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Hydraulic modelling for pressure reducing valve controller design addressing disturbance rejection and stability properties

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Abstract

Pressure reducing valves (PRVs) are widely used in water distribution systems to reduce excess pressure caused by variations in terrain elevation or by excessive pumping. The fundamental role of a PRV is to maintain a desired outlet pressure irrespectively of hydraulic conditions in the water distribution network (WDN). Unfortunately, even a stable PRV can exhibit poor disturbance rejection resulting in variations of outlet pressure around the setpoint due to randomly varying demands. The aim of this paper is to better understand this phenomenon and to develop models which would facilitate designing effective controllers considering the stability and disturbance rejection issues.

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Keywords: pressure reducing valve (PRV), stability, disturbance rejection, controller design

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1. Introduction

After a number conversations with practitioners and researchers working on pressure management in water distribution networks (WDNs) we have noticed that there seems to be a misconception regarding the cause of occasional oscillations observed in pressure reducing valves (PRVs). This so-called ‘hunting’ is often attributed to the occurrence of pressure waves which affect pressure readings (in case of electronically controlled valves) causing large temporal variations in controller error and thus, control action. Although such behaviour can in principle be reduced, if not eliminated, by e.g. window averaging of PRV outlet pressure readings and by specifying lower and upper bounds on the control signal, we have found that the main cause of valve instability lies in the intrinsic property of the valve rather than in the hydraulic conditions inside the network. As described in Ulanicki and Skworcow[1] PRVs tend to oscillate under low flow conditions because their dynamic gain decreases nonlinearly with opening. Hence, PRVs have higher gain for lower valve openings than higher ones. Oscillations in valve position can cause significant transients if the opening and closing rate of the control element is sufficiently large. Transients thus seem to be more of a result of PRV instability rather than the cause of it.

Even with the stability issue properly addressed, PRV outlet pressure can still vary around the set-point during normal operation. This variability in the outlet pressure of typically ±(2-3) m H_2O is mainly due to random changes

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in water demand across the network, which from the point of view of the controller, is considered a disturbance. Since demand patterns, similarly to instability, also have a periodic character, usually on more than one time scale, it is often difficult to an untrained eye, looking at just pressure measurements, to classify the cause of pressure oscillations as either a PRV instability problem or a lack of disturbance rejection problem. Although the dynamics of PRVs [2] and PRV control systems [3] are now better understood, we are still faced with a number of unanswered questions which need to be addressed in order to improve the robustness, stability, and disturbance rejection within PRVs.

Firstly, we would like to find out whether under normal operating conditions water compressibility and pipe elasticity play any noticeable role in the dynamics of the PRV-WDN system or whether the above effects can be omitted in the model without any significant impairment of accuracy. If the latter is true, the hydraulic equations can be reduced to an incompressible flow problem also known as rigid column. Thus, distributed partial differential network equations are simplified into a lumped ordinary differential equation (ODE) model which allows us to carry out a formal analysis using system and control theory, to ultimately gain a deeper understanding of the performance and the stability of the closed-loop PRV-WDN system. If it turns out that the rigid column model is sufficiently accurate for some operating conditions, we need to determine whether this statement is also true for other operating conditions and draw bounds within which such an assumption is valid. For example, it is very likely that in most industrial applications where actuators are designed such that the rate of valve opening and closure is limited in order to reduce the risk of transients, rigid column approach will yield satisfactorily accurate results whilst in case where the valve is designed to change the control element faster than the travel time of the pressure wave along the pipeline, pressure transients may need to be included in the model.

Second, it is important to understand the interactions between the PRV and other components of a WDN. Specifically, we are interested in understanding how network size and topology affect the stability of the closed-loop PRV-WDN system and how changes in water demands affect the PRV outlet pressure. Whilst the first problem is concerned with system stability the second one addresses the problem of disturbance rejection.

Finally, mathematical analysis of a closed-loop PRV-WDN system prompted a re-examination of the concept of demand-driven WDN simulation from the PRV control perspective. Numerous publications, i.e. Jung et al.[4] already questioned the correctness of a demand-driven approach by providing the evidence that demand-driven simulations in which the flow in the network nodes is forced and thus, is independent from the nodal pressures, overestimates the magnitude and the duration of pressure waves. On the contrary, head-driven simulations in which water demand is pressure-dependent and hence a result of nodal pressures, tend to give more accurate predictions. There are additional implications of fixing demands independently of pressure which shall be discussed, from the control point of view, in Section 4.

2. Model structure

Since the main purpose of this paper is to gain a deeper understanding of the operation of PRVs, not WDNs in general, the network model has been reduced to the upstream and downstream feed pipe only. The rest of the network, shown in dotted lines in Fig. 1, was not modelled. Instead, demands in all major nodes were summed up and total demand was ‘simulated’ at the end of the downstream pipe at node 4 (see Fig. 1). As our hydraulic model is pressure-driven not demand-driven, for the reasons mentioned in Section 1 and later explained in Section 4, demand flow Q is a function of pressure head at node 4 (H_4) and modelled with Toricelli’s orifice equation: $Q(t) = A_{orifice}(t)\ \sqrt{2\,g\ (H_4(t) - z_4)}$ in which z_4 denotes the elevation of node 4 and g is the gravitational constant. The true demand flow pattern is thus approximated with time-dependent total orifice surface area $A_{orifice}(t)$.

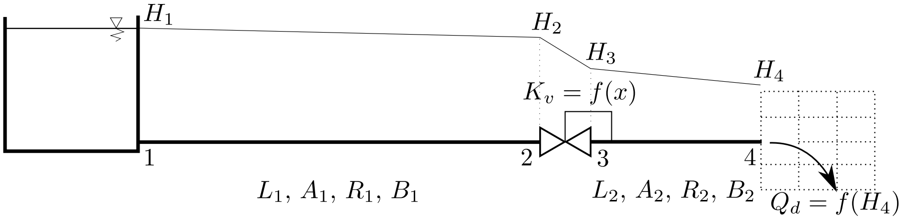

Fig. 1: Schematic of the hydraulic model used for the simulations of the PRV under different operating conditions and network properties.