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Procedia Engineering 70 (2014) 1131 – 1136

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

The skeletonization of Milan WDS on transients due to pumping switching off: preliminary results

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Abstract

This paper is an extension of a previous paper (Brunone et al., 2013), in which a transient test procedure is discussed on the basis of field tests executed in the steel water distribution system (WDS) of Novara in the northwestern part of Milan, Italy, managed by Metropolitana Milanese S.p.A. In this paper, tests are repeated by modifying test conditions and improving the successive analysis. In particular, since the pump switching off is slow and unmodifiable, some of the main connections reached by the pressure waves before the end of the maneuver have been closed during the test. In such a way, the interference between the maneuver and the system has been reduced. The wavelet transform (WT) is used to evaluate the pressure wave speed of the supply pipe. In order to estimate the other pressure wave speeds, an optimization procedure is carried out. First of all, a skeletonization of the network is operated and then a Lagrangian model (LM) and a Genetic Algorithm (GA) are coupled considering such a skeletonized system. By minimizing the difference between numerical and experimental pressure signals, the optimal values of the pressure wave speeds are obtained. Finally the procedure is checked by comparing the experimental pressure signal and the one obtained by LM considering the optimal values of the pressure wave speeds and the actual network.

Keywords: distribution pipe systems, transient tests, diagnosis

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1. Introduction

In a previous paper (Brunone et al., 2013), a procedure to diagnose a water distribution system (WDS) by means of transients is presented. The examined steel pipe system is the Novara WDS in the northwestern part of Milan. The system is supplied by a pumping station with four pumps. A check valve is installed immediately downstream the pumping group. During tests, only one pump was functioning and pressure signal was measured immediately downstream the check valve. The analyzed transient is generated by the pump switching off; the schematic of the

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doi:10.1016/j.proeng.2014.02.125

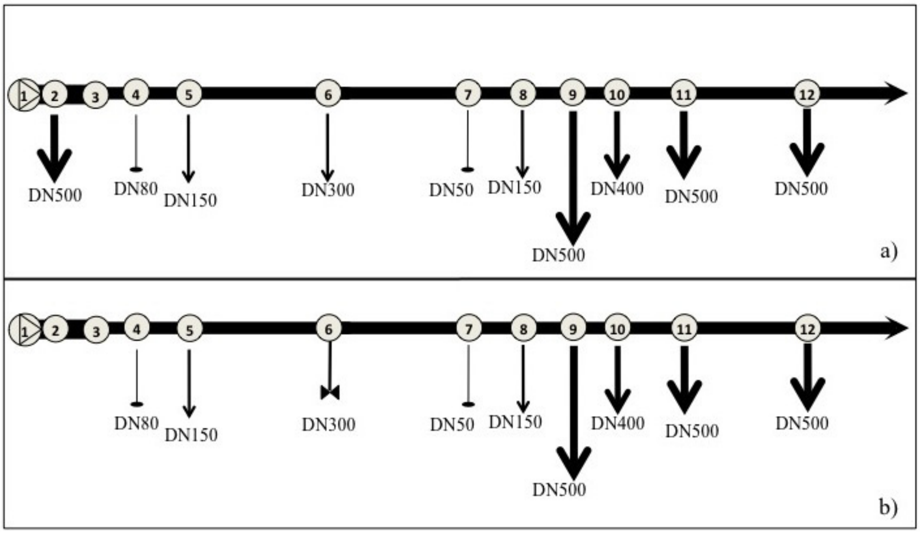

Fig. 1. Schematic of the main pipe of the Novara WDS: a) preliminary test (test no. 1); b) present test (test no. 2)

main pipe is shown in Fig. 1a. The acquired pressure signal — test no. 1 — is reported in Fig. 2 by a dashed line (the maneuver begins at $t = 0$, and the subscript E indicates the experimental data). As discussed in Brunone et al. (2013), the procedure is not as reliable as it should be for several problems in the execution of the test. Particularly, during the test, the full scale of the pressure transducer (= 100 m) was too large with respect to the acquired maximum value of the pressure (= 53 m). Moreover, because the maneuver is really slow and there are several open junctions very close to the pumping station, during the maneuver there is a combined effect of the maneuver itself and such junctions on the pressure signal measured downstream the check valve. Consequently, since the exact efflux curve of the pump is not known, it is difficult to distinguish the effect of the maneuver from those of the singularities. Finally, there is not a characteristic section close to the measurement section useful to calculate the pressure wave speed. A Lagrangian Model (LM) is performed in order to capture the main characteristics of the pressure signal and evaluate the causes of its discontinuities. Such a model is based on the solution of the differential equations governing frictionless transients in pressurized pipe systems (Swaffield and Boldy, 1993) and assumes the instantaneity of the maneuver. However, as shown in Brunone et al. (2013), since the pipe system configuration of Fig. 1a is inappropriate, LM is inefficient; thus, to improve the efficiency of the diagnosis, the transient test was repeated by closing some of the connections closest to the pumping station. Particularly, the DN500 pipe, connected to the supply pipe by means of junction 2, is temporary disconnected as well as the DN300 valve immediately downstream of the node 6 is completely closed (Fig. 1b and Table 1). Furthermore, to improve the accuracy of the pressure signal, a transducer with a smaller full scale is used (= 70 m for a maximum pressure of 63 m).

The pressure signal acquired in the Fig. 1b pipe system — test no. 2 — is reported in Fig. 2 by a continuos line. As predictable, during test no. 2 the steady-state pressure is higher than the value acquired during test no. 1 because of the closure of part of the network. The maneuver which gives rise to the transient is the same: however, it seems longer during test no. 2 because there are not singularities which hid it, as it happened during test no.1. The wavelet transform (WT), which allows the automatic detection of singularities in noisy pressure signals, is used to evaluate the pressure wave speed of the supply pipe. In order to estimate the other pressure wave speeds, an optimization procedure is carried out. First of all, a skeletonization of the network is operated for a hydraulic transient solver. Secondly, LM and a Genetic Algorithm (GA) are coupled considering such a skeletonized system. By minimizing the difference between the numerical and experimental pressure signals, the optimal values of the pressure wave speeds are found. Finally, the procedure is checked by comparing the experimental pressure signal and a signal obtained by the LM considering the optimal values of the pressure wave speeds and the actual network.

Table 1. Principal characteristics of the main pipe of the Novara WDS.

initial node	end node	Length, *L* (m)	Nominal diameter, *DN* (mm)
1	2	13	900
2	3	14.5	900
3	4	260.5	800
4	5	310	800
5	6	1759.6	800
6	7	1750.2	800
7	8	476.1	800
8	9	171.7	800
9	10	107.4	800
10	11	446.3	800
11	12	989.4	800

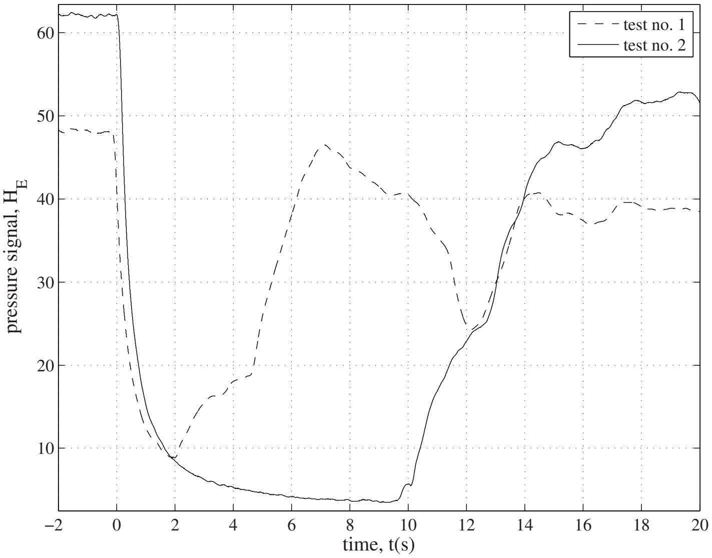

Fig. 2. Novara WDS: experimental pressure signal, H_E, acquired during a pump switching off during tests no. 1 (Fig. 1a pipe system) and no. 2 (Fig. 1b pipe system)

2. Analysis of the pressure signal

2.1. Evaluation of the pressure wave speed of the supply pipe

The pressure signal was analyzed by WT (Fig. 3). For further details about this method see Mallat and Zhong (1992), Mallat and Hwang (1992) and Ferrante et al. (2007, 2009b,a). Thanks to procedures described in Mallat and Hwang (1992) and Donoho (1995), it is possible to filter noise which degrades the information content of experimental signals and, then improve the identification of singularities: in correspondence to these, the maximum local moduli of WT appear in typical form with the variation of scales, organizing themselves into chains. Such chains, by exposing singularities in the pressure signal, also identify the passage of waves through the measurement section, even if this is marked by a modest fluctuation in pressure. After the end of the maneuver, the first clear singularity of the pressure signal evidenced by WT is at time $t = 9.607$ s; it determines a 2.2 m increment of pressure. Since the check valve is completely closed, it behaved as a dead end and then such an increment is double with respect to the pressure wave that caused it. Such a wave can presumably be ascribed to junction 8 at a distance 4587.04 m from the measurement section. This junction caused an increase in the pressure signal that LM sets to 2.02 m at the check valve. By

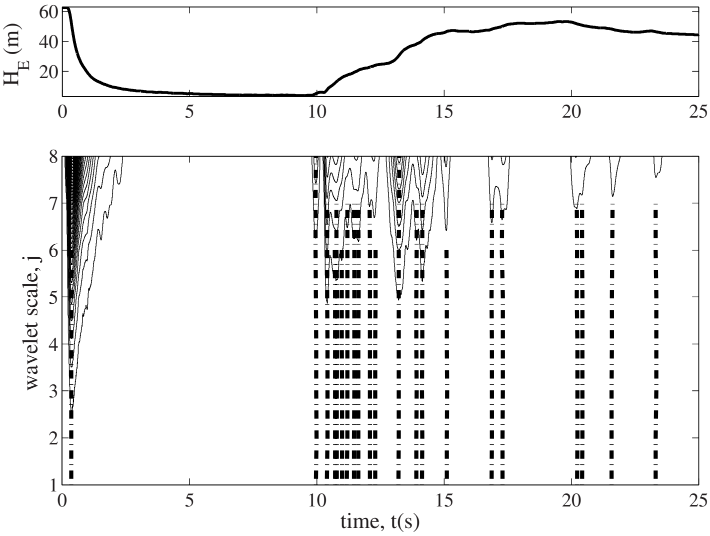

Fig. 3. Wavelet transform of the experimental pressure signal (test no. 2)

associating the discontinuity of the pressure signal with junction 8, the resulting value of the pressure wave speed of the supply pipe is equal to a_{800} = 954.26 m/s, which is compatible with the characteristics of the pipe.

2.2. Skeletonization on WDS hydraulic transient model

Skeletonization is the process of representing a WDS by selecting only the “most important” pipes from the transient modeling point of view. To skeletonize the network for a hydraulic transient solver, the operating way is different with respect to the skeletonization executed to analyze a system in steady-state conditions. The proposed procedure is the following: i) the entire network is considered with all pipes with the same pressure wave speed (= a_{800}) and LM is run; ii) the results of LM are analyzed. The frequency distribution of the numerical relative amplitude of the pressure waves, h_N, at the measurement section is plotted in Fig. 4, with the subscript N indicating the numerical model results. The relative amplitude, h, is defined as:

$$h = \frac{H - H_0}{H_0 - H_T} \tag{1}$$

with the subscripts 0 and T indicating the steady-state condition and the duration of the maneuver, respectively. h_N is evaluated for $t \leq 13.21$s, with $t = 13.21$ s being the time at which the pressure wave generated by the maneuver reaches section 12 (Table 1 and Fig. 1b); iii) only pressure waves with h_N larger than three times their standard deviation, σ, are considered (Fig. 4). Thus, only the pipes closest to the pumping station and, at the same time, crossed by the largest pressure waves are considered.
The resulting pipes are 31 with a maximum distance of 6303 m from the measurement section. In such pipes, pressure waves with a relative amplitude larger than 0.6192 occur. The diameter of such pipes pipe ranges from 0.08 m to 0.9 m.

2.3. Evaluation of pressure wave speeds by means of a Genetic Algoritm

The values of the pressure wave speed derive from an optimization technique which minimized the difference between numerical and experimental pressure signals. The Nash-Sutcliffe model efficiency coefficient, E_f, is used:

$$E_f = 1 - \sum_{i=1,t>T}^{M} \frac{(H_{E,i} - H_{N,i})^2}{(H_{E,i} - \bar{H}_E)^2} \tag{2}$$

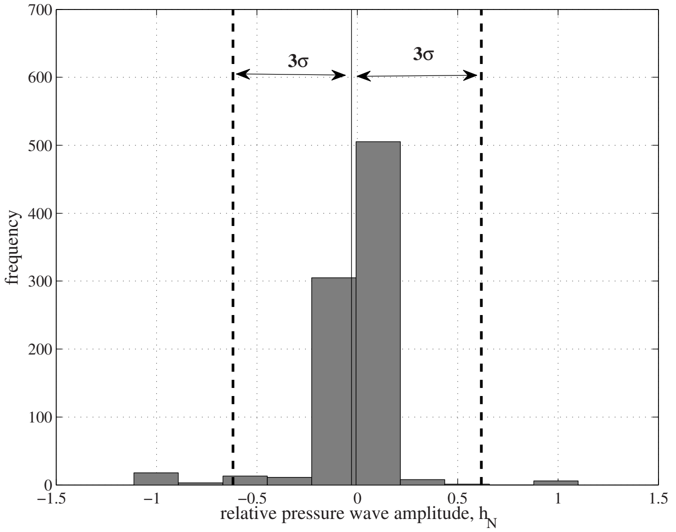

Fig. 4. Frequency distribution of the relative amplitude of the pressure waves given by LM for test no. 2

where M is the number of samples after the maneuver time ($= T$). Nash-Sutcliffe efficiency can range from $-\infty$ to 1. An efficiency of 1 ($E_f = 1$) corresponds to a perfect match of modeled pressure signal to the experimental data. An efficiency of 0 ($E_f = 0$) indicates that the model test is as accurate as the mean of the experimental data, whereas an efficiency less than zero ($E_f < 0$) occurs when the residual variance is larger than the data variance. Essentially, the closer the model efficiency is to 1, the more accurate the model. The optimal values of the pressure wave speeds were determined by a novel heuristic procedure carried out by a Genetic Algorithm (GA), for each value of pipe diameter (Goldberg, 1989). Specifically, the maximization of the Nash-Sutcliffe model efficiency coefficient was carried out by the Genetic Toolbox of MATLAB. The GA was carried out for 40 generations with a population composed of 20 individuals with a crossover percentage equal to 0.8. The graph of the network is derived by the skeletonization procedure described above. At the forth generation, the GA provides the pressure wave speeds for all the pipe diameters. The corresponding Nash-Sutcliffe model efficiency coefficient was $E_f = 0.9873$.

3. Results and discussion

When the pressure wave speed are evaluated, LM is run for the actual network. In Fig. 5 the comparison between the numerical and experimental pressure signal is shown. To improve the efficiency of the numerical simulation, during the maneuver the convolution between the impulse response function evaluated by LM and the derivate of the pressure signal is carried out. In Fig. 5, the LM reconstruction of the pressure signal is shown in the case of all the terminal connections active (dashed line), with the actual characteristics of the maneuver. The resulting value of E_f for $t > T$ is satisfactory ($E_f = 0.8119$). The differences between H_E and H_N are due, among the others, to the important simplifications in the numerical model (such as the frictionless approach) and the uncertainties related to the values of the pressure wave speeds which could be affected by the actual pipe diameter and thickness of the pipe and the skeletonization of the network. However, the reliability of procedure increased with respect to the preliminary test (Brunone et al., 2013). In fact, there is a quite good agreement between the discontinuities in the numerical and experimental pressure signals, having in mind that the aim of this work is to detect possible anomalies and not to simulate the system behavior in all details. Because of the complexity of the investigated WDS, further improvements can be obtained by increasing the number of measurement sections.

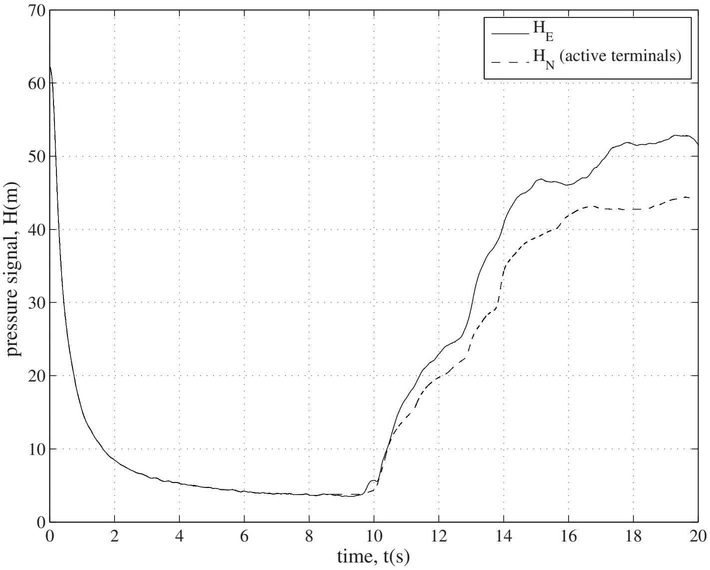

Fig. 5. Experimental vs numerical pressure signals for test no. 2.

Acknowledgements

This research has been supported by the Italian Ministry of Education, University and Research (MIUR) under the Projects of Relevant National Interest “Advanced analysis tools for the management of water losses in urban aqueducts”, “Tools and procedures for an advanced and sustainable management of water distribution systems” and Fondazione Cassa Risparmio Perugia under the project “Hydraulic characterization of innovative pipe materials (no. 2013.0050.021)”.

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