Predictive PI strategy for hydrographs control in a experimental microscale flume

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Abstract: Hydraulics, specifically the engineering related to river infrastructure, has had always to deal with issues as floods, erosion debilitating important civil infrastructure (bridges, etc.). In recent years it has been shown that there is predictive value for hydraulics in studying and analyzing these phenomena at a reduced scale. For this reason the microscale experimental canal was build at the Hydraulics Laboratory at the Universidad of Concepción, with a second copy for control purposes at the Control Systems Laboratory (LCS). The partial differential equations that govern the process are unnecessarily complex for control purposes. Known literature offers the alternative of a third order linear system, capturing the canal standing wave with a second order system together with an integrator to account for the mass accumulation. However, such a proposal, even when slowing the control to discard the standing wave dynamics is only valid for long canals. The microscale experimental canal does not satisfies that assumption, therefore we propose and adjust a first order structure to the process, which proves adequate for any given operating point selection. Nevertheless, the main three parameters of the plant model (gain, time constant and time delay) vary with the operating point. As a preliminary control approach we consider a plant model selection for a specific operating point as the nominal plant and adjust a PI control using the reaction curve method of Ziegler-Nichols. We compare the previous PI tuning with a predictive PI λ tuning to achieve robustness, and thus better deal (in this preliminary control approach) with the inherent variability of the plant model parameters.

Keywords: PID controller,PPI ,discrete system, time delay, hydrographs, open channel, PLC.

1. INTRODUCTION

It is a central objective of Rivers Engineering the optimal design of fluvial works, such as channeling, river defenses, bridges, potable water and irrigation catchments, hydroelectric power stations and irrigation dams, among others; thus maximizing its safety against floods and preserving the ecological functionality of the river where they are located. Since its inception, Rivers Engineering has studied the movement of water, that is, hydraulics, imposing conditions with a constant flow, although in reality the conditions imposed by the variable flow during floods control most of the problems associated with the design of river works. Among them are the overflowing of rivers and floods, alluviums, or the undermining of bridges and other structures. This needs to be improved urgently, since, in the context of natural disasters, fluvial floods represent a threat of central importance for people and, on the other hand, scour is the most recurrent cause of bridges failure throughout the world. Lamentable examples of this are the floods suffered in the Biobío Region during 2006, the alluvions that occurred in the northern zone of Chile in 2015 and 2017, as well as the collapses of the Tadcaster bridge, UK, in December 2015, and the Pitrufquén bridge railway on the Toltén river, in 2016. Moreover, the expected scenarios of climate change indicate that these extreme events will increase their intensity (Pachauri and Meyer, 2014).

It is a fact that when the velocity of the water on the bed exceeds a threshold velocity, it occurs movement of the sediment particles. Specifically, the particles around the pillars of a bridge move quickly, because the water flow accelerates in the vicinity of the obstacle, causing local undermining. Studies of undermining have been done in the past, imposing a constant flow (Link et al., 2017; Pizarro et al., 2017).

In open channel flows, the dynamics is usually represented mathematically by the Saint-Venant equations. This is a system of two partial derivative equations that derive from the physical laws of conservation of mass and momentum, which describe the process of one-dimensional flow in free surface (Litrico and Fromion, 2009). These equations in their non-conservative formula are nonlinear equations in partial derivatives, so they usually have no analytical solution. Because of the complexity of modeling using the Saint-Venant equations, in addition to the enormous computational cost involved, numerical methods should usually be used for their resolution. Other efforts to identify open channel flows and indeed complete river systems can be found for example in (Li et al., 2005; Nasir and Weyer, 2016).

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Fig. 1. Experimental setup at the LCS.

This work presents a data acquisition (SCADA), identification and control solution for the experimental microscale canal that will allow the generation of controlled growing waves, the measurement of scour around bridge pile models and hysteresis measurement (that is, of the lag between the waves of speed and depth) in a laboratory setup. We propose in this study the use of a Proportional Integral (PI) control strategy and compare it to a Predictive Proportional Integral (PPI) control strategy, Shinskey (2001); Ren et al. (2003); Hassan et al. (2017), to initially manipulate the level reliably and in a repeatable manner.

The main contribution of the present work is a model identification exercise for control purposes of the experimental microscale canal which results in a first order with time delay structure with plant parameters dependent on the operation point. The aforementioned contribution has a high impact in various areas related to River Engineering, since it allows to initiate the experimental study of fluvial processes under more realistic conditions, such as tracking of hydrographs from real scaled data.

The second contribution is a preliminary study on the plant requirements for PI tuning, comparing the use of a standard PI, tuned using the reaction curve method Goodwin et al. (2001), and the necessity of a robust PI design, for which we investigate the use λ tuning of a PPI controller (Åström and T.Hägglund, 1995).

This paper is organized as follows: Section 2 introduces the main assumptions and preliminary information on the models available for water canals. Section 3, based on real data from the experimental microscale canal available at the "*Laboratorio de Control de Sistemas*", propose a model structure and identifies the plant model for a range of operating points. Section 4 compares the standard PI control tuning with a PPI control tuning in light of the robustness necessity that arise from the model. Section 5 concludes the present work with final remark and future directions of inquires.

2. PRELIMINARIES

2.1 Assumptions

In this work we consider,

- There are no leaks in the experimental setup.
- Variable flow.
- Constant sluice gate opening.

2.2 Experimental setup

The microscale canal of 6.38 m long and 14.6 cm wide (see Figure 1) was studied for this work. The channel has several actuators and sensors, of which we use a centrifugal pump that handles the flow manipulation by means of a VFD and also we have a stepper motor at our disposal to adjust the opening of the sluice gate. The sensors used will be an electromagnetic flow meter and an ultrasonic level sensor, the latter being the best for the identification of parameters due to their non-contact characteristics. A Piping & Instrumentation Diagram (P&ID) is provided in Figure 2.

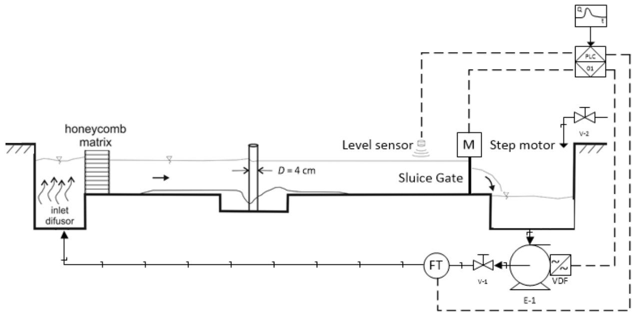

Fig. 2. Model P&ID.

2.3 Control and data acquisition

For the manipulation of the actuator signals and sensing, a graphical interface was developed through the GUI, see Figure 3, where,

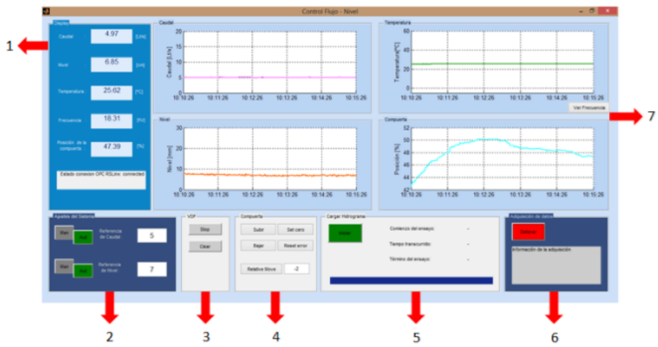

Fig. 3. Graphic interface implementation.

(1) Display: visualization of flow, level, frequency and position of the gate.
(2) System settings: manual / automatic control for flow and level with their respective set point of independent flow and level.
(3) Variable-frequency drive (VFD): Start / Stop of the VFD and performs fault elimination.
(4) Sluice Gate: status of the sluice gate, raise, lower, set to zero and relative movement.
(5) Hydrogram load: start of the test, elapsed time and end of the test.
(6) Acquisition of data: acquisition information and emergency stop.
(7) Signal Plots: plot of flow, level, temperature, frequency and gate.

3. MODEL IDENTIFICATION

In this section we obtain a mathematical model of the experimental microscale canal that will then allow for the simulation of the process and the following up controller tuning.

3.1 Model structure selection

We define the following variables of interest:

- d: is the height for the sluice gate, measured from the bottom of the microscale canal.
- u: the flow of water from the water pump.
- θ: the transport delay associated with the water traveling the length of the microscale canal.
- y: the water level inside the microscale canal.

See Figure 2 for the relative location of d, u and y inside the microscale canal. From (Litrico and Fromion, 2009) the most detailed structure for the physical process at end should be the Saint-Venant structure given by

$$\frac{\partial A(x,t)}{\partial t} + \frac{\partial Q(x,t)}{\partial x} = 0$$

$$\frac{\partial Q(x,t)}{\partial t} + \frac{\partial}{\partial x}\left[\frac{Q^2(x,t)}{A(x,t)}\right]$$

$$+gA(x,t)\left(\frac{Y(x,t)}{\partial x} + S_f(x,t) - S_b(x)\right) = 0 \qquad (1)$$

where $Q(x,t)$ is the discharge, $A(x,t)$ is the wet area, g the gravitational acceleration, $S_b(x)$ is the bed slope, $S_f(x,t)$ is the friction slope and $Y(x,t)$ is the water level. A nonlinear model also based on the conservation of mass principle, taken from (Li et al., 2005), results in (relatively speaking) simplified candidate structure for the plant model

$$\pi\left(\frac{d}{dt}\right)y(t) = u(t-\theta) - d^{3/2}(t), \qquad (2)$$

where $\pi(\cdot)$ is a polynomial on the derivatives of y and represents the pool dynamics. It is well known that for short pools the polynomial is known to be of order three, the integrator resulting from the mass balance and a second order lightly damped oscillatory mode due to the standing traveling wave that take place inside the pool. Under the consideration of a control solution working below the frequency of the pool's traveling wave we can replace simplify the model to

$$a\frac{d}{dt}y(t) = u(t-\theta) - d^{3/2}(t), \qquad (3)$$

where a represents the surface area of pool-i. As stated in Li et al. (2005), a linearization through the change of variable $\tilde{d} = d^{3/2}$ converts the model in (3) into

$$Y(s) = \frac{1}{sa}\left(e^{-s\theta}U(s) - \tilde{D}(s)\right), \qquad (4)$$

where in (4) we have moved into the Laplace domain. The problem with the above structure is that the microscale canal does not satisfies the assumption of a long pool and thus, even below the frequency of the pool's traveling wave, the observed behavior does not fit an integrator response. Indeed the best structure for such a reduced scale process is a structure defined by

$$Y(s) = \frac{K_p}{\tau s + 1}\left(e^{-s\theta}U(s) - \tilde{D}(s)\right), \qquad (5)$$

Also, if the gate remains constant, then we can assume $\tilde{D}(s)$ as a constant $\tilde{D}_p$, and ignore the terms associated to dynamic, so that equation (5) would look like,

$$Y(s) = \frac{K_p}{\tau s + 1}e^{-s\theta}U(s) - K_p\tilde{D}_p, \qquad (6)$$

and then $K_p\tilde{D}_p$ we consider it as a level offset and that we assume it as part of the level, giving as final result a first order model with delay, like the equation in (7), and whose parameters can be estimated with the minimum squares method with data obtained experimentally.

$$Y(s) = \frac{K_p}{\tau s + 1}e^{-s\theta}U(s), \qquad (7)$$

In this way, we can say that a first-order model is sufficient to capture the most significant information from an experimental canal and then apply a control strategy, which is confirmed by (Weyer, 2000)

The logic behind the proposed model structure in (7) lies in the fact that the output mass (and volume) flow is proportional to the square root of the difference of water levels before and after the sluice gate (Litrico and Fromion, 2009, 6.2). If there is a sudden increase in the input flow, the water level before the sluice gate will increase after τ seconds, and therefore the output flow will also start to increase after τ seconds. As result the water level inside the microscale canal will start increasing from the previous level up to a a new greater level, when the output flow will again be equal to the increased input flow. The described behavior is ideally captured by a first order model with delay structure as proposed, and as validated in the following identification exercise.

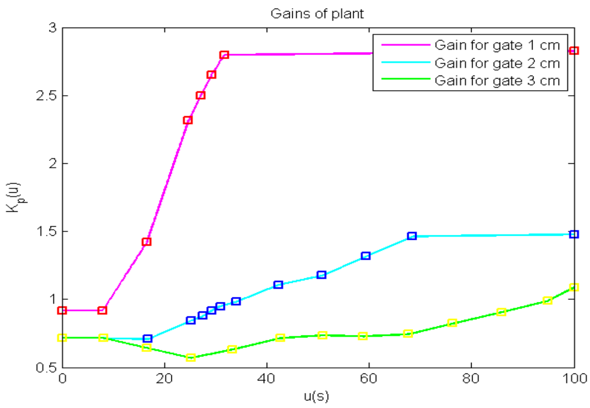

Fig. 4. Gains of plant (K_p)

We proceed to adjust the structure for different operating points. For this we realized, 3 experimental tests, maintaining a fixed gate opening at 1, 2 and 3 cm respectively and applying steps of rise and fall in between 0% and 100% with amplitude of 10% in each step. In this way, we obtain the values of K_p depicted in Figure 4, τ values in Figure 5 and θ values as reported in Figure 6.

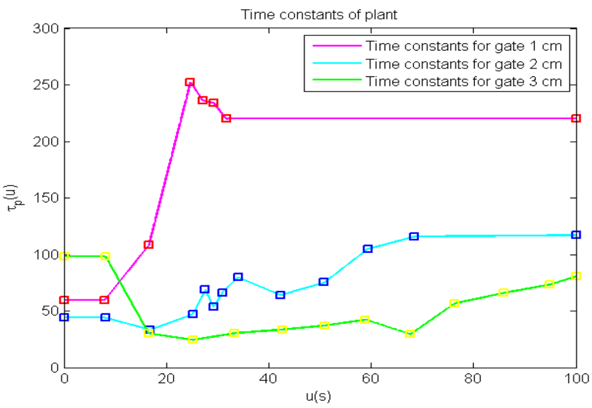

Fig. 5. Plant time constant (τ)

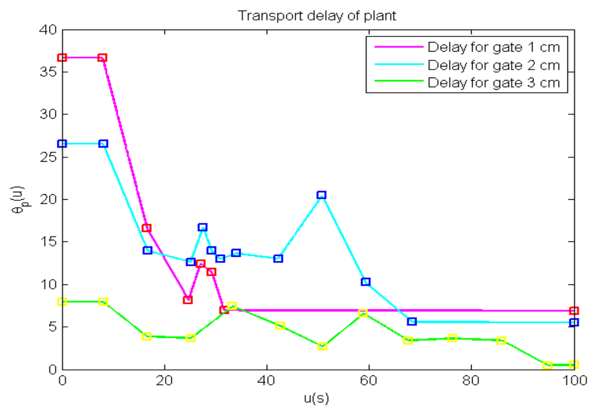

Fig. 6. Transport delay of plant (θ)

Observe that the values for each parameter are variable functions of the operating point, in this case represented by the percentage of water pump flow (the operation point is really defined by a triplet of values given by the input flow, sluice gate height and water level height, but to better report the obtained results we only use the percentage of input flow and three different sluice gate heights).

Table 1. Variables

Variable	max. value
Flow	5 [lt/s]
Level	25 [cm]
Frequency	50 [Hz]
Sluice Gate	25 [cm]

As a reference, in Table 1 we show the physical quantities that represent the maximum value of the variables used in the international system that represent 100% in engineering variables, considering that these are valid for Setup.

Finally, the following block diagram represents the proposed closed loop system:

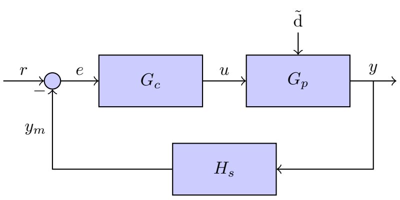

Fig. 7. Closed loop block diagram.

Where:

- G_c: controller transfer function . See (8) and (11).
- G_p: plant transfer function .
- H_s: sensor transfer function .

Consider that:

- G_p: is represented by equation (5) if the sluice gate position is variable, otherwise, if the gate is at a fixed height, it is better represented by equation (7).
- H_s: the sensor block, as the VFD, is characterized together with the process in the structure proposed in (7). That is we assumed $H_s = 1$, Goodwin et al. (2001).

In this section we have proposed and identified the block G_p standing for the real process. In the next section we proceed to discuss the tuning of block G_c as a PI structure.

4. CONTROLLER DESIGN

Given the non-linearity of the process, we consider the design of the controllers for an operating point defined by $U(s)$ at 50 % with a sluice gate opening of 2 cm (or 8 %) . With this choice, the plant parameters are $Kp = 1.244$, $\tau = 89.69$ y $\theta = 15.44$.

4.1 PI Control

The PI controller is determined using the Ziegler-Nichols reaction curve method (Goodwin et al., 2001) where

$$U(s) = K_c \left(1 + \frac{1}{T_r s}\right) E(s), \qquad (8)$$

and K_c is the controller gain and T_r is the integral time. Both can be estimated as $K_c = \frac{0.9\tau}{K_p \theta}$ and $T_r = 3\theta$. The tuned PI controller transfer function for the selected operating point is then (9)

$$U(s) = 4.2026 \left(1 + \frac{1}{46.32s}\right) E(s), \qquad (9)$$

4.2 PPI Control

The PPI control is a PI controller with a predictive control action component suited for process with long times delay, (Shinskey, 2001). A design method for the PPI controller is known as λ-tuning (Åström and T.Hägglund, 1995). This tuning method assume that the desired closed-loop transfer function between the output and setpoint signal is specified as,

$$\frac{Y(s)}{R(s)} = \frac{\mathrm{e}^{-s\theta}}{1 + s\lambda\tau}, \qquad (10)$$

where λ is a tuning parameter that allows to modify the time constant. The controller transfer function that satisfy (10) can then be obtained as

$$U(s) = \frac{1 + s\tau}{K_p\left(1 + s\lambda\tau - \mathrm{e}^{-s\theta}\right)} E(s). \qquad (11)$$

The choice of λ as suggested in Åström and T.Hägglund (1995) must be between 0.5 and 5. To stress the potential improvement of a PPI controller, over a standard PI controller, when closed-loop robust stability might be a necessity we provide in Figures 8 and 9 the gain margin and phase margin of the PPI controller for different values of lambda, blue line, compared to the standard PI, dashed red line. It is necessary to mention that both the gain margin and phase margin consider the approximations made later in section 4.3. We can notice that the PPI controller complies with better characteristics throughout the tested range. Therefore, according to the recommendation, we select a λ value of 0.5 , guaranteeing a response twice as fast than the open loop plant response, which achieves a gain margin of 6.305 and a phase margin of 77.32.

After the above analysis we have that the designed transfer function for the PPI controller is then

$$U(s) = \frac{1 + s89.69}{1.244\left(1 + s44.845 - \mathrm{e}^{-s15.44}\right)} E(s). \tag{12}$$

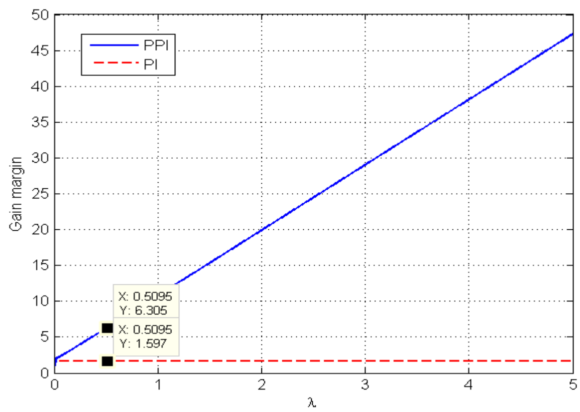

Fig. 8. Gains margin

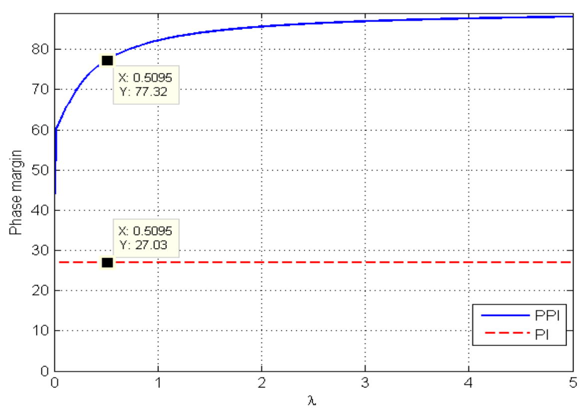

Fig. 9. Phase margin

4.3 Experimental Implementation

For the experimental implementation we make use of a programmable logic controller (PLC), which works in discrete time. Therefore we now have to find the discrete-time counterparts of both controllers from the previous two subsections. First, we have that the PI controller in the z-plane is given by

$$U(z) = K_c \frac{z - z_c}{z - 1} E(z), \tag{13}$$

v where K_c is the same of the continues controller $K_c = 4.2026$ and $z_c = 0.9611$ for a sampling time of 1.8 seconds. Then we rewrite it as

$$U(z) = U(z)z^{-1} + K_c\left(E(z) - z_c E(z) z^{-1}\right), \tag{14}$$

and return to the time domain representation in discrete

$$u(k) = u(k-1) + K_c e(k) - K_c z_c e(k-1), \tag{15}$$

to obtain the recursive equation that will be programmed in the PLC. The implementation of a PPI control with λ different of 1 is not so evident. We consider using the method as in (Åström and T.Hägglund, 1995), but approaching the plant time delay using a fourth order Pade function approximation. The transfer function for the PPI controller is then

$$G_c = \frac{1}{G_p} \frac{GT_o}{1 - T_o}, \tag{16}$$

were,

$$G_p = \frac{K_p}{1 + s\tau} L(s), \tag{17}$$

and for design condition

$$T_o = \frac{L(s)}{1 + s\lambda\tau}, \tag{18}$$

were the $L(s)$ is the fourth order Pade function for delay $\theta = 15.22$, then

$$\mathrm{e}^{-s\theta} \approx L(s) = \frac{s^4 - 1.295s^3 + 0.75s^2 - 0.228s + 0.0296}{s^4 + 1.295s^3 + 0.75s^2 + 0.228s + 0.0296}. \tag{19}$$

From this we have an approximate PPI controller in continuous time defined as

$$\frac{U(s)}{E(s)} = \frac{1.6s^5 + 2.1s^4 - 1.24s^3 + 0.4s^2 - 0.05s + 0.0005}{s^5 + 1.3s^4 + 0.8s^3 + 0.2s^2 + 0.039s} \tag{20}$$

and its z equivalent, for a sampling time of 1.8, considering the parameters of the plant at the operating point, defined as

$$\frac{U(z)}{E(z)} = \frac{1.6z^5 - 4.76z^4 + 5.69z^3 - 3.47z^2 + 1.06z - 0.12}{z^5 - 2.94z^4 + 3.49z^3 - 2.13z^2 + 0.67z - 0.09} \tag{21}$$

Finally the implemented controller follows the next recursive equation,

$$\begin{aligned} u(k) &= 2.94u(k-1) - 3.49u(k-2) + 2.13u(k-3) \\ &- 0.67u(k-4) + 0.09u(k-5) + 1.61e(k) - 4.76e(k-1) \\ &+ 5.69e(k-2) - 3.47e(k-3) + 1.06e(k-4) - 0.12e(k-5). \end{aligned} \tag{22}$$

4.4 Experimental Comparison

For the experimental comparison we perform a water height step change, from 60% to 80% as reported in Figure 10. Observe that at the start, a 60% water height coincides with an input flow of 50% (the state operating point). The requested change also results in an increase of the input flow to 60%, green line. Such as, this setpoint excursion reports from the cyan lines in Figures 4, 5 and 6 (recall that the chosen operating point considers a sluice gate opening of 2cm), changes in the plant model gain K_p

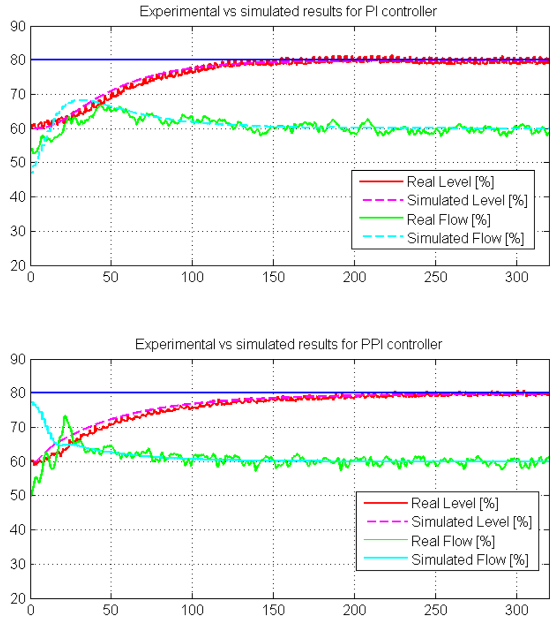

Fig. 10. Results of implementation

from (approximately) 1.2 to 1.3, time constant from 80 to 100 and time delay from 20 to 10. We clearly have that the above reported plant model parameters excursions, interpreted as modeling errors, were no match for the gain margin (1.6 for the PI and 6.3 for the PPI) and phase margin (27.03 for the PI and 77.3 for the PPI) as clearly the water height closed loop behavior of the PI and PPI controller solutions in Figure 10 are quite similar, red lines. Nevertheless, Figures 8 and 9 suggest that worse variations would result in a better behavior for the PPI controller over the PI controller. Finally, we also observe from Figure 10 the presence of the standing wave as a ripple in the measured real level signal. This motivates and confirms as a future research direction, the inclusion of this feature in the proposed plant model structure.

5. CONCLUSIONS

Motivated by the recently tested predictive value of microscale setups for Hydraulics, we have modeled and controlled the microscale experimental canal at the LCS. For control purposes a first order transfer function with time delay was successful in capturing the essentials of the plant dynamics. The drawback was that due to the reduced scale of the canal and the nonlinearities present in it, the three plant model parameters are not constant and vary as functions of the chosen operating point. In a preliminary control approach we compared a standard PI tuning, with a PPI λ tuning that offered a more robust solution, to better deal with the variable nature of the plant model parameters. Future research should aim to include the modeling of the standing wave, on the identification side of the problem, and the application of more advanced control algorithms to achieve either robust performance or directly treat the parameters variability (as in a gain scheduling approach, nonlinear control, etc.)

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