fault detection using controlled transients in laboratories and real networks have been reported in different countries such as Australia, New Zealand, Hong Kong, and US. Recently, the Smart Urban Water Supply Systems project has been analysing the use of actively generated acoustic waves in pipe systems for a superior resolution and damage identification than the described TTBTs, and a promising and noise-tolerant signal processing method called Time-Reversal for pipeline leak localization [15]; [16]; [17]. ■

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