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FLOW OSCILLATIONS IN A STEEP WATER MAIN

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KEY POINTS

- *We consider a steep water main whose flow rate is regulated by a needle-valve located at its downstream end*
- *The opening of the valve is continuously and automatically adjusted to keep the level of the upstream tank constant*
- *Resonance between surge waves generated by the adjustments of the valve opening cause flow oscillations*

1. PROBLEM STATEMENT

Over the last decades, the exploitation of water sources located at high elevation in mountain regions has become a popular practice (*Fellini et al.,* 2018). Such sources are often fed by glaciers, snowfields, or large aquifers; and are thus little affected by droughts or quality issues.

A typical setup intended to convey downstream the water collected from a high-altitude spring is reported in Fig. 1. The upstream (US) tank collects the water from the source. The downstream (DS) tank is connected to the water distribution network. The storage capacity of the DS tank equalizes the daily water demand fluctuations. The US tank is only intended to collect water from the high-elevation sources, and to convey this water to the DS tank.

Due to the high elevation of the sources, hydropower production is often integrated in these systems. To this aim, a Pelton turbine is installed at the end section of the water main (*Sitzenfrei et al.* 2015). The turbine is not intended solely for energy production, but it can also be used to regulate the flow rate conveyed by the water main. This last task is performed by adjusting the opening of its needle-valve (Fig. 1). Nowadays, needle-valves in Pelton turbines are fully automated, and the valve opening can be controlled by the SCADA of the water distribution system.

In order to regulate the flow rate discharged by the turbine in simple systems like those of Fig. 1, it is a common practice to follow a tank-level-based approach. With this approach, the opening of the turbine needle-valve is continuously adjusted to keep the level in the US tank at a constant level. In this way, tank emptying and water overflows are avoided, and the turbine works with the highest head.

The aim of this work is to analyse the interactions between the pressure surges generated by the continuous adjustment of the turbine valve opening. It is shown that, under some operative conditions, resonance between successive pressure waves occurs. These resonance waves interact with the algorithm devoted to regulate the valve opening, and induce oscillations of the flow rate, a sequence of opening/closing events of the valve, and strong and frequent oscillations of the upstream tank level.

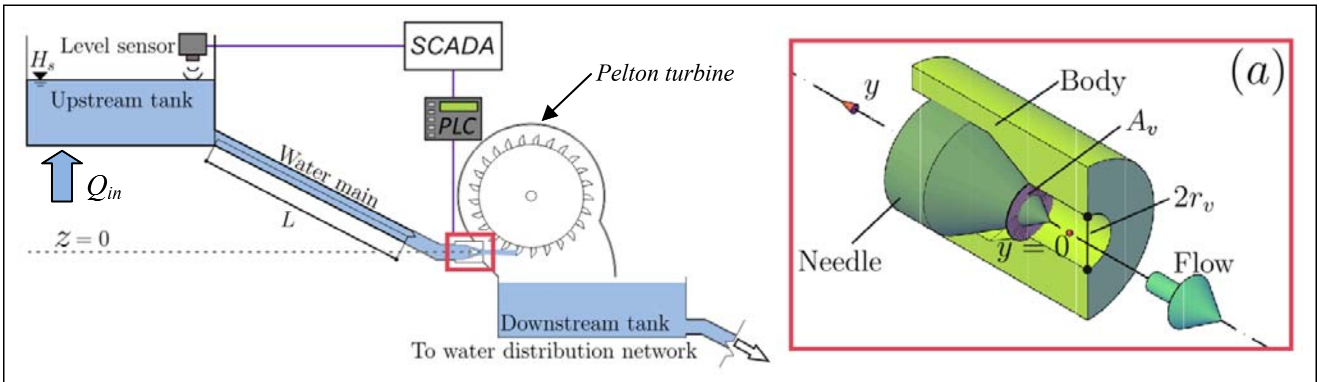

Figure 1. Scheme of a water distribution system with a steep water main and a Pelton turbine used to regulate the flow rate.

2. REGULATION SYSTEM

In order to regulate the flow rate discharged by the water main, the SCADA monitors the level of the US tank. Then, a regulation algorithm analyses the dynamics of this level, and prescribes adjustments of the opening of the turbine needle-valve.

2.1 Instrumentation for level measurement and flow regulation

A level sensor connected with the SCADA is installed in the US tank, and measures the water level, H_s. In the final section of the water main, the needle-valve of a Pelton turbine regulates the flow rate. The flow rate through the valve, Q_v, depends on the valve opening area, A_v, through the relation

$$Q_v = A_v\, c_v\, \sqrt{2\mathrm{g}\, H_v}\ , \tag{1}$$

where c_v=0.6 is the coefficient of discharge, and H_v is the net-head upstream the valve. Hence, the opening of the valve, A_v, has to be set to regulate the discharged flow, Q_v. To do this, an hydraulic actuator adjusts the position of the needle-shaped plunger (see inset *a* in Fig. 1). The needle is raised or lowered along the longitudinal y axis of the valve seat. For $y=0$, the plunger exactly fits the seat and the nozzle opening area, A_v, is 0 . When the plunger is completely retracted, $y=y_{\max}$, the valve is fully open, and $A_v= A_{v,\max}$. Finally, the plunger moves with the velocity v_c. The needle actuator is connected through a PLC with the SCADA that sets the position of the valve plunger, y, and thus the flow to be discharged, Q_v.

2.2 Algorithm for the flow regulation

The task of the flow control system is to keep the water level of the US tank at the constant target value H_{trg} by adjusting the position of the valve plunger, y, and thus the discharged flow, Q_v. In the tank-level-based regulation scheme usually adopted in systems like those of Fig.1, the current tank level, H_s, given by the level sensor is compared to the target value, H_{trg}. Regulation has to be performed if the difference between H_s and H_{trg} exceeds a tolerance δ. The regulation rationale is as follows: as the level rises, the valve opening is increased. Conversely, as the level in the tank decreases, the valve partially closes. In order to reduce flow and level oscillations, the magnitude of the regulation (i.e., the change of the valve opening) is based on the rate of level changes. Finally, a waiting time is set between consecutive operations, in order to give time the system to respond to the regulation. This waiting-time is defined as the α-th multiple of the travel time of the pressure surge in the water main. For the sake of space, the detailed description of the analysed algorithm is not reported, but can be made available by the corresponding author upon request.

3. RESPONSE OF THE REGULATION SYSTEM TO PERTURBATIONS

The US tank receives the flow rate Q_{in} from the water sources (Fig. 1). If Q_{in} is constant, and the valve opening, $A_{v,eq}$, is such that $Q_v(A_{v,eq}) = Q_{in}$, then the system is in steady conditions. It follows that the level of the US tank keeps constant, the water distribution system is in equilibrium, and no valve adjustment is required.

This configuration of equilibrium is uncommon in real systems. Variations in the incoming flow rate, instrumental errors, leakages or water uptakes between the US and the DS tank, and transient flow events occur. The result of all these disturbances is that the flow discharged by the DS valve is different from the flow entering the US tank. Since $Q_v \neq Q_{in}$, the level of the US tank deviates from its target value H_{trg}, and adjustments of the valve opening have to be performed. The deviation of the tank level from its target value, and the deviation of the valve opening from its equilibrium configuration are called *disturbances*. It is a key point to assess the fate of the disturbances induced by external forcing. In particular, two different scenarios are possible. In the first scenario, the characteristics of the water distribution system and of the regulation algorithm are such that the disturbances are damped, and the equilibrium configuration is restored. In the second scenario, the disturbances amplify, and flow, level, and pressure oscillations arise.

In order to study the response of the water distribution system and of its regulation system to disturbances, numerical simulations are performed. In order to consider the non-linear interactions among surge waves, the methods of characteristics was adopted to tackle this problem (*Chaudhry*, 1987). The simulations were run as follows. First, the initial conditions adopted in the simulations are those of equilibrium: in any reach of the water main the flow rate is Q_{in}, while the head at the US tank is the target level H_{trg}. Second, the system in equilibrium conditions is simulated for a few hundred seconds, in order to check the absence of pressure surges in the pipeline and that the level of the US tank keeps constant. Third, the system is perturbed by an alteration of the valve opening. In particular, the valve opening is increased by 5%, with respect to $A_{v,eq}$. This is done to take into account –in a simple but comprehensive way– the effect of all the external forcing that may affect the system. Fourth, the response of the system to this perturbation is simulated. The water level at the US tank is changed at any time step of the simulation according to the mass balance equation at the tank. Moreover, the valve opening area, A_v, may change between two consecutive time steps according to the operations prescribed by the flow regulation algorithm.

4. RESULTS

4.1 Case study

In order to show the possible response to perturbations of a system like that reported in Fig. 1, we focus on a specific case study. The described case study is a simplified version of a real water distribution system. The US tank has a head H_s=200 m above the reference z=0, and the flow rate Q_{in} from a potabilization plant is in the range [0.1, 1] m^3/s. The water main is characterized by a length L=20 km. The maximum flow rate that can be conveyed by the water main is $Q_{\max}$=1 m^3/s and the diameter is D=0.8 m. This large diameter was chosen to reduce the friction losses and thus to improve the hydropower production. A key characteristic of this system is that the valley's topography severely constrained the size of the US tank. Thus, the area of the US tank is A_s=35 m^2.

In the tank-level-based regulation scheme adopted, the target value of the US tank is H_{trg}=200 m, while the tolerance is δ=1 cm. In the analysed case, the waiting-time parameter is α=5. When the needle-valve of the Pelton turbine that regulates the flow rate is fully open, A_v= $A_{v,\max}$=384 cm^2 and y=$y_{\max}$= 33 cm. Finally, the plunger moves axially with the velocity v_c=1.1 mm/s.

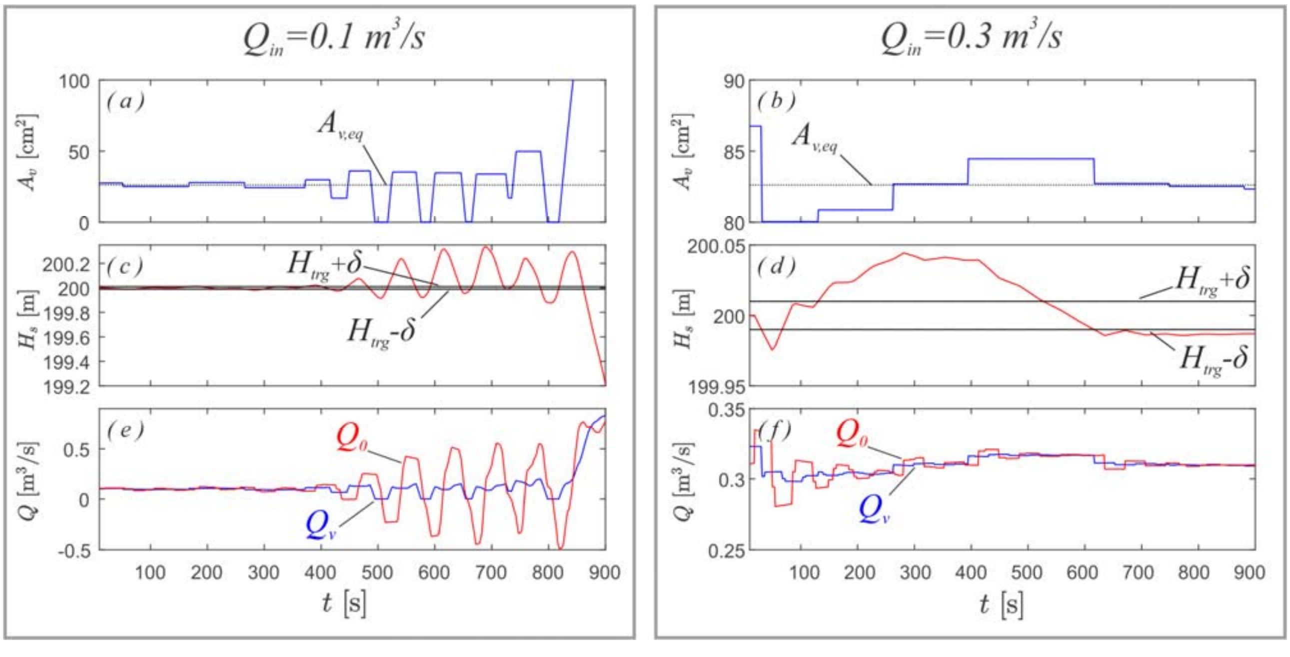

Figure 2. First row: valve opening area A_v (blue) and equilibrium opening area $A_{v,eq}$ (black dotted). Second row: US tank level H_s (red) and $H_{trg} \pm \delta$ (black). Third row: flow rate discharged by the DS valve Q_v (blue line) and flow rate leaving the US tank Q_0 (red line). Panels in the left column refer to Q_{in} =0.1 m^3/s. Panels in the right column refer to Q_{in} =0.3 m^3/s.

4.2 Generation of flow oscillations in the water main

The response to external perturbations was studied through the analysis of the time series of: (i) the valve opening area A_v; (ii) the US tank level H_s; (iii) the flow rate leaving the US tank Q_0. Fig. 2 reports the time series for the cases Q_{in} =0.1 m^3/s (left column) and Q_{in} =0.3 m^3/s (right column). When Q_{in}=0.1 m^3/s (panels *a, c, e*) the external perturbations amplify over time. At t=0 the equilibrium opening area is altered of ~1.3

cm^2, with respect to the value $A_{v,eq}$=26 cm^2. While the system evolves, the opening of the valve oscillates around $A_{v,eq}$ with a period of about 2 minutes (panel *a*), but the equilibrium opening area is not reached. More in details, the absolute value of the valve opening perturbation grows while time passes, and at t=500 s this deviation is ~50 cm^2. As a result of these oscillations in the valve opening, the flow leaving the US tank (red line in panel *e*) is not constant (the flow rate varies in the range [-0.4, 0.8] m^3/s). In turn, the level of the US tank oscillates between -0.8 m and +0.3 m around the target level H_{trg}=200 m (panel *e*). It was found that flow and tank-level oscillations are triggered by a resonance between the surge waves generated by multiple regulation operations.

In contrast, the external perturbations damp when Q_{in}=0.3 m^3/s. At t=0 the equilibrium opening area is altered of ~4 cm^2, with respect to the equilibrium value $A_{v,eq}$=80 cm^2. While the system evolves, the opening of the valve returns to the equilibrium value $A_{v,eq}$ with very mild oscillations, and the equilibrium opening area is reached at t=500 s. The absolute value of the valve opening perturbation monotonically decays over time, and never exceeds the initial perturbation of 4 cm^2. The flow leaving the US tank (red line in panel *f*) varies in the very narrow range [0.28, 0.32] m^3/s. In turn, the level of the US tank oscillates just between -3 cm and +2 cm around the target level H_{trg}=200 m.

5. CONCLUSIONS

The flow rate in steep water mains that connect two tanks is regulated by a downstream needle-valve. The opening of the valve (needle position) is set by a regulation algorithm aimed at keeping the level of the upstream tank at a constant value. In the specific case study considered, it was found that under some operative conditions (low flow rate, with respect to the maximum capacity of the system) the amplification of external disturbances takes place. This leads to the oscillation of the flow rate conveyed in the water main, to a sequence of opening/closing events of the valve, and to strong and frequent oscillations of the US tank level. Previous studies (e.g., *Ulanicki et al.,* 2014) already highlighted that pressure reducing valve aimed at dissipating energy, regulating pressure, and at controlling the flow rate in water networks may lead to strong flow and pressure oscillations. This study increases the current knowledge on this topic with the analysis of a water main regulated by a needle-valve. This study represent also an advance with respect to the current theory of run-of-river hydropower plant stability (e.g., *Jiménez*, 1992). In fact, the transient flows occurring in the penstock are accounted for.

This analysis has a critical importance for the realization and management of water systems. The design of water distribution networks and/or regulation algorithms should in fact consider the response of the system to external perturbation. As the amplification of disturbances is induced –at least in some cases− by the non-linear interactions of surge waves, a suitable numerical method capable to describe transient flow conditions (e.g., the methods of characteristics) should be adopted. Future analyses should also determine for which range of design parameters (e.g., upstream tank area, length of conduit, etc.) the amplification of external perturbation is more prone to develop.

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