

Unsteady flow modelling of RTC in water distribution networks

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ABSTRACT

This paper describes the use of the unsteady flow modelling (UFM) for the simulation of remote Real Time Control (RTC) of pressure in water distribution networks (WDNs). The developed model combines UFM with specific simulation modules for generation of pulsed nodal demands and dynamic adjustment of pressure control valves. The results of the application to a skeletonized WDN show that UFM provides a sound description of the amplitude of the pressure head variations at the controlled node. Further calculations prove the RTC algorithm to be stable in the presence of measurement errors on the monitored variables.

Keywords: Control valves; Hydraulic transients; Water demand; Feedback control; Demand pulses; Water distribution systems; Real Time Control.

1 BACKGROUND

Nowadays, service pressure control is a well-established practice in water distribution network (WDN) management. In fact, studies have recently proven it to bring significant benefits in terms of reduction in leakage [1] and pipe bursts [2]. Other benefits [3] include an extension of the infrastructure useful life, an attenuation of the growth rate of hidden leakage, an abatement of the customers' complaints and a reduction in the costs associated with the third-party liability insurance.

While performing service pressure regulation, remote real time control RTC can be used to regulate control valves. This approach is based on using remote measurements, mainly concerning the service pressure at the critical node(s), with the lowest pressure head in the WDN (e.g., [4], [5], [6]). In detail, RTC operates by monitoring the pressure head at the critical node(s) and by signaling the reading to the control valve. Based on this reading, a programmable logic controller (PLC) can suitably set the valve to maintain the minimum desired pressure at the remote critical node(s). As it is shown in [7], the performance of RTC improves when a further measurement is acquired and signaled to the PLC, concerning the water discharge in proximity to the valve. The larger initial cost of a valve controlled in real time (RTC valve) is paid back in the long run, especially in the case of high water unit cost [8].

While most of the work in the scientific literature concerns the use of steady flow modelling for the simulation of RTC, this paper, which is the summarized version of paper [9], explores the advantages of unsteady flow modelling (UFM). In the simulations presented in this paper, the presence of pulsed demands at network nodes is also considered. The focus of this paper is on the modelling of the instantaneous pressure head variations and on the numerical analysis of the

stability of RTC. In the following sections, first the methodology is described, followed by the application to a skeletonized WDN and the conclusions.

2 METHODS

2.1 Pulsed demand at WDN nodes

The trends of nodal demand were obtained using the pulse generation model cor-PRP [10], based on the Poisson stochastic process. This model generates demand pulses with durations and intensities as random variables following pre-fixed probability distributions. In detail, the variant adopted in [11] was used, in which pulse durations and intensities were generated through the bivariate beta distribution.

After that the pulses were generated at the generic node, they were scanned at a fixed time step (e.g., one second), and the nodal demand at any time step was obtained as the sum of the intensities of all the simultaneously active pulses.

2.2 RTC algorithm

The control algorithm proposed in [7] was used in this work. This algorithm is based on measuring the water discharge Q (and therefore the flow velocity V) upstream from the valve and the pressure head at the critical node, which needs to be controlled through valve setting variations.

To describe this algorithm, let us assume that, at the generic time t_1 , the valve closure setting is equal to $\alpha_{reg,1}$. Thus, the corresponding local head loss in the valve is equal to:

$$\Delta h_1 = \xi_1 V^2 / 2g, \quad (1)$$

where ξ_1 is the local head loss coefficient associated with $\alpha_{reg,1}$. In this configuration, the pressure head h_1 at the critical node has a deviation e from the desired set point value h_{sp} equal to:

$$e_1 = h_1 - h_{sp}, \quad (2)$$

Under the assumption of Q being constant in time and pressure independent, the deviation can be led to 0 from time t_1 to time $t_2 = t_1 + \Delta t_{cont}$, with Δt_{cont} being the control time step, by modifying the valve local head loss from Δh_1 to Δh_2 :

$$\Delta h_2 = \Delta h_1 + e_1. \quad (3)$$

To accomplish this, the valve head loss coefficient at time t_2 has to be equal to:

$$\xi_2 = \xi_1 + \frac{2g e_1}{V^2}. \quad (4)$$

The value of $\alpha_{reg,2}$ associated with ξ_2 can be easily derived from the curve $\alpha_{reg}(\xi)$ supplied by the valve manufacturer.

Whether Q is not constant in time (as is the case with a temporal change in network demand due to the presence of pulses) and/or is pressure dependent, eq. (4) can still be used for assessing the actuator setting corrections in RTC. However, the temporal average of e_1 and V over Δt_{cont} have to be used inside eq. (4).

2.3 UFM

The unsteady flow modelling UFM [12] enables analyzing the hydraulic transients due to rapid nodal demand and/or valve setting variations.

In this work, the 1D unsteady flow model of [9] was used, in which network pipes are discretized with spatial steps. Along the pipes, total heads and water discharges are calculated at prefixed

temporal steps by solving the water hammer partial differential equations. Suitable boundary conditions were prescribed in correspondence to the network nodes, depending on whether a source node or a demanding node with assigned total head or demand, was referred to. Nodal demands are modelled through the demand-driven approach.

Inside the model, the pipe friction slope was suitably corrected in order to correctly represent the unsteady flow resistances [13]. Furthermore, the leakage q [m²/s] per unit of pipe length is evaluated through the following formula:

$$q = \alpha_{leak} h^\gamma, \quad (5)$$

where h is the pressure head along the pipe. Furthermore, α_{leak} and γ (-) are the leakage coefficient and exponent, respectively.

3 APPLICATIONS

3.1 Case study

The applications of this work concerned the skeletonized WDN of a town in Northern Italy [14], the layout of which is reported in Figure 1. The network is made up of 27 nodes (26 nodes with unknown head with ground elevation of 0 m a.s.l. and 1 source node with ground level of 35 m a.s.l.) and 32 pipes. In the applications, an average daily demand of 50.5 L/s was considered. As for leakage evaluation through eq. (5), exponent γ was set to 1, typical value for plastic pipes [15]. Coefficient α_{leak} was set to $9.4 \cdot 10^{-9}$ m/s in order to obtain a leakage percentage rate of about 20%, to reproduce a realistic estimate of that relevant to the real system. Furthermore, all the pipes were assumed to be made up of PVC ($E=3$ GPa and $n=0.01$ s/m^{1/3}). More details on the case study, including parameterization of pulse generation modelling, can be found in [9].

Simulations under RTC were performed assuming a control valve installed downstream of the pipe with end nodes 26 and 20, in a link with $D=300$ mm (see Figure 1). The RTC algorithm of [7] was applied considering valve shutter velocity $V_{reg}=1$ mm/s, which enables full valve closure from $\alpha_{reg}=0$ to $\alpha_{reg}=1$ in 300 s. The valve setting α_{reg} was bounded within the range [0, 0.95]. The target node for the implementation of the selected RTC architecture was node 1, which is the remote node of the downstream network with the lowest pressure head. The set point pressure head to achieve at the target node was fixed to 25 m. Following calculations done in [9], Δt_{cont} was set to 180 sec.

The results of two simulations (simulations 1 and 2) can be found hereinafter. Simulation 1 concerns the unsteady flow modelling of the WDN controlled in real time during a whole day, in the presence of pulsed demand at network nodes. In this simulation, the measurements useful for RTC, that is the pressure head at the controlled node and the water discharge in the pipe upstream from the valve, were assumed error free. Simulation 2, which has a duration of 3 hours, was, instead, aimed at assessing the stability of RTC in the presence of $\pm 5\%$ measurement random errors on both the pressure head at the controlled node and the water discharge in the pipe upstream from the valve. In this latter simulation, nodal demands were kept constant, without pulses, and equal, for the three hours, to the average values in the time slot between 8 am and 9 am of simulation 1. Similarly, the source head is kept constantly equal to the average values from 8 am and 9 am of simulation 1. The choice to keep these variables constant is due to the attempt to focus on the behaviour of RTC in reply to measurement errors.

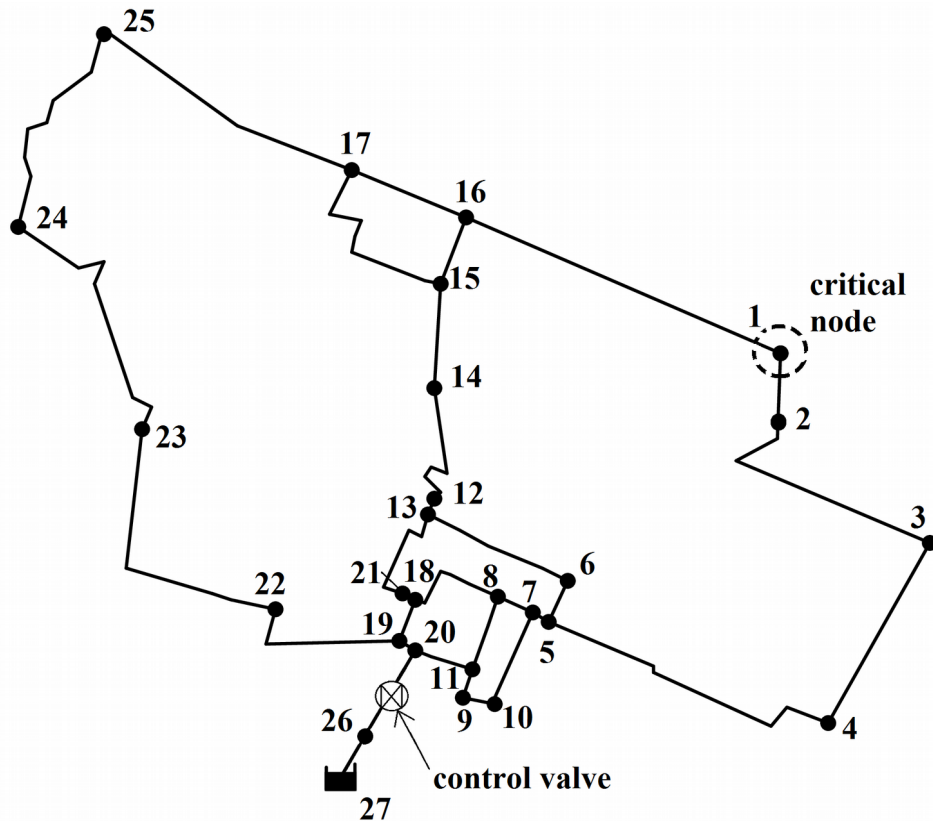


Figure 1. Network used for the work.

3.2 Results

The results of simulation 1 are reported in Figure 2, which shows the daily trends of α_{reg} and h . The results show that the valve tends to close (high value of α_{reg}) and open (low values of α_{reg}) at night time and daytime, respectively, consistently with the daily pressure pattern. As for h , it is on average close to the set-point even if the demand pulse related-pressure head variations cause undershooting and overshooting down to about 22 m and up to about 28 m, respectively. However, the presence of pressure undershooting is not believed to create risks of water demand shortfalls in this case.

Compared to the traditional modelling of RTC, which was used by previous authors (e.g., [4], [5], [6] and [7]), the new approach described in the present paper has the advantage of enabling, simultaneously, proper description of actuator setting variations and of pressure head oscillations in the presence of pulsed demand at WDN nodes. The comparison of the new approach with the traditional one is analyzed in further detail in [9].

The results of simulation 2 are reported in the graphs in Figure 3. The graph on the left shows the trend of α_{reg} , which slightly oscillates around its average value. The graph on the right highlights a similar behavior for the real pressure head at the controlled node. As expected, the oscillations of the measured pressure head at the controlled node are much larger (amplitude of about 0.25 m = 1% of the measured head due to the measurement errors). Overall, the fact that the oscillations do not increase in time gives evidence of the stability of RTC, and in detail of the control algorithm of [7], in the presence of measurement errors.

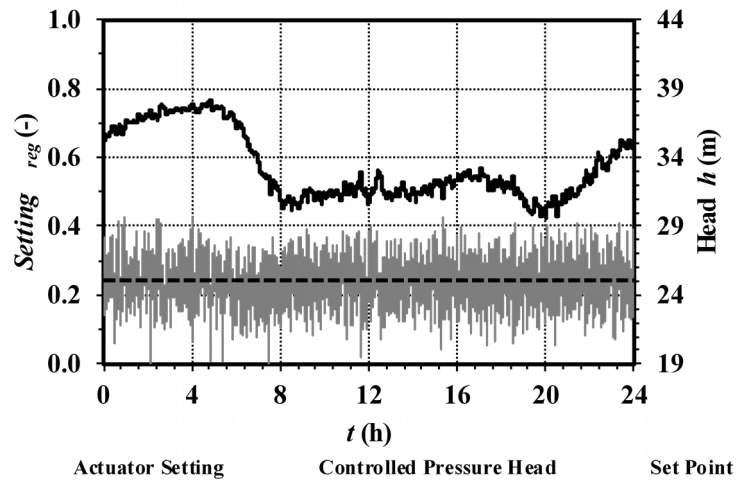


Figure 2. Daily trends of α_{reg} and h in simulation 1.

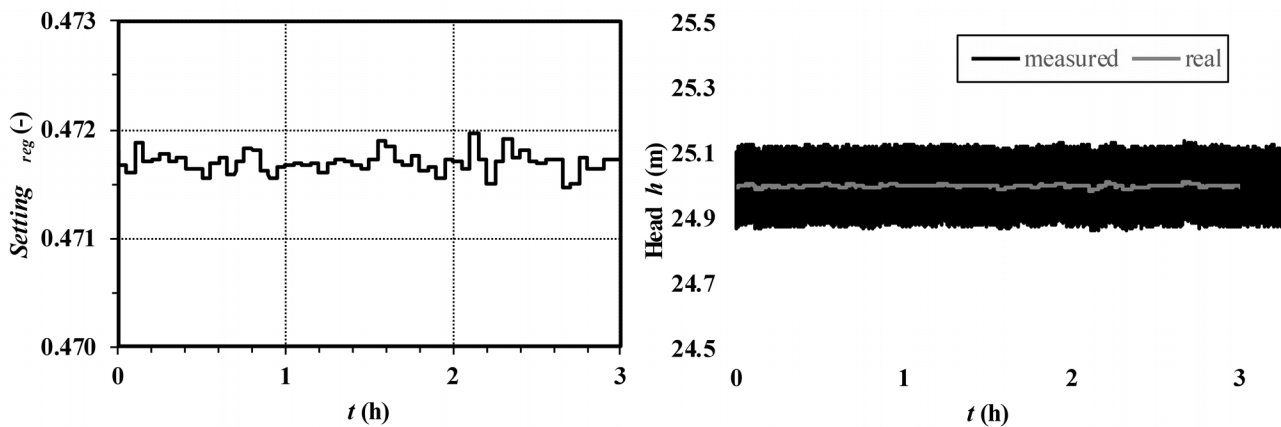


Figure 3. Results of Simulation 2: trends of α_{reg} on the left and of (real and measured) h on the right.

4 CONCLUSIONS

This paper presented a novel methodology that simulates the remote RTC in WDNs. Its main novelty lies in the adoption of UFM. The applications to a skeletonized real network showed that the new methodology is able to give sound indications on the actual amplitude of the actuator setting corrections and of the pressure head variations at the target node, in the presence of pulsed nodal demands, as is the case with real WDNs. Furthermore, the applications gave evidence of the stability of RTC, and in detail of the control algorithm of [7], when measurement errors are considered in both the pressure head at the controlled node and the water discharge in proximity to the control valve.

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