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Robust Fractional Order PI Controller for a Main Irrigation Canal Pool

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Abstract: A new method is proposed to design a class of robust fractional order *PI* controller (*FPI*) based on frequency specifications for water distribution in a main irrigation canal pool. The robustness features of the obtained *FPI* controller are compared with the ones of an equivalent standard *PI* controller with the same design frequency specifications. A justification of its enhanced properties it is also provided. The interest of such fractional order controllers is justified by the fact that dynamical parameters of main irrigation canal pools may change drastically in function of its operation regimes. The designed *FPI* controller was implemented in a PLC of the Siemens company (Simatic 300) and was installed in a real main irrigation canal pool. The real time experimental results carried out comparing both *FPI* and standard *PI* controllers for different discharge regimes showed the superiority of the obtained *FPI* controller over the standard *PI* controller in terms of time domain performance and robustness. These results proved that the proposed design method leads to an efficient realistic *FPI* controller for main irrigation canal pools.

Keywords: Robust fractional order *PI* controller design; Main irrigation canal control system design; Modeling and control of agriculture; Management of hydraulic resources

1. INTRODUCTION

Nowadays, a lot of water in irrigation canals is wasted because of the lack of an effective control. Automatic control may be considered as a powerful tool for improving efficiency of water distribution in irrigation systems. Then introduction of automatic control systems in main irrigation canals has been increasingly considered in recent years.

Designing a control strategy that leads to a practical controller is a difficult task, because irrigation canals are complex systems distributed over long distances, with significant time delays (between the water resources located upstream and the water users located downstream) and dynamics that change with the operating conditions (Malaterre, Rogers and Schuurmans, 1998).

Experiments developed by some authors confirm that main irrigation canals may exhibit large time variations in their parameters when the discharge regimes change in the operation range $(Q_{\min}, Q_{\max})$ and/or other hydraulic parameters change (Feliu Batlle, Rivas Perez and Sanchez Rodriguez, 2007; Litrico and Fromion, 2006). Then any controller to be designed for this class of main irrigation canals has to be robust to parameter variations (Deltour and Sanfilippo, 1998; Litrico, Fromion and Baume, 2006).

Different studies have shown that simple *PID* controllers do not perform well when the canals are characterized by a difficult dynamical behaviour: significant time delay, time varying parameters in large range, etc. (Rivas Perez, 1990; Clemmens and Schuurmans, 2004). Therefore, systematic methods to design effective and robust controllers for main irrigation canals are desirable (Wahlin and Clemmens, 2002). Development of such methods is a challenging and critical issue, in the aim to improve water management and distribution in main irrigation canals (Litrico and Fromion, 2006).

In the last years, due to the better understanding of fractional calculus, fractional operators have been applied with satisfactory results to model and control processes with complex dynamic behaviors, being most of them distributed parameters processes. Fractional calculus represents the field of mathematic that involves differentiation and integration of non-integer (arbitrary) order (Podlubny, 1999).

The qualitative behaviour, as well as the robustness of conventional *PID* controllers can be sensibly improved by its generalization to a $PI^{\alpha}D^{\lambda}$ fractional controller involving an integrator of order α and a differentiator of order λ (Podlubny, 1999). Consequently, fractional order *PID* controllers ($PI^{\alpha}D^{\lambda}$) have also been proposed and have received considerable attention. An interesting feature of fractional order controllers is that they exhibit some advantages when designing robust control systems in the frequency domain for processes whose parameters vary in a large range.

Recently, different works have appeared about the application of fractional order *PID* controllers to control water distribution in main irrigation canals (Feliu Batlle, Rivas Perez and Sanchez Rodriguez, 2007).

The problem of effective control of main irrigation canals has been the subject of numerous scientific publications (Mareels et al, 2005), (Cantoni et al, 2007). However, only few of the proposed controllers have been effectively implemented in real main irrigation canals (Clemmens and Schuurmans, 2004). The *PI* control strategy is the most commonly used in real irrigation canal control systems because it can be tuned properly more easily than a *PID*. The approach classically used to tune *PI* controller for a canal pool is by trial and error or by optimization (Clemmens amd Schuurmans, 2004). These methods are usually based on a nominal model, while the dynamic parameters of the canal pools vary with the change of hydraulic conditions (Litrico, and Fromion, 2006; Rivas Perez, Feliu Batlle and Sanchez Rodriguez, 2007). It is well known that the ultimate goal of a controller for canal pools is to function under different hydraulic conditions guaranteeing a minimum performance. This is the robust performance design problem.

The objectives of our paper are a) to derive a systematic and analytic design method of robust fractional order *PI* controller *(FPI),* which guarantees a minimum performance when the canal pool dynamic changes due to discharge and/or other hydraulic parameters variations, b) to implement and validate this controller in a real main irrigation canal pool. This paper focuses on the *FPI* controller for a single main irrigation canal pool only. We mention that objective a) may cope to some extent with the interaction with other adjacent pools, though our control is applied to the first pool of the canal which is connected upstream to the river.

The main contributions of this paper are: 1) we develop a new method to design robust fractional order *PI* controllers (*FPI*) from frequency specifications, 2) we compare the robustness features of the obtained *FPI* with the ones of an equivalent standard *PI* controller (with the same design frequency specifications) and we provide with a justification of its enhanced properties, 3) we study and compare the behaviour of both controllers when implemented in a real main irrigation canal pool.

This paper is organized as follows. A main irrigation canal pool mathematical model for control is obtained in Section 2. A new method to design robust fractional order PI controllers for main irrigation canal pools is proposed in Section 3. Section 4 describes the application of this new method to a particular main irrigation canal pool and its simulated results are compared with the results obtained from the standard PI controller designed for the same specifications. Section 5 reports some real time experimental results obtained from the practical implementation of both controllers, and finally some conclusions are drawn in Section 6.

2. MAIN IRRIGATION CANAL POOL MODEL FOR CONTROL

Since our objective is to design a linear controller, we need a linear model of a main irrigation canal pool. Linear models are usually sufficient to capture the main dynamic properties of a main irrigation canal pools for control design (Litrico and Fromion, 2006; Feliu Batlle, Rivas Perez and Sanchez Rodriguez, 2007). This linear model is obtained by using identification tools (Rivas Perez, Feliu Batlle and Sanchez Rodriguez, 2007).

A typical main irrigation canal consists of several pools separated by gates that are used for regulating the water distribution from one pool to the next one (see Fig. 1). The gate opening is modified adequately to maintain a given profile of water along the canal pool. In particular, in automatically regulated canals, the controlled variables are the water levels $y_i(t)$ measured near the end of the canal pool (it is called downstream end control), the manipulated variables are the gate positions $u_i(t)$ and the fundamental perturbation variables are the unknown offtake discharges $q_i(t)$, where $i = 1, 2, ..., n$; n - the canal pools total number.

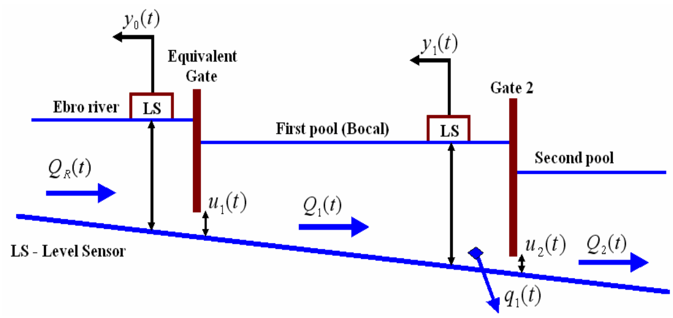

Fig. 1. Equivalent diagram of the canal pool "Bocal".

For effective control of water distribution in a main irrigation canal pool, it is not necessary to know the water level variations along the whole pool. It is enough to measure it in some specific points that depend on the regulation method to be used. Considering this, a linear model with concentrated parameters and a time delay can adequately characterize the dynamical behaviour of a main irrigation canal pool in a measurement point (Litrico and Fromion, 2006; Rivas Perez, Feliu Batlle and Sanchez Rodriguez, 2007).

Results reported in this paper come from the first pool which is known as the Bocal of the Aragon's Imperial main canal (AIMC) which belongs to the Ebro Hydrographical Confederation (Spain). This canal gets its water from the Ebro river thanks to the elevation produced by the Pignatelli dam. It is a cross structure canal pool of 8.0 km. long, a variable depth between 3.5 and 4.0 m., a variable width between 26.9 m. and 8.0 m., a design discharge of 30.0 m^3/s, in all it extension.. This canal pool is operated by means of the downstream end water level regulation method (Malaterre, Rogers and Schuurmans, 1998). The downstream end water level is controlled by means of 10 undershoot gates located in the House of Gates at the beginning of the pool. The measurements available are the upstream (Ebro river) and downstream end water levels and the gates positions (see Fig. 1).

Experiments based on the response to a step signal like command were carried out in order to obtain a linear mathematical model that describes the dynamic behaviour of this main irrigation canal pool. A total of 4 upstream gates received a simultaneous increment in its opening magnitudes of 25 cm. That is to say, it was carried out an increment in the gates total opening magnitude of 100 cm. The experimental response to a step command is exhibited in Fig.2. Such response shows that the canal pool dynamic behavior can be represented by a second order system with a time delay, that is to say:

$$G(s)=\frac{\Delta y_1(s)}{\Delta u_1(s)}=\frac{K}{(T_1 s+1)(T_2 s+1)}e^{-\tau s}, \qquad (1)$$

where: $\Delta y_1(s)$ - downstream end water level variation; $\Delta u_1(s)$ - upstream gate position variation; K - static gain; T_1, T_2 - time constants; τ - time delay. We consider that T_1 is the dominant time constant (the larger one associated to the dynamics of the canal pool), while T_2 is the smaller time constant that represents the motors + gates dynamics, which is much faster than the canal pool dynamics.

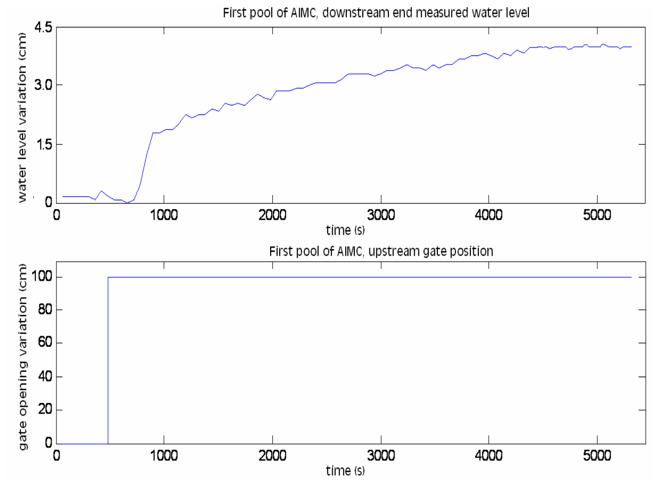

Fig. 2. Step test of the main irrigation canal pool "Bocal".

When the discharge through the upstream gates corresponds to the normal operation regime (nominal hydraulic conditions) of this canal pool the nominal values of the model parameters (1) were obtained (nominal plant), which are represented as $K_0, T_{10}, T_{20}, \tau_0$ and whose values are the following: $K_0=0.0401$, $T_{10}=880.79$ s, $T_{20}=81.27$ s, $\tau_0=360$ s. However, when the discharge regime changes through the upstream gates in the operation range $(Q_{\min}, Q_{\max})$ the dynamical parameters of our main irrigation canal pool model experiment large variations in the following ranges:

$0.01 \le K(t) \le 0.1$;
$500 \le T_1(t) \le 15000$;
$10 \le T_2(t) \le 300$;
$300 \le \tau(t) \le 360$.

For this reason, any controller to be designed for this canal pool should guarantee an a priori a specified minimum level of performance for the range of variation of the main irrigation canal pool dynamical parameters. This is the robust performance control system design problem.

3. FRACTIONAL ORDER PI CONTROLLER DESIGN

In this Section it is proposed an analytical method to design a robust *FPI* controller for a main irrigation canal pool based on the generalization of a *PI* controller. Moreover we will justify the robustness properties of this controller compared with the standard *PI* controller. We will design an *FPI* controller that exhibits the same performance than a standard *PI* controller for the nominal hydraulic regime (both controllers were designed for the same specifications), but our controller presents less sensibility to main irrigation canal pool parameter variations (i.e. it is more robust).

The robust performance design problem consists of tuning a unique controller such that some minimum design specifications are fulfilled for a set of discharges in the operation range $(Q_{\min}, Q_{\max})$ and/or variations of others hydraulic parameters. We pursue to design a robust fractional order controller that maintains stable the control system in the whole region of variation of parameters and whose behavior improves the dynamics of the one installed *PI* controller in that region. The proposed fractional *PI* controller (*FPI*) is of the form:

$$u_{FPI}(t)=K_p(D_t^{-1}e(t)+T_d D_t^{\alpha-1}e(t)), \quad 0\le\alpha\le 1, \qquad (2)$$

whose transfer function is:

$$R_{FPI}(s)=\frac{K_p}{s}+\frac{K_p T_d}{s^{1-\alpha}}=K_p\frac{1+T_d s^{\alpha}}{s}. \qquad (3)$$

Notice that the standard *PI* controller is a particular case of (3) when $\alpha=1$. Three parameters can be tuned in this controller: K_P, T_d and α. They are one more than in the case of the standard *PI* controller. The fractional order α can be used to fulfil additional specifications of the controlled system. The block diagram of the fractional order control system of our main irrigation canal pool is shown in Fig. 3.

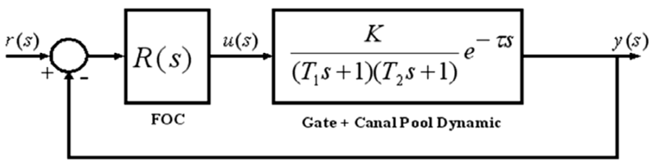

Fig. 3. Block diagram of canal pool control system.

The proposed design method obtains a fractional order controller that verifies the typical control system design frequency specifications: a) a desired phase margin (ϕ_m), which guarantees desired nominal damping and robustness to changes in the time delay; b) a desired crossover frequency (ω_c), which guarantees desired nominal speed of response; c) a desired gain margin (M_g), which garantees desired robustness to gain changes; and d) zero steady-state error. The last specification implies that the controller must include an integral term.

We propose to use the additional parameter α to obtain the desired gain margin (when it is possible) and to improve the robustness of the control system to the dynamic model parameter variations as well as high frequency noises. Parameters of controller (3) that fulfil specifications a)-d) can be calculated by the following procedure.

The condition of having a given phase margin ϕ_m and a crossover frequency ω_c can be expressed in a compact form using complex numbers:

$$R(j\omega_c)G(j\omega_c) = -e^{j\phi_m}, \tag{4}$$

where $R(j\omega_c)$ is the controller transfer function and $G(j\omega_c)$ represents the plant dynamics (1). If we take into account the fractional controller structure (3) we get that:

$$R_{FPI}(j\omega_c) = K_p \frac{1 + T_d \omega_c^\alpha e^{j\frac{\pi}{2}\alpha}}{j\omega_c} = \frac{-e^{j\phi_m}}{G(j\omega_c)}, \tag{5}$$

and operating it the next two conditions it follows:

$$K_p(1 + T_d\omega_c^\alpha \cos(\frac{\pi}{2}\alpha) = \mathrm{Re}(-\frac{j\omega_c e^{j\phi_m}}{G(j\omega_c)}) = P_r; \tag{6}$$

$$K_p(1 + T_d\omega_c^\alpha sen(\frac{\pi}{2}\alpha) = \mathrm{Im}(-\frac{j\omega_c e^{j\phi_m}}{G(j\omega_c)}) = P_i, \tag{7}$$

where $\mathrm{Re}(\ )$ and $\mathrm{Im}(\ )$ mean real and imaginary part of a complex number.

Conditions (6) and (7) lead to:

$$K_p = P_r - P_i ctg(\frac{\pi}{2}\alpha); \tag{8}$$

$$T_d = \frac{P_i}{\omega_c^\alpha [P_r sen(\frac{\pi}{2}\alpha) - P_i \cos(\frac{\pi}{2}\alpha)]}, \tag{9}$$

which allow a direct determination of K_p and T_d once P_r and P_i have been calculated. If we consider the plant (1) and the R_{FPI} controller (3) with values $\alpha \le 1$, then the magnitude Bode diagram of the open loop system $G(j\omega)R_{FPI}(j\omega)$ will exhibit an asymptotic behavior at high frequencies defined by a negative constant slope of $-20(3-\alpha)$ dB/dec. This means that the lower α is, the larger is this slope (its absolute value) yielding to larger gain margins and, therefore, improving the robustness to gain changes, high frequency noises and high frequency unmodelled dynamics.

These last issues are very important in main canal control systems because a) the gain of the plant experiences large variations as consequence of change in the exploitation regime (linearization of the Saint-Venant equations depends on the nominal flow of the canal pool), b) measurement noise is important in these systems because sensors that measures the canal pool water level usually are not very precise as they are relatively cheap and have to be installed in the field, c) high frequency water surface waves that appear when opening the gates may distort the measured signals.

4. COMPARISON OF CONTROLLERS

The fractional control system of a main irrigation canal pool whose block diagram is shown in Fig. 3 is considered. For comparison purposes we design two controllers in this section: a *PI* and a *FPI*. Both controllers are designed to make the system have the same speed of response in nominal conditions. The open loop settling time is $t_{so} \approx 4000$ s and we desire to make the system two times faster. Then a closed loop settling time about the half of the previous one has to be achieved. The *PI* controller was designed to have a crossover frequency $\omega_c \approx 0.00084$ rad/s and a phase margin $\phi_m = 68^\circ$ for the nominal plant. With these frequency specifications we obtain a settling time about $t_{sc} \approx 2160$ s and an overshoot of $M_p \approx 0.7$ %. This means that the closed-loop control system is nearly critically damped. The resulting controller is:

$$R_{PI}(s) = 0.0212 \frac{1 + 850s}{s}. \tag{10}$$

The controlled system has a gain margin $M_g \approx 4.5$ and its phase crossing frequency is $\omega_g \approx 0.0036$ rad/s.

Two specifications have been designed by tuning the two parameters of the *PI* controller: the crossover frequency and the phase margin. Then we could achieve the same two specifications in the *FPI* controller in order to get comparable controllers. Our *FPI* is designed to have the same crossover frequency (the same settling time) than the *PI*, but it is designed to have about the same gain margin than the previous *PI* instead of the same phase margin. The reason for this is the next robustness consideration. The phase margin specification defines the robustness to changes in the time delay while the gain margin defines the robustness to changes in the plant gain. The range of variation of the canal pool parameters experimentally obtained in Section 2 show that changes in the time delay are relatively small while changes in the gain are very large. Therefore it is more significant to define a gain margin rather than a phase margin in order to prevent unstabilization of our closed-loop system.

The *FPI* controller has three parameters to be tuned, and then three specifications can be fulfilled. We define as the third specification for this controller that the settling time be smaller with the *FPI* than with the *PI* in most of the plants of the range of variation of the canal parameters (obviously, for the nominal plant, both controllers would exhibit about the same settling time). In order to design this controller we have run a search procedure that uses expressions (8) and (9) varying the phase margin and α, with the constraints of having a given crossover frequency and a given gain margin.

A *FPI* controller that has the same ω_c and about the same M_g than the *PI* controller, and has a significantly faster response in the range of parameter variations was found for $\alpha = 0.8$ being this:

$$R_{FPI}(s) = 0.021\frac{1+155s^{0.8}}{s}. \qquad (11)$$

This controller has a phase margin $\phi_m = 55^\circ$, and a phase crossing frequency $\omega_g \approx 0.0026$ rad/s for the nominal plant, which is smaller than the one of the *PI*. This last feature shows that the magnitude of the open loop system frequency response is below one at frequencies smaller in the *FPI* than in the *PI*, and this magnitude is lower at high frequencies for the *FPI*. Moreover in order to compare the sensitivity of both controllers to high frequency sensor noises in the measurements, we calculate the magnitude of the corresponding open loop systems at the Nyquist frequency $\omega_n = \pi / T = 0.0524$ rad/s (the sampling period of our sensor is $T = 60$ s). They are -48.9 dB and -57.7 dB for the *PI* and the *FPI* controllers respectively. Then the *FPI* controller attenuates this noise 2.8 times more than the *PI*. Fig. 4 shows the Bode plots of the open loop control system with both controllers. The frequency specifications attained above for these two controllers can be easily traced in these plots.

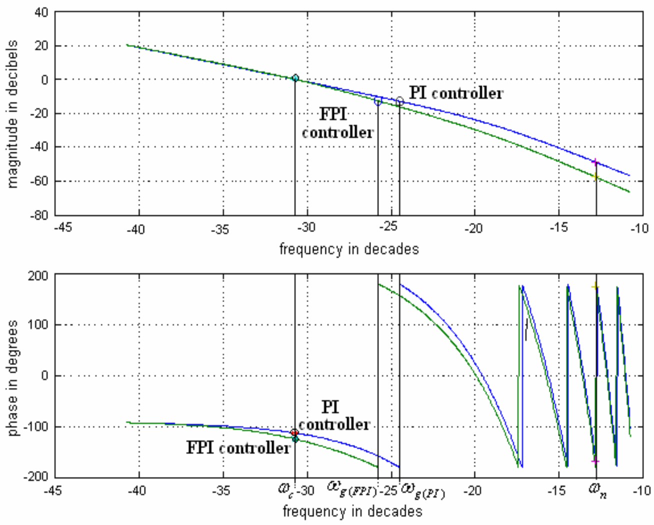

Fig. 4 Frequency response of the open loop system with both controllers

5. EXPERIMENTAL RESULTS OF PRACTICAL IMPLEMENTATION

The feasibility and robust performance of the proposed *FPI* controller was demonstrated by implementing it in a Siemens PLC (a Simatic 300) installed in the control room of the first pool of the AIMC. This PLC contains the *PI* controller (10), and our *FPI* controller (11) was installed in parallel to this one. Our *FPI* controller was implemented as a *FIR* filter obtained from numerically approximating the fractional operators by using the Grundwald-Letnikov definition combined with the short memory principle (Podlubny, 1999).

The robustness and effectiveness of the designed *FPI* controller was verified by carrying out real time working comparison tests of both controllers in front of the same discharge regime variation through the upstream gates. As it was pointed out in the Section 2, when the discharge regime changes through the upstream gates in the operation range $(Q_{\min}, Q_{\max})$ the dynamical parameters of our main irrigation canal pool experiment large variations. In this case, the controller should fulfil the design specifications with at least a minimum level of time-domain performance for all main irrigation canal pool dynamical parameter variations.

The first test consisted of going down the target level (set point) of the downstream end water level from 3,25 m to 3,17 m, that is to say to lower it 8.0 cm. In this case, the discharge regime through the upstream gates decreased. The downstream gate stayed with a fixed position. The upper graphs of the Fig. 5 show the comparison results of the water level variation in the Ebro river and the lower ones the comparison results of the downstream end water level variation with the *PI* and *FPI* controllers. The water level variations in the Ebro river present an aleatory character and they cannot be controlled by our control system. These water level variations originate changes in the canal pool discharge and our controller should compensate them in an operative way. The upper graphs show that the water level in the Ebro river stayed without large variations (approximately ± 5.0 cm) along each one of the experiments. One can see from the lower graphs that with both controllers the downstream end water level variations present a region of maximum error lower than 2.0 cm of the desired final value (set point), but the set point is reached quicker with the *FPI* (52.5 min) than with the *PI* (64.0 min) and at the end of the 120.0 min the *FPI* concludes its settling time with zero steady state error while the *PI* still presents an steady state error of 1.0 cm.

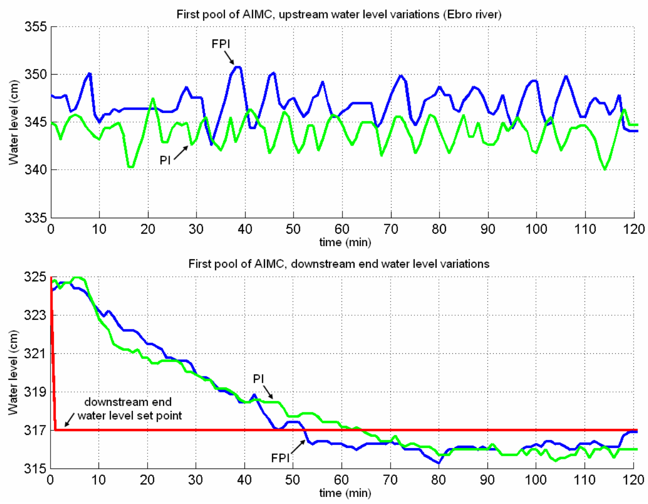

Fig. 5. Upstream and downstream end water level variation when the discharge decreased 8 cm.

The second test consisted of going up the set point of the downstream end water level from 3,10 m to 3.20 m, that is to say to upper it 10.0 cm. In this case, the discharge regime through the upstream gates increased. As in the previous test the downstream gate stayed with a fixed position. The comparative evolution of the upstream and downstream end water levels with the two controllers under study is shown in Fig. 6. The lower graphs show that with both controllers the downstream end water level variations present a region of maximum error lower than ± 1.0 cm of the desired final value (set point), but again the set point is reached quicker with the *FPI* (38.0 min) than with the *PI* (51.0 min) and at the end of the 80.0 min the *FPI* concludes its settling time with zero steady state error while the *PI* still presents an steady state error of 0.5 cm. On the other hand, one observes from the upper graph of Fig. 6 that during the experiment with the *FPI* controller a water level abrupt descent in the Ebro river was originated. This descent could be provoked by the operation entrance of a hydroelectric power station located at the same Ebro river height than the House of Gates but in the contrary riverbank. This disturbance caused a variation of the Ebro river water level larger than 22.0 cm during the experiment with the *FPI* controller, while the Ebro river water level stayed with an approximate variation of ± 5.0 cm during the experiment with the *PI* controller. That is to say, the *FPI* controller was subjected to a larger discharge variation than the *PI* controller and, consequently, to larger main canal pool parameter variations.

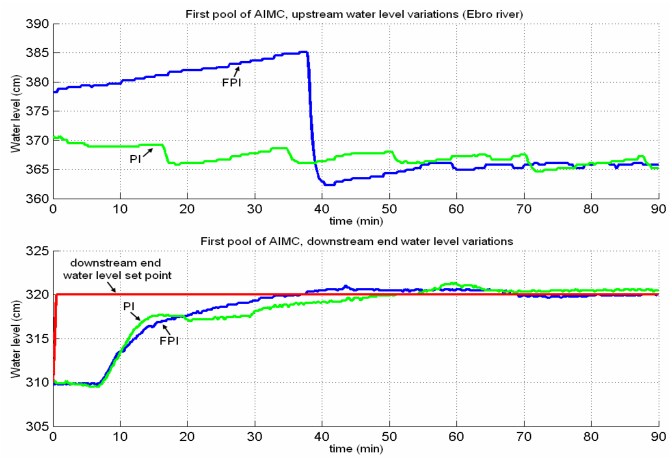

Fig. 6. Upstream and downstream end water level variation when the discharge increased in 10 cm.

These figures prove that our *FPI* controller exhibits a better behavior than the *PI* controller in the sense that it reaches the set point quicker (in about half of the time needed by the *PI* controller, as otherwise it was expected from the design Section) and with higher accuracy. These results show too a better robustness of our fractional order controller than the *PI* controller in front of main canal pool parameter variations, fulfilling the design specifications with a good level of time-domain performance.

6. CONCLUSIONS

We have presented in this paper the design and real time implementation of a new class of fractional order PI controllers (*FPI*) which are more robust than standard *PI* controllers to high frequency noises and modeling inaccuracies. These problems are of special relevance in irrigation main canal pools whose dynamics strongly change with the discharge regime variations, and noises from different sources are present.

A new design procedure has been developed for this class of *FPI* controllers. The robustness properties of these controllers have been justified theoretically in a qualitative way. The interest of such fractional order controllers is justified by the fact that dynamical parameters of main irrigation canal pools may change drastically in function of its operation regimes

Experiments have been carried out in a real main irrigation canal pool comparing both *FPI* and *PI* controllers. These experiments showed the superior performance and robustness of the *FPI* controller over the standard *PI* controller. Finally we want to mention that this is the first time that a fractional order controller has been implemented in a real main irrigation canal pool. It was programmed in an industrial PLC and we did not have to face any special implementation problem.

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