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Transient Test-Based Techniques for Checking the Sealing of In-Line Shut-Off Valves and Capturing the Effect of Series Junctions—Field Tests in a Real Pipe System

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Abstract: In-line valves are devices typically used for isolation or flow regulation in pipe systems, playing a key role in the operational management of transmission mains (TM). However, there is no fast and expeditious procedure available for checking the efficacy of the sealing mechanism, and its ability to prevent leakage, unwanted flow or partial blockages, which is a crucial action for any maintenance operation. Due to the different values of the conveyed discharge, the diameter changes along the TM at a series junctions which therefore makes diameter changes a very common singularity. This paper has two aims. The first one is to evaluate the feasibility of Inverse Transient Analysis (ITA) for checking the sealing of in-line valves. In particular, the primary objective of the numerical model is to identify the distinctive features of the measured pressure signals that correspond to the status of an in-line valve, discerning whether it is fully sealed or partially closed. The second objective is to use Direct Analysis (DA) of the pressure signals to appropriately capture the transient response of the series junctions. To address these issues, safe transients have been generated in a real TM by means of a Portable Pressure Wave Maker (PPWM) device, refined at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy. The results of the field tests and numerical model point out that the positive pressure wave reflected by the in-line valve is smaller than the one expected if it were perfectly sealed. Moreover, the transient response of the series junction has been properly captured by the DA of the pressure signal. Accordingly, the proposed procedures have been demonstrated to be suitable tools for the management of long transmission pipelines.

Keywords: inverse transient analysis; fault detection; in-line valve; valve sealing check; transmission mains; series junction

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1. Introduction

In long water supply systems, the in-line shut-off valves of Transmission Mains (TMs) allow for the execution of maintenance procedures and other types of interventions by isolating selected parts of the system. Alongside TMs, the flow conveyed may vary depending on the number of downstream users being supplied. As a result, series junctions where the diameter changes are a very common singularity.

An unwanted, albeit small, opening degree in the in-line valve provokes leakage, unwanted flow or partial blockages, with the consequent emptying of pipes, flooding of manholes and possible damage to workers and equipment. Particularly in TMs, the check of the sealing of the in-line valves may be a difficult and time-consuming task. This is due to the quite large depth of installation of TMs and the narrowness of space in underground chambers (e.g., [1]). The practice of listening to the noise of the water flowing through the valve provides only qualitative information and may fail in a noisy environment.

An alternative method to assess in-line valve sealing is based on the properties of the pressure waves generated during transient tests, which produce small and sharp pressure waves that are significantly different from those generated by maneuvers performed to completely close a valve (e.g., [2]). Within Transient Test-Based Techniques (TTBTs), an "ad hoc" small pressure wave propagates along the pipe and is reflected at the boundaries (e.g., the reservoirs) and by any change in the pipe features (e.g., diameter, material, tee-junctions) or in flow characteristics (e.g., flow rate) (e.g., [3–6]). The shape of the reflected pressure wave allows us to identify the type of anomaly, while the size of the reflection is related to the anomaly severity. The timing of the reflected pressure wave allows the location of the anomaly, as long as the speed of the pressure wave is known [7]. A partially closed in-line valve, for example, reflects a positive pressure wave, ΔH_R, which will depend on the valve opening degree, δ. More precisely, the smaller the opening degree δ is, the larger the reflected pressure wave ΔH_R becomes (e.g., [8–13]). When the valve is fully closed, the pipe system divides into two completely independent parts and the in-line valve behaves as a dead-end, where the incident pressure waves are reflected with doubled amplitude. Conversely, in the case of a leak, the reflected pressure wave is negative and, for a given pressure at the leak site, the larger the leak flow is, the larger ΔH_R also is (e.g., [14–18]). The transient behaviour of a branch is similar to that of a leak (whether active or not) [19], while pipe wall reduction (due to deterioration or corrosion) can be identified as it gives rise to a negative bell-shaped pressure wave [20,21]. At the same time, within TTBTs, singularities (e.g., series junctions) in the pipeline also give rise to pressure waves that interact with those generated by faults. Therefore, in order to identify the existing anomalies or pipe faults, it is crucial to correctly identify the transient behaviour of any singularity in the pressure signals.

The above-mentioned clear hydrodynamic behaviour of faults (and singularities) is not the only strength of TTBTs for fault detection in pressurised pipe systems. In fact, the effects of transient tests, characterised by small overpressures, are short-lived and hardly interfere with the operating conditions of the tested system. Moreover, since they do not induce fatigue phenomena in pipes, transient tests can be repeated whenever necessary. Finally, once the procedure has been established, the tests can be carried out autonomously by water utility technicians.

As shown in the cited literature, within TTBTs, information about the characteristics of faults and singularities can be extracted from the pressure signals acquired during the transient tests using three different approaches [4]: (i) direct analysis (DA) or time-domain reflectometry, (ii) transient damping method (TDM) and (iii) inverse transient analysis (ITA). DA identifies the characteristics of defects and singularities by measuring the reflected pressure waves in the acquired pressure signal. TDM focuses attention on the additional pressure decay due to the fault relative to the defect-free pipe. However, TDM is affected by a certain ambiguity and can then only be considered as a preliminary method for fault detection. In ITA, the acquired pressure signal is simulated by a numerical model and the characteristics of the faults are obtained within a calibration procedure by minimising the difference between the experimental data and the results of the numerical model.

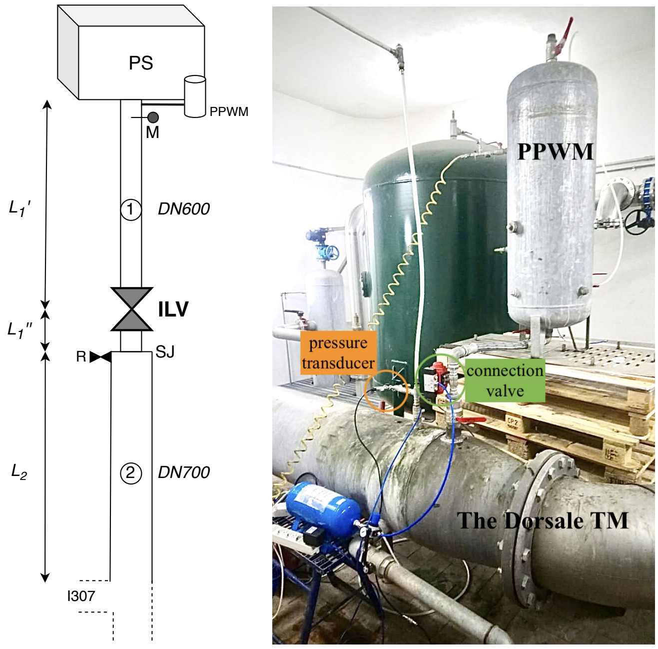
According to the objectives of the research project and the characteristics of the TM under investigation, both ITA and DA are analysed in this paper. Specifically, ITA is used to determine whether an in-line valve is perfectly sealed or not, while DA is used to analyse the interaction between the pressure waves and a series junction. In relation to the existing literature, one of the strengths of this approach is that the results of the field tests are used to verify the proposed procedure with specific reference to real systems by comparing numerical and field test results. This paper emphasises the role of field tests, a rare commodity in the literature as they are very difficult and expensive. In fact, field tests allow us to point out the actual transient behaviour of real pipe systems, where the effects of devices, singularities and possible faults combine.

Accordingly, this paper is organized as follows. In Section 2, the considered real TM, field tests and refined numerical model are described. In Section 3, the results of the numerical simulations executed for different values of the local head loss coefficient at the valve, and then its opening degree, are presented, as well as the results given by the DA for capturing the transient response of the series junction. Finally, in Section 4, the obtained results are summarised and the practical applications of the proposed approach in real life transmission mains are discussed.

2. Materials and Methods

2.1. The Dorsale TM and Field Test Description

The Dorsale TM, a cast iron pipeline with a total length of 15,592 m, supplies a pumping station (PS). In this paper, attention is focused on the in-line shut-off valve (ILV) installed at a distance from PS, L_1', equal to 1313.5 m on a DN600 pipe (Figure 1a).



(**a**) (**b**)

Figure 1. The Dorsale TM: (**a**) layout of the part where the ILV is installed and (**b**) the PPWM at the PS (PS = pumping station, PPWM = Portable Pressure Wave Maker device, M = measurement section, ILV = shut-off in-line valve, R = branch shut-off valve and SJ = series junction).

At a distance L_1'' = 40.3 m upstream of the ILV, there is a series junction (SJ) where the diameter becomes DN700. At the same location, there is a very short branch that is not considered in the analysis since the shut-off valve R, installed at its initial section, is fully closed. At a distance L_2 (= 1674.5 m) upstream of the SJ, there is the I307 branch. Further details about the characteristics of the whole TM, managed by CAP Holding SpA (Milan, Italy), are reported in [22].

To generate controlled transient tests, the Portable Pressure Wave Maker (PPWM), a device developed at the Water Engineering Laboratory (WEL) of the University of Perugia [23], has been used. The PPWM, connected to the TM by a short pipe with a small connection valve (CV) at the downstream end section, has been installed at PS (Figure 1b). Before starting the test, the pressure inside the PPWM is set at a value larger than the one in the TM. Successively, the fast opening of the connection valve generates a pressure wave propagating into the pipeline. For a given connection valve, the entirety of the pressure wave inserted by the PPWM can be fixed precisely by adjusting the difference between the pressure in the PPWM and the one in the TM. Due to its small size, the connection valve can be opened very quickly and, then, a sharp pressure wave is generated. It is worth noting that the sharper the pressure wave is, the more precise the characterization of faults and singularities is.

The measurement section M has been arranged just upstream of the PPWM. Pressure signals have been measured by means of a piezoresistive pressure transducer with a full scale, fs, equal to 3.5 bar G and an accuracy of 0.25% fs. During tests, the pressure was sampled at a frequency, f_a, of 2048 Hz by a National Instrument cDAQ-9188 data acquisition system.

To check the ILV sealing, and possibly capture the transient response of the series junction (i.e., if the ILV were not perfectly sealed), two transient tests, referred to as test #1 and #2, have been carried out, with the ILV nominally fully closed. Pressure signals depicted in Figure 2 confirm both the repeatability and safety of the transient tests. In fact, the pressure traces are almost indistinguishable (accordingly, only test #1 will be considered below) and the generated pressure wave is quite small, equal to 2.51 m. In Figure 2, the following symbols are used: $\Delta H = H - H_0$, in which H = piezometric head, t = time elapsed since the beginning of the test and the subscript 0 refers to quantities of the pre-transient conditions. The repeatability of the tests is also confirmed by the frequency-domain analysis of the pressure signals by the Fast Fourier Transform (FFT). In fact, generally, the analysis of the pressure signals carried out in the frequency domain clearly highlights some of the features already observed in the time-domain analysis, evidencing significant harmonics, whilst the random noise contamination in the data is reduced [24]. In particular, the FFT of the pressure signals shown Figure 2a are shown in Figure 2b for frequencies f from 0 to 20 Hz. Such a result highlights that in both tests the system is excited in a very similar way. In addition, it is worth noting that in both tests #1 and #2, quite steady-state conditions have been reached in the phase preceding the transience. In fact, the value of the standard deviation, σ, of the part of the pressure signals preceding the maneuver (i.e., for $t < 0$ s) is very small. Particularly, for tests #1 and #2, this results in $\sigma_{\#1}$ = 0.006 m and $\sigma_{\#2}$ = 0.004 m, respectively. Such a result confirms that no significant pressure oscillations happened in the pre-transient phase. This means that the about twelve minutes elapsed between tests #1 and #2 allowed us to avoid further undesired pressure waves that could prejudice the analysis of the pressure signals.

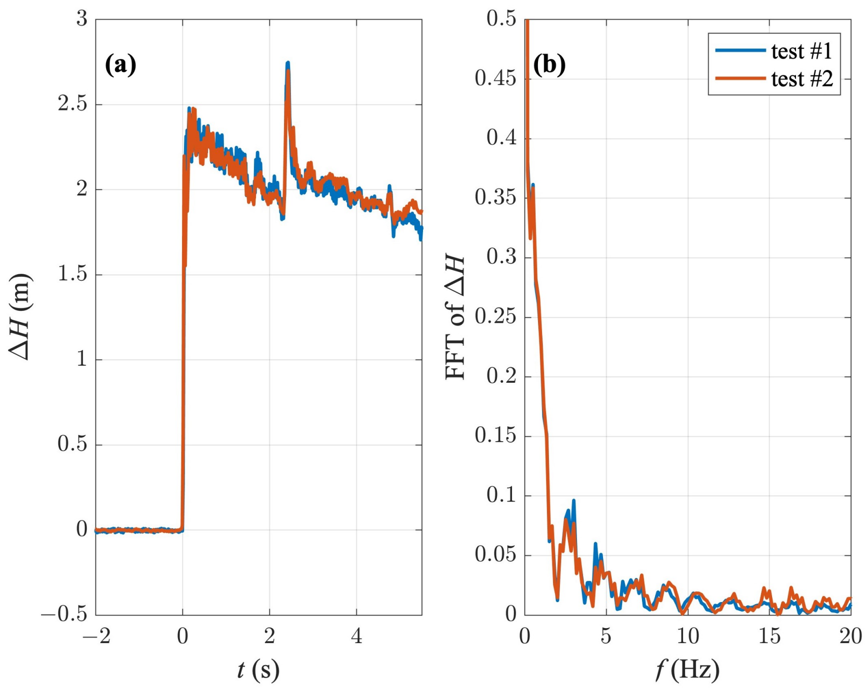


Figure 2. The Dorsale TM: (**a**) field tests executed for checking the sealing of the in-line valve and their repeatability and (**b**) Fast Fourier Transform (FFT) of the acquired pressure signals.

2.2. The Numerical Model

The 1-D numerical model is based on the differential equations governing pressurised transient flows in elastic pipelines [25–27]:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial s} = 0 \tag{1}$$

$$\frac{\partial H}{\partial s} + \frac{1}{gA}\frac{\partial Q}{\partial t} + J_s + J_u = 0 \tag{2}$$

where Q = discharge, s = axial co-ordinate, a = pressure wave speed, A = pipe cross-sectional area, g = acceleration of gravity and J_s (J_u) = steady-state (unsteady) friction term. Equations (1) and (2) are integrated numerically by the Method of Characteristics (MOC). Accordingly, each pipe with constant geometric and initial kinetic characteristics is divided into reaches with a length of Δs_j, so that $\Delta s_j = a_j \Delta t$, with Δt = time step and the subscript j indicating the pipe. In the numerical simulations, Δt has been assumed to be equal to the experimental time step used for pressure measurements (i.e., equal to $1/f_a$). Within MOC, for any internal computational node, Equations (1) and (2) are transformed into the following set of algebraic compatibility equations:

$$C^+ : \quad H_i^t = C_P - B_P Q_i^t \tag{3}$$

$$C^- : \quad H_i^t = C_N + B_N Q_i^t \tag{4}$$

valid along the straight characteristic lines, C^+ and C^-, with the subscript i and superscript t indicating the node and time, respectively. Coefficients C_P, C_N, B_P and B_N are known quantities depending on the values of Q and H at the previous time step. The expression of such coefficients descends from the numerical model used for simulating the friction term. In particular, if the unsteady-state friction term, J_u, is evaluated by means of an instantaneous acceleration-based (IAB) model, the following relationships can be written:

$$C_P = H_{i-1}^{t-\Delta t} + B_j Q_{i-1}^{t-\Delta t} - k_B B_j [(Q_{i-1}^{t-\Delta t} - Q_{i-1}^{t-2\Delta t}) + sign(Q_i^{t-\Delta t})|Q_i^{t-\Delta t} - Q_{i-1}^{t-\Delta t}|] \tag{5}$$

$$C_N = H_{i+1}^{t-\Delta t} - B_j Q_{i+1}^{t-\Delta t} + k_B B_j [(Q_{i+1}^{t-\Delta t} - Q_{i+1}^{t-2\Delta t}) + sign(Q_i^{t-\Delta t})|Q_i^{t-\Delta t} - Q_{i+1}^{t-\Delta t}|] \tag{6}$$

$$B_P = B_j + R_j |Q_{i-1}^{t-\Delta t}| \tag{7}$$

$$B_N = B_j + R_j |Q_{i+1}^{t-\Delta t}| \tag{8}$$

where k_B is the unsteady-state decay coefficient [28], $B_j (= a_j/(gA_j))$ is the characteristic impedance and $R_j (= f_j \Delta s_j/(2gD_j A_j^2))$ is the pipe resistance coefficient, with f_j being the steady-state friction factor. As discussed below, as attention is focused on the first phase of the transients to capture the response of the ILV, the unsteady-state friction term has been neglected (i.e., $k_B = 0$).

At PS, where the Portable Pressure Wave Maker (PPWM) is connected to the DN600 pipe, the following set of boundary conditions has been imposed [23]:

$$Q_{PS}^t = \frac{U_{PPWM}^t - U_{PPWM}^{t-\Delta t}}{\Delta t} \tag{9}$$

the continuity equation at the PPWM, with U_{PPWM} being the volume of air in the PPWM,

$$H_{PPWM}^t {U_{PPWM}^t}^n = \text{const} \tag{10}$$

the state equation for the air in the PPWM, with the exponent of the thermodynamic transformation, n, assumed as equal to 1.41, and

$$Q_{PS}^{t} = (C_d\Sigma)^{t}\sqrt{2g(H_{PPWM}^{t} - H_{PS}^{t})} \tag{11}$$

the orifice equation that relates the discharge from/to the PPWM to the hydraulic characteristics of the connection valve and head differential between the PPWM and the pipe; in Equation (11), C_d and Σ are the discharge coefficient and area of the free aperture of the connection valve, respectively.

At the in-line valve ILV, the case of sealing that is not perfect is simulated as a partially closed in-line valve [8,13]:

$$Q_{ILV}^{t} = C_{ILV}(B_{P1} + B_{N1}) - \sqrt{C_{ILV}^{2}(B_{P1} + B_{N1})^{2} - 2C_{ILV}(C_{P1} - C_{N1})} \tag{12}$$

where B_{P1}, B_{N1}, C_{P1} and C_{N1} are given for pipe 1 (DN600) by Equations (5)–(8), and $C_{ILV} = gA_1^2/\chi_{ILV}$, with χ_{ILV} being the local head loss coefficient of the ILV for a given opening degree. As the hydraulic characterization of the ILV—i.e., the curve providing the values of χ_{ILV} vs. the valve opening degree—is not available (as often happens for shut-off valves), in Equation (12), different values of χ_{ILV} have been assumed within the ITA procedure described below, according to the literature [29]. Moreover, as referenced for the ILV, cases where there is a fully closed/open in-line valve have been also simulated. For the former (i.e., χ_{ILV} = $+\infty$), the assumed boundary condition is H_{ILV} given by Equation (3) with Q_{ILV} = 0; and for the latter (i.e., χ_{ILV} = 0), the generated pressure wave propagates in an undisturbed manner.

Finally, at the series junction, SJ, the following equation can be written:

$$Q_{SJ} = \frac{C_{P1} - C_{N2}}{B_{P1} + B_{N2}} \tag{13}$$

while H_{SJ} is given by Equation (3).

Hydrostatic conditions have been assumed as the pre-transient ones, with the pressure wave generated by the pressure drop between the PPWM and the Dorsale TM.

As the ultimate goal of the numerical simulation is to capture the interaction between the ILV and the pressure waves generated by the PPWM to check the sealing of the ILV, the following time interval has been considered as an appropriate duration for the numerical simulations:

$$T_s = 2(L_1' + L_1'')/a_1 + 2L_2/a_2 \tag{14}$$

The values of the pressure wave speed (a_1 = 1121.30 m/s and a_2 = 1095.27 m/s) have been obtained by considering the travel time of the pressure waves propagating along the pipes [22].

3. Analysis of the Pressure Signal

In the Section 3.1, ITA is used to assess the in-line valve sealing, thus comparing the experimental signal with those simulated by means of the numerical model described above for several values of the ILV head loss coefficient. In the Section 3.2, DA of the experimental pressure signal, based on the evaluation of reflection and transmission coefficients [25], is used to capture the transient response of the series junction.

3.1. Assessment of the Sealing of the In-Line Valve by Inverse Transient Analysis (ITA)

To apply ITA, twenty logarithmically spaced values, between 1 and 10^5 of the local head loss coefficient of the ILV, χ_{ILV}, have been considered in the transient solver for describing the reflected wave by the ILV for different valve opening degrees. The results of these twenty simulations for some of the considered values of χ_{ILV} are compared with collected data and presented in Figure 3a. This figure shows that the larger the value of χ_{ILV} is, the larger the reflected pressure wave at the ILV is. The results of the numerical model are strongly influenced by the value of χ_{ILV}, which is related to the ILV opening degree, which confirms the key role of the valve opening in the transient response of the pipeline. On the other end, the larger δ is, the smaller the accuracy of the fault detection becomes, since the ILV reflected wave is smaller. It is worth noting that, for small values of χ_{ILV}, the negative pressure wave reflection at the SJ is more evident. This feature is analyzed in detail in Section 3.2.

For each numerical pressure signal, it is therefore important to evaluate the determination coefficient, R^2:

$$R^2 = 1 - \frac{\sum_1^N (\Delta H_e - \Delta H_n)^2}{\sum_1^N (\Delta H_e - \Delta H_e^*)^2} \tag{15}$$

where $N = \frac{T_s}{\Delta t}$, whereas ΔH_e and ΔH_n indicate the experimental and numerical pressure head variations with respect to initial conditions (Figure 3b), respectively, and ΔH_e^* is the mean value of experimental pressure variation over T_s.

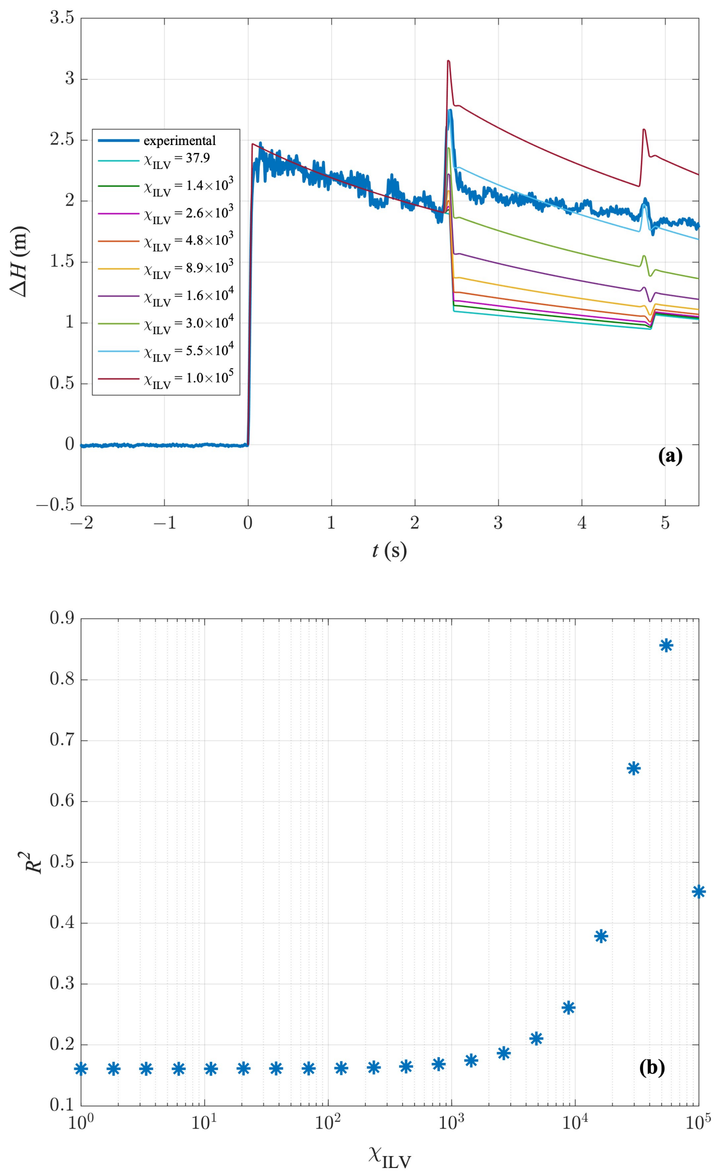


Figure 3. The Dorsale TM: (**a**) numerical pressure signals simulating the transient response for different values of the ILV local head loss coefficient χ_{ILV}, and then its opening degree vs. experimental results; (**b**) corresponding values of the determination coefficient, R^2.

According to the values of R^2, the best performance of the numerical model is for $\chi_{ILV} = 5.5 \times 10^4$. This implies that the ILV is almost fully closed, but not perfectly sealed [29]. The aim of numerical modeling of transients in real systems is to capture the main features of the transient response. A total agreement between numerical and experimental results, in fact, is not expected, nor it is essential from a management point of view. Unavoidable differences are due to uncertainties in the knowledge of the pipe physical characteristics (e.g., pipe roughness) and boundary conditions, in addition to the noise affecting field data.

The validity of the above procedure is demonstrated by two further results. Firstly, by the local inspection of the pressure signal, with the determination coefficient evaluated in close proximity of the pressure rise due to the ILV, as

$$R^2_{local} = 1 - \frac{\sum_{N_1}^{N_2} (\Delta H_e - \Delta H_n)^2}{\sum_{N_1}^{N_2} (\Delta H_e - \Delta H_e^*)^2} \tag{16}$$

with $N_1 = \frac{2.2s}{\Delta t}$ and $N_2 = \frac{2.6s}{\Delta t}$, by considering a set of ten logarithmically spaced values of χ_{ILV} between 10^4 and 10^5 (Figure 4). Such an analysis provides the value χ_{ILV} = 46,416 that can be considered to be in good agreement with the one given by the analysis of the R^2 behavior. The second confirmation is provided by the fact that a very similar value (χ_{ILV} = 46,311) has been obtained by considering the entirety of the transmitted pressure wave within the direct analysis of the pressure signal in the time domain executed in [22].

Figure 5 shows the pressure signal obtained for three particular conditions: (i) the system with the fully open ILV (χ_{ILV} = 0), (ii) the partially closed ILV (with χ_{ILV} = 46,416), which simulates the behavior of a not perfectly sealed valve, and (iii) the system with the fully closed ILV ($\chi_{ILV} = +\infty$), which simulates perfect sealing. Accordingly, in the pressure signal simulating the case with $\chi_{ILV} = +\infty$, the reflected pressure waves almost double their amplitude at the measurement section. On the contrary, in the pressure signal for χ_{ILV} = 0, the generated pressure wave propagates in an undisturbed manner, while the one for the SJ is predominant. Finally, in the pressure signal for χ_{ILV} = 46,416, both the positive pressure wave reflected by the ILV and the negative one reflected by the SJ are present and there is a good agreement with the field data. This latter result confirms the not perfect sealing of the ILV.

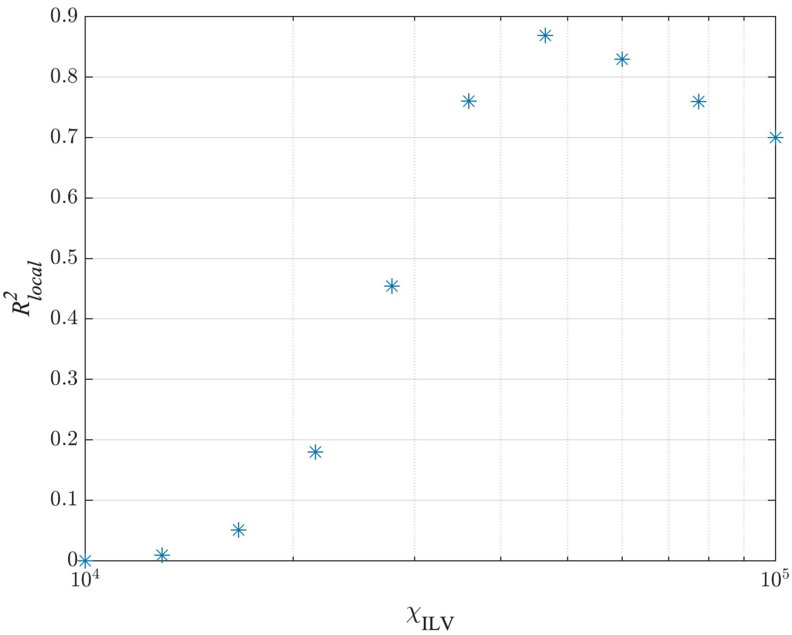


Figure 4. Local inspection of the pressure signal by considering the value of the determination coefficient in close proximity of the positive reflected pressure wave due to the interaction with the in-line valve, ILV.

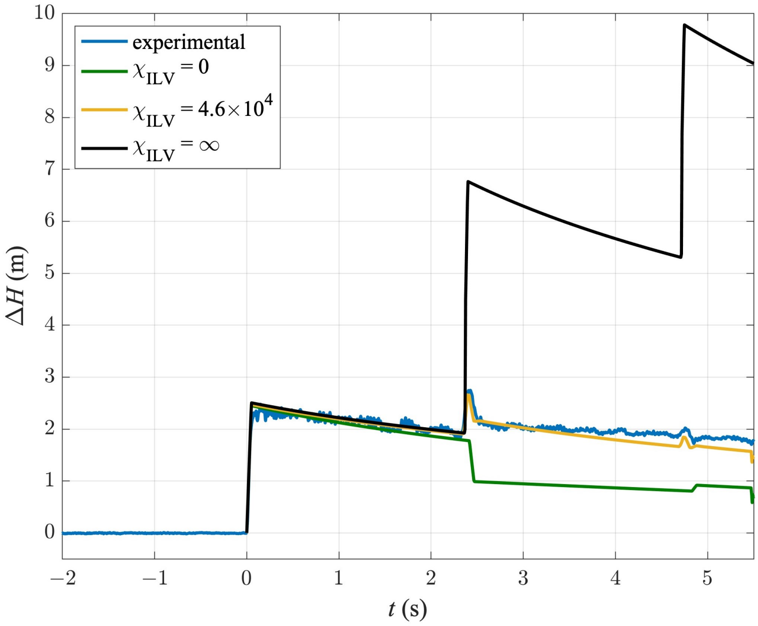


Figure 5. Transient response of the Dorsale TM for different conditions of the in-line valve: fully open, partially closed (i.e., not perfectly sealed) and fully closed (i.e., perfectly sealed).

3.2. Capturing the Transient Response of a Series Junction by Direct Analysis (DA)

The features characterizing the experimental pressure signals can be analysed by considering the reflection and transmission coefficients—C_R and C_T, respectively—as they describe the dynamics of the propagation of the pressure waves in the system and their interaction with faults and singularities. As mentioned, a pressure wave encountering a singularity is partially reflected and partially transmitted, with the amplitude and sign defined by formulas available in the literature [25,30]. In the considered system, it is possible to follow the path of the pressure waves as shown in Figure 6; in such a context, the interaction with the series junction SJ can be analysed. This figure shows that the system layout is recalled on the left side as a reference, while in each of the other columns—defining the steps for wave propagation—for the sake of clarity, only the interactions of the single pressure waves with the ILV, SJ and PS are highlighted.

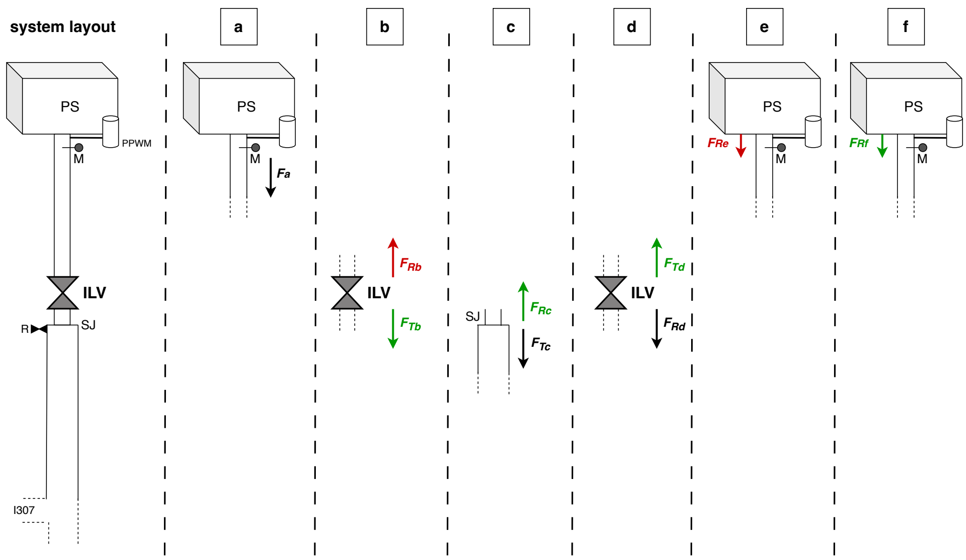


Figure 6. Path of the pressure waves with their interaction with the in-line valve (ILV), series junction (SJ) and pumping station (PS). Small letters in the boxes indicate the path steps.

When the field test is carried out, indicated as step "a", the pressure wave F_a = 2.51 m is generated. Such a wave experiences the first interaction (step "b") with the ILV, where, according to [22], the reflection coefficient, C_{Rb}, is equal to 0.16 (with the second subscript indicating the step). As a consequence, the reflected pressure wave, $F_{Rb} = C_{Rb}F_a$ = 0.4 m, can be evaluated. Accordingly, the transmitted pressure wave, $F_{Tb} = C_{Tb}F_a$ = 2.11 m, is obtained by considering that the following relationship holds between the reflection and transmission coefficients:

$$|C_R| + |C_T| = 1 \tag{17}$$

which gives C_{Tb} = 0.84.

Successively, in step "c", while F_{Rb} travels back to the PS, F_{Tb} moves forward and interacts with the series junction, where:

$$C_{Rc} = \frac{\frac{A_1}{a_1} - \frac{A_2}{a_2}}{\frac{A_1}{a_1} + \frac{A_2}{a_2}} = -0.164 \tag{18}$$

It is worth recalling that the interaction between the incident pressure wave and the diameter increase gives rise to a negative reflected pressure wave, $F_{Rc} = -0.35$ m. Such a wave, when traveling back, interacts again with the ILV in step "d", with $C_{Rd} = C_{Rb} = 0.16$. Therefore, the transmitted wave through the ILV can be evaluated as $F_{Td} = (1 - |C_{Rd}|)F_{Rc} = -0.29$ m.

In step "e", at t = 2.34 s, the first reflected pressure wave at the ILV, F_{Rb}, reaches the PS where the valve is closed. As a result, such an interaction is equivalent to the one with a dead end (i.e., with a reflection coefficient equal to 1). Afterwards, the reflected pressure wave measured at M is equal to $F_{Re} = 2F_{Rb}$ = 0.8 m. In Figure 6, these two waves are highlighted in red to better pinpoint the wave path of the first reflected pressure wave at the ILV. Similarly, the waves indicated in green allow us to visualize the path followed by the first transmitted pressure wave. Such a wave, once it arrives back at the PS, experiences the same interaction of F_{Rb} and doubles, giving way to a F_{Rf} equal to -0.58 m at t = 2.41 s. The values of the reflected pressure waves, F_{Re} and F_{Rf}, are consistent with those that can be obtained directly from the acquired pressure signals where, after t = 2.34 s, an increase followed by a decrease in the pressure can be noticed. Such a behavior confirms that the ILV is not perfectly sealed. In other words, this is the reason why the pressure waves inserted by the PPWM can interact with the SJ.

4. Conclusions

The management of devices installed in long Transmission Mains (TMs) can present unexpected difficulties. This is the case for checking the tightness of in-line shut-off valves, which is of great importance when maintenance work has to be carried out. Currently available methods are rather inefficient and time consuming. This paper proposes a practical, simple and efficient methodology to assess the opening status of in-line valves, based on the analysis of the pressure signals acquired during transient tests that generate small overpressures. Within such an approach—attributable to the Transient Test-Based Techniques (TTBTs)—particular attention has been given to the type of maneuver that generates the pressure waves that "explore" the TM. Ease of use and reliability have been suggested as reasons to insert the pressure waves by means of the Portable Pressure Wave Maker (PPWM), a device developed at the Water Engineering Laboratory of the University of Perugia, Italy.

Field tests have been carried out in the Dorsale TM managed by CAP Holding SpA, Milan (Italy), to demonstrate the application and effectiveness of the proposed methodology. During the tests, a small pressure wave with an amplitude of approximately 2.5 m and, thus, absolutely safe for the TM, was generated. The results of these tests were used to verify the performance of a numerical transient model within an Inverse Transient Analysis

(ITA) procedure. In addition, Direct Analysis (DA) of the pressure signals was carried out in order to complement ITA by also capturing the transient response of a series connection.

The use of ITA allowed us to demonstrate the actual status of the investigated in-line valve. The positive pressure wave reflected by the valve was much smaller than what was expected if it were perfectly sealed. On the other hand, the numerical simulations showed that the larger the value of the valve opening degree, the lower the accuracy of the method, since the reflected wave by an almost fully-open valve is smaller.

Given the simplicity, short duration and repeatability of the transient tests, they can be carried out regularly and autonomously by the water company's technicians. Additionally, the necessary equipment (i.e., Portable Pressure Wave Maker, PPWM) has a low cost and the analysis of the results can be carried out quite rapidly by the proposed methods based on ITA and DA. For these reasons, the proposed Transient Test-Based Techniques (TTBTs) have been demonstrated to be suitable tools for detecting different types of faults and singularities in pressurised pipelines.

In terms of future research, further tests should be carried out in real systems to assess the capability of this approach to distinguish overlapping pressure wave reflections associated to very closely located pipe features or to identify different singularities with similar reflected waves (e.g., diameter decrease and wave celerity increase). Also, further research should be developed for using machine learning methods to automatically detect pipe system faults based on transient pressure signals.

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