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Real-time adjustment of pressure to demand in water distribution systems: Parameter-less P-controller algorithm

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Abstract

Remote real-time control is currently the most advanced form of pressure management. Here the parameters describing pressure control valves (or pumps) are changed in real-time in such a way to provide the most optimal pressure in the water distribution system (mostly at the consumer location), as demand and reservoir levels change. An existing parameter-less P-controller based on the flow in a pressure control valve being known is argued to be easy to implement, and is used to develop an efficient controller to adjust the pressure. Its performance compared to an analogous existing parameter-dependent controller is discussed.

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Keywords: Water distribution system; Pressure management; Remote real-time control; Closed-loop pressure control; Hydraulic modelling

1. Introduction

It has widely been shown that higher pressures lead to an increase in leakage in pipes, increased damage of pipes and consumption increases [1]. In an advanced form of managing pressure to be low and constant, the pressure in the WDS can be adjusted via the use of PCVs and VSPs [2], in response to real-time pressure measurements at various remote control nodes. This is called RRTC [3], a form of *closed loop pressure control* which is the real-time

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version of what is known as *remote node-based modulation* [1]. The version which updates the control profile through statistical procedures, as well as time-based and flow-based modulation, are not discussed here [1]. Many optimization methods for PCVs, in terms of the number of valves, valve locations, and valve settings, have been proposed. A common disadvantage of most of these methods is that they rely on a hydraulic model of the real-world WDS. The methods may hence (a) be difficult to implement in practise due to the need to construct a hydraulic model; and (b) may not match well onto the real-world WDS because of inaccuracies of the hydraulic model [4]. However, a subclass of methods, based on PID-type controllers, removes both problems, because they are not based on a hydraulic model. Specifically, because of the PID control characteristics, the method can match onto a real-world WDS (because a *range* of control parameter values can be used).

There has been recent work on P-controllers (a simplified version of PID control), which forms the context of this work [3, 5, 6, 7, 8]. In particular, such controllers are studied where the flow in the PCV is known [3, 5]. The P-controllers proposed typically depend on one unknown control parameter. We believe that the most useful P-controller is a parameter-less one, because of the ease of implementation, even though its controlling ability is expected to be worse than that of a controller with some optimal (and WDS-dependent) control parameter. The ease of implementation stems from the fact that a field test of the WDS, or hydraulic model to simulate the WDS, is not required for the determination of the control parameter. Nor is there a need for tuning rules. Moreover, for a parameter-dependent controller the control parameter is tuned for specific WDS conditions (for example, the water demand and reservoir conditions considered later in this work), so that the controller might not provide satisfactory performance (without extra retuning) for different conditions [9].

There are recent reviews of the entire field of pressure management [1], and the sub-area of hydraulic modelling techniques [10]. An existing parameter-less and parameter-dependent controller that depend on the PCV flow being known are analysed in detail in a distinct WDS, expanding various conclusions obtained previously. The novel aspects of this work are highlighted in the Conclusion section.

Nomenclature

WDS	water distribution system
PCV	pressure control valve
VSP	variable speed pump
RRTC	remote real-time control
PID	proportional integral derivative
P	proportional
PRV	pressure reducing valve

2. Parameter-less P-controller based on known PCV flow

The aim of PCVs is to maintain a set pressure value at a (remote) control node of the WDS. PCVs maintain the pressure setting by reducing (PRV) or sustaining (pressure sustaining valve) the pressure by means of the movement of the shutter. In particular, a PRV is a device which increases/reduces the internal head-loss in order to reduce/increase the pressure at the control node to the set-point. PCVs can be modelled by expressing the head-loss across the PCV by a formula that is the same as that of minor friction loss across a pipe [3, 5, 6]. For electrically controllable valves, manufacturers provide mathematical curves that allow the calculation of the head-loss coefficient ξ (the same notation used by [3, 5, 6]) in this formula as a power-law function of the normalised shutter opening α, using two constants commonly denoted k_1 and k_2 (the same notation used by [3]). Here α is the ratio of the shutter opening and the maximum stroke of the PCV [3, 5, 6]. It varies between $\alpha = 0$ (PCV fully closed) and $\alpha = 1$ (PCV fully open) (the convention used by [3, 6]). In the example later, $k_1 = 2.8$ and $k_2 = 1.5$ (used in [3, 6]).

PCVs, remotely controlled in real-time by using downstream control node pressures, have been proposed. One can seek to control using several individual node pressures, or an average of node pressures in the WDS. However, here we adopt the usual approach to use as many individual nodes as there are PCVs, and to use the sensitive nodes in the WDS which have the lowest pressures. The position of these *critical* points [7, 11] usually does not vary over time [3], which is confirmed for the WDS that we study.

The shutter opening is changed at each control time-step T_c, with the restriction that the change is limited by the maximum shutter speed (for details, see equations 2-3 of [6]). The restriction limits unsteady flow processes [3, 5, 7] and improves convergence of the controller [3]. In the controllers the dimensionless maximum shutter velocity v_{shut}, which equals the ratio of the maximum shutter velocity and the maximum stroke of the PCV, is set equal to 0.0005 s^{-1}, as in [3]. Adopting $T_c = 5$ min (in accordance with [3, 5, 6]), yields a maximum change in α of $v_{shut}\, T_c = 0.15$ in one time-step. Note that even if the physical PCV allows a larger v_{shut}, convergence of the controller will limit the value of v_{shut} that should be used in the controller.

The only parameter-less P-controller based on knowing the flow rate Q in the PCV was recently proposed (called "valve resistance control" [3]), and was shown to be very effective compared to an earlier P-controller which controls the shutter opening directly [6, 7]. The parameter-less method, does, in contrast to the earlier method, require Q to be known by field measurement or through a hydraulic model. Installing a flow meter at the site of the PRV would incur additional financial cost.

At iteration i, the controller uses the deviation of the head at the control node H_i from the target set-point H_{sp} to calculate the change in ξ, and hence the change in the PCV shutter opening α. At the next iteration $\xi_{i+1} = \xi_i + 2gA^2 K (H_i - H_{sp})/Q_i^2$; where g is the gravitational acceleration and A the cross-sectional area of the PCV. The proportional constant K (notation of [5]) is unity based on theoretical considerations [5], which is also the choice implemented for the parameter-less controller. The theoretical derivation of the controller assumes that Q remains unchanged from iteration to iteration [5]. This is not the case in most WDSs. The constant K can hence be inserted in an attempt to correct for this [5]. In the example WDS studied later, it will be shown that the performance of the parameter-less controller worsens exactly when the change in Q from iteration to iteration is the largest (evidence for this was also noted by [6]). There is an additional interesting feature of the control formula: Mathematically, if Q is constant, H_i converges to H_{sp} if and only if ξ_i converges if an only if α_i converges. This suggests that controller convergence properties are likely to be the best when Q can be "forced" to be constant for application of the controller.

In principle, the controller with known flow Q requires the ability to set ξ directly in the field. However, this is considered to be impractical. The practical implementation of the controller is hence based on the ability to set α precisely (because it is a physical property of the PCV). Assuming that the relationship between ξ and α is precise, this enables ξ to be set precisely, as is required to implement the controller. On the other hand, it will be shown that the controller performs quite well with Q differing from the actual Q, suggesting that Q does not have to be known precisely. The results of this work do not take into account imprecision in the manufacturer's relationship between ξ and α, and imprecise readings of the pressure meter, yielding incorrect H_i.

3. Hydraulic model of the example WDS

The Jowitt and Xu WDS [12], specifically as implemented by Araujo et al. [13], is used as a hydraulic model of an example WDS (see Figure 1(a)). The same WDS was used in some earlier pivotal P-controller studies [6, 7]. The chosen WDS is a frequently applied bench test for applications oriented towards pressure control and leakage reduction. Jowitt and Xu used an extended version of a model previously analysed by other authors. The three reservoirs have time-varying water levels and the demand factor varies substantially between 0.6 and 1.4 (see Figure 1(b)) [12]. As such, the latter variation is found to drive most of the change of Q over time. Leakage is implemented according to [13]. In addition, the effect of pressure-dependent demand is taken into account.

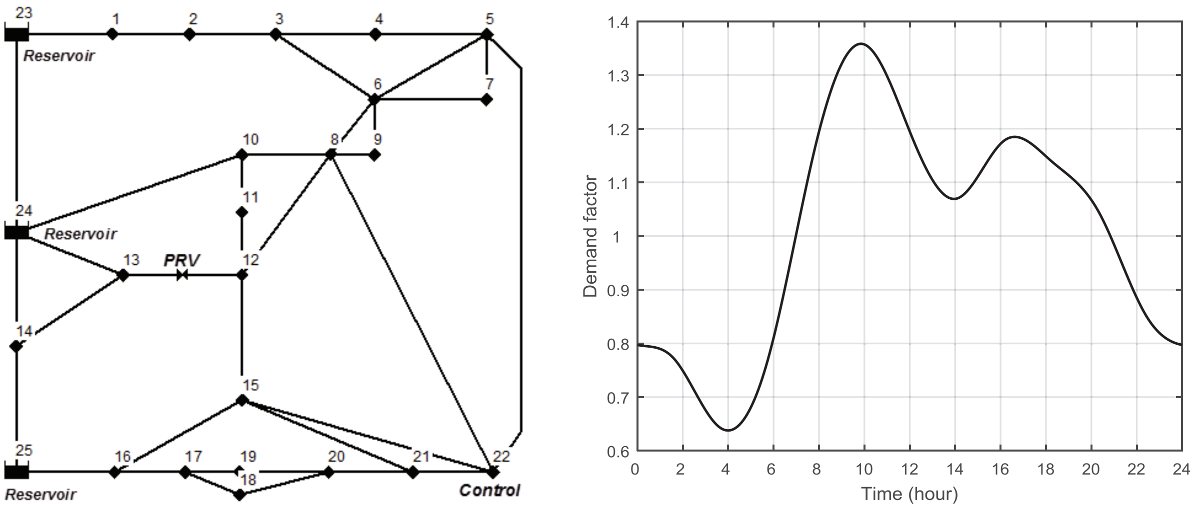

Figure 1: (a) WDS of Jowitt and Xu [12]. (b) Time dependence of the demand factor.

Following the previous results [13, 14] one PRV with diameter 350 mm is installed at the location shown in Figure 1(a) as the best valve site to control the water losses. It is confirmed that node 22 has the lowest pressures and is sensitive to the PRV shutter opening, so that it is chosen as the remote pressure control critical point. These choices are consistent with earlier P-controller studies [6, 7]. The target set-point pressure p_{sp} is taken to be 30 m (also used in [13, 15]).

A new algorithm has been written from scratch in the programming language C++. It interacts with a hydraulic solver, so that the controller can be validated on a hydraulic model of a WDS. The algorithm can read in any WDS specified by an EPANET2-formatted input file. This enables the controller to be validated on hydraulic models generated by various software packages. The time-variation of the demand factor and reservoir levels are read at intervals T_c. Experimental progress on water demand measurement via a smart meter system has been reported [16, 17], paving the way for the present project on smart water infrastructure [18] (including a study of the management of WDSs [19, 20]), of which this work is a part.

4. Validation of the P-controller on a hydraulic model of the example WDS

The usual application of pressure control is to bring the pressures in the WDS down to a low level with which all consumers are comfortable. Figure 2(a) shows the pressure at the control node (the node at which the pressure is usually the lowest) with a very nearly open PRV shutter opening that does not change, i.e. with no pressure control. This shows the typical situation where the control node pressure is larger than the set-point p_{sp}. As expected, there is an inverse relationship between the demand (Figure 1(b)) and the pressure (Figure 2(a)). Controlling the pressure at the control node via the parameter-less controller, forces the shutter opening to change as shown in Figure 2(b), spanning a range from very nearly open to nearly closed. When the uncontrolled pressure is large, the value of α needed for control is small, and vice versa.

The maximal uncontrolled pressure variation of 7.2 m (Figure 2(a)) is brought down to a maximal controlled pressure variation of 0.7 m (Figure 3(a)). In fact, the average controlled pressure variation is approximately just $2\Delta = 0.2$ m. Here $\Delta = 0.102$ m is defined as the temporal average of the absolute value of the difference between the head at the control node and H_{sp}, according to equation 2 of [5]. Δ is a measure of how near the control node pressures are to the set-point pressure, and hence how well the controller controls the pressure. Define δ as the maximum over time of the absolute value of the difference between the head at the control node and H_{sp}. This occurs at the sixth hour and $\delta = 0.41$ m (Figure 3(a)). The quantities Δ and δ quantify the mean and maximum deviations respectively.

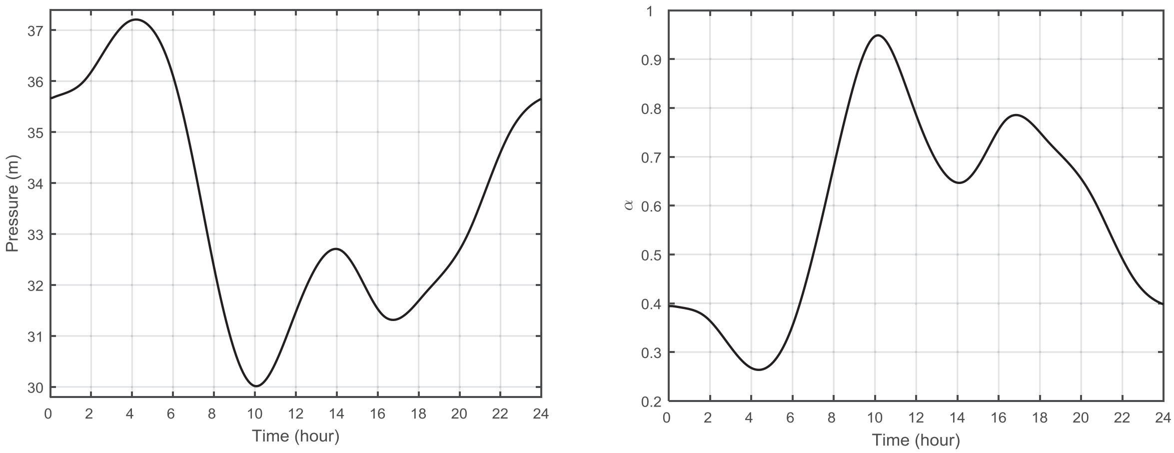

Figure 2: (a) Time-dependent pressure at the control node for constant shutter opening $\alpha = 0.95$. (b) Time-dependent shutter opening α when the pressure is controlled with the parameter-less P-controller.

It is noticeable that the times with larger pressure deviations from p_{sp} in Figure 3(a) approximately coincide with the times when the demand in Figure 1(b), and hence Q, changes the fastest. This is in accordance with the expectation that the performance of the controller worsens exactly when Q changes the fastest.

The effect of forcing Q, for application of the controller, to be constant for periods of time, is investigated, with the hope of improving the convergence properties. The value of Q_c used in the controller is kept constant until the current Q differs from it by more than a certain percentage. At this time, Q_c is set to equal Q. For percentages in the range 0-5%, which should keep the flow used in the controller similar enough to Q, no significant change is observed for controller convergence. Hence forcing Q to be constant does not appear to improve convergence properties.

One can move away from the parameter-less controller ($K = 1$) by varying K [5]. The values of Δ and δ are shown in Figure 3(b) as K is varied. The ratio δ/Δ ranges from 3.0 to 5.4 as K changes. The generic behaviour is the same as shown in Fig. 3 of [6]. PID controllers have two common characteristics, both of which are confirmed by Figure 3(b). Firstly, for very small K convergence is slowed, causing poorer performance of the controller. Secondly, for very large K convergence may not be achieved, leading to breakdown of performance. A safe practice is to prefer a smaller value of K than the optimal one, to improve the chance of convergence.

For the WDS studied, Figure 3(b) shows that the controller performs optimally for K near 2.2, where Δ is a tiny 0.019 m, and δ a tiny 0.057 m. The time-dependence of the pressure at the control node is shown in Figure 3(a). For the Central-Northern Italy WDS, a value of K near 2.5 was found to allow the same controller as implemented here to perform optimally, with $\Delta = 0.09$ m [5]. The optimal K was found to be very similar ($K = 2.5$-2.6) for very different demand scenarios [5]. For the Jowitt and Xu WDS, the optimal value of K is similar (although Δ is quite different). This leads to the hypothesis that there is a small range of optimal K for different WDSs. This should be tested in further research.

For the Jowitt and Xu WDS, K in the range 1.6 to 3.2 yields values of Δ within a factor of two of its minimal value, and the variation shape of Δ as a function of K is fairly flat (Figure 3(b)). This range of K is the "effective" range for the controller to operate in [6]. A safe practice choice may hence be $K = 1.6$. For the reasons mentioned before, the parameter-less controller is the easiest to implement. However, in time the controller can gradually be adjusted to $K = 1.6$ if improved convergence is desired (see below).

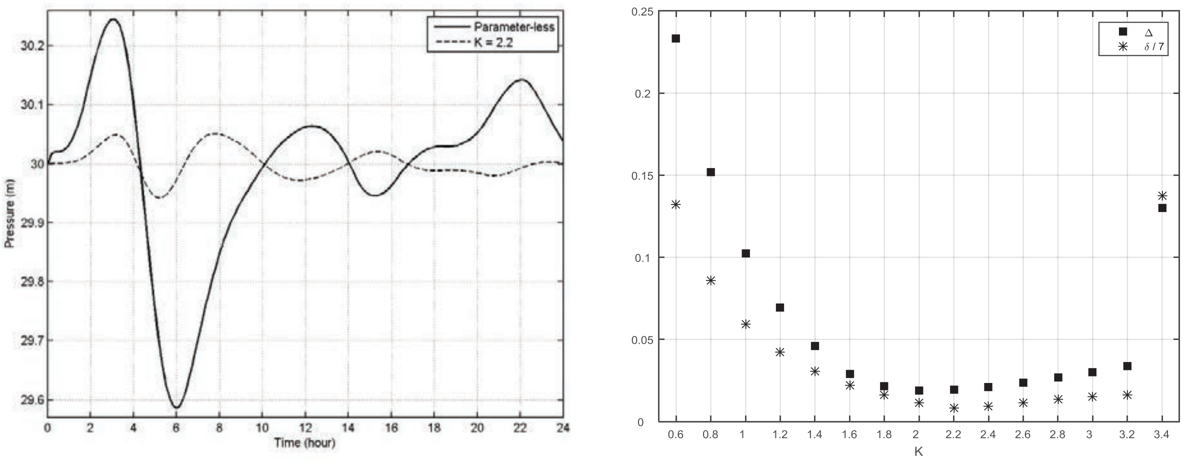

Figure 3: (a) Time-dependent pressure at the control node for parameter-less and $K = 2.2$ P-controllers. (b) Dependence of Δ and δ (in m) on selected K, where δ has been rescaled by 7.

If acceptable performance of a controller is for example defined as the control node having $\delta/p_{sp} \leq 5\%$ (often accompanied by acceptable stability of pressures *throughout* the WDS [8]), the parameter-less controller clearly performs well. However, under various conditions the value of δ is expected to increase (due to the variation in Q from iteration to iteration being larger) to the point where the controller's performance is no longer acceptable. These conditions are: the demand factor or the reservoir levels changing by larger amounts or on a faster time-scale (real time); or T_c increasing (evidence for this comes from the T_c variation study in [6]). It is hence preferable to operate the controller in the effective range of K where Δ is small. In contrast, it was found that the leakage reduction from the case with no control, obtained by controllers with Δ's differing by up to a factor of three, is very similar [5]. Hence leakage reduction is not expected to require the controller to operate in the effective range.

To improve the performance of the parameter-less controller for given demand and reservoir level change conditions, variation of Q can be reduced by installing the PRV at a location where the variation is lower [5], or by reducing T_c.

The time-dependence of the shutter opening for $K = 2.2$ is almost identical to that of the parameter-less controller shown in Figure 2(b). The temporal average of the absolute value of the difference between the shutter openings α for the two cases, a measure of the mean deviation, is only 0.0060. The time-dependence of the shutter opening for K in the range 0.6 to 3.2 is similar to that for the optimal case $K = 2.2$. However, $K = 3.4$ shows oscillatory behaviour, signalling the onset of convergence problems.

5. Conclusion

The two previous studies on a P-controller where the PCV flow is known [3, 5] are supplemented by testing the controller on a WDS not used in these studies. The following results are novel, to the best of our knowledge. The preference for a parameter-less controller is argued for. The quantities that need to be known precisely are pointed out. The conditions under which the controller performs less well are clearly stated and investigated. The attractiveness of using a constant flow in the controller is argued for, but is found not to improve performance. The time-dependence of the shutter opening is similar for all proportional constants K (except in the region characterised by convergence problems). A hypothesis is formulated that there is a small range of optimal K for different WDSs. It is suggested that the parameter-less controller be implemented for a WDS, but that in time the controller be gradually adjusted via parameter-dependent control to larger K (1.6 for the WDS studied) if improved convergence is desired.

In this work the preference and efficacy of parameter-less control is pointed out. Considering the prospect of not having to tune any parameter, the controller becomes particularly easy to use. The parameter-less controller is the only such controller known that ultimately relies on setting the shutter opening, which is the common and practical PCV property to set. In contrast to most controllers, the controller has the ability to respond to changing WDS conditions, through its dependence on the PCV flow which is required to be known. Ongoing research should be conducted in this area with concomitant adoption in commercial and experimental environments [9, 21].

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