Chapter 9
Automatic Tuning of PI Controllers for Water Level Regulation of a Multi-pool Open-Channel Hydraulic System

D. Dorchies and P.-O. Malaterre

Abstract The underlining philosophical statement of this chapter is that the promotion of automatic control for open-channel hydraulic systems will be greatly facilitated when simple algorithms and tuning procedures are available and adapted to this type of systems. The objective is therefore to contribute to an "automation for hydraulic systems for dummies" approach. In this chapter, we propose an automatic method to tune a series of distant downstream PI controllers for a cascade of pools. The methodology we present could also be used for local upstream controllers, with minor changes. The method is based on the Auto-Tuned Variation principle (ATV) carrying out a relay experiment. The information obtained from this experiment allows to estimate the parameters of a simplified integrator-delay model of each pool. Finally this allows tuning automatically a series of feedback PI controllers, with given gain and phase robustness margins, and a feedforward controller based on simple time delay. This relay experiment is performed for each pool of the canal or river, in sequence, with automatic activation of the previously tuned PI controllers. Different decoupling configurations, in order to reduce interactions between pools, are evaluated in simulation on the benchmark canal 2 of the ASCE Task Committee on Canal Automation Algorithms.

9.1 Introduction

Transport of water with open-channel hydraulic system has the main objective to convey water from a source (dam, river) to users (agricultural lands, but also industries and cities). Such systems can be very large (several hundreds of kilometers), and varying objectives are assigned to their managers. The main general one is to provide water to the different users at the right moment and in the right quantity, and to guarantee the safety of the infrastructure. Some of these hydraulic

D. Dorchies (✉) • P.-O. Malaterre
UMR G-EAU, Montpellier, France
e-mail: david.dorchies@irstea.fr; pierre-olivier.malaterre@irstea.fr

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systems have also navigation purposes (e.g., Rhône river, Canal du Midi, etc.). In this case, additional constraints on water depth, water level fluctuations, and velocities are also to be satisfied. Long time ago, all hydraulic systems (canal, rivers, sewage systems) were controlled in an upstream control logic [15], since it is the easiest to implement in both manual or automatic approaches. In the case of transport of water, it became internationally recognized that the downstream control logic is hydraulically more efficient, but technically more difficult to design and implement. In the case of pure transport over the water, we could possibly claim that the corresponding classical control objectives could be reached by a simple upstream control logic. But such pure navigation systems are rare, and combined systems are becoming more popular. The development of simple and efficient control algorithms adapted to open-channel hydraulic systems, flexible enough to adapt to local constraints, to upstream or downstream logic configurations, easy to tune and to make evolving, is necessary to continue promoting improvement of the management of such systems through automation.

Most of the technics that have been used so far, for the automation of irrigation canals, are based on PID, Internal Model and Fuzzy Control [13] and are mainly Single-Input Single-Output (SISO) algorithms. Several works on Predictive Control, LQG, $\mathcal{H}_\infty$ or ℓ_1 design methods are also described in the literature, and present the advantage of providing naturally Multiple-Inputs Multiple-Outputs (MIMO) mathematical frameworks. They have been tested on numerical simulators or laboratory canals, and some have applications such as the Predictive Control on the Rhône river since 2000 [7] and on some systems in The Netherlands.

Canal managers or consultant companies designing canals and proposing automatic control rules for their cross-structures, usually prefer simple control technics, that they can tune easily, understand, and transfer onto real systems. It can seem strange that a canal manager needs to understand the controllers applied to the control devices of his canal. But, this is often true, since the dynamics of the canal can change during time (vegetation growth, sedimentation, etc.) or he can be unsatisfied with the behavior of his controllers and may want to change this. This is why, despite possibilities of improvements with more advanced technics, that the well-known PID controllers are still very popular on irrigation canals or rivers. For a single pool, tuning a PI controller can be easy. For a series of pools, with interactions between them, this can become more difficult. The technics based on models and frequency analysis are powerful [6], but far too complicated for civil engineering consultant companies or canal managers. The ATV (Auto-Tuned Variation) is an automatic tuning method first proposed by Aström [1, 2]. An application to the automatic tuning of controllers for irrigation canal pools has been presented by the authors in previous papers on a single pool [9] (for local upstream, local downstream and distant downstream control logic), or on three long pools with little interactions between them [8] (for distant downstream control logic in cascade).

The believe of the authors is that many more applications of automatic control will appear on open-channel systems, for both transport of or over the water, if simple methods can be used. Simple enough to be implemented as standard options in hydraulic softwares (as already done in the SIC^2 software we will use in the chapter), used by civil or hydraulic engineers designing such systems without any knowledge of automatic control, and understood and accepted by canal or river managers. Methods that could also be tuned directly and automatically on real systems, without the use of any simulation tool, for subsequent tuning for improvement of the original tuning if the manager is not satisfied or if the hydraulic or structural conditions of the canal or river have changed.

This contribution proposes to extend this automatic tuning method to the case of multiple pools irrigation canals or rivers using different decoupling options and a feedforward controller. Results have been checked on the second bench-mark canal proposed by the ASCE Task Committee on Canal Automation Algorithms [4].

9.2 Design of the PI Controller with ATV Tuning Method

9.2.1 Description of ATV Tuning Method

The relay feedback auto-tuning method proposed by [2] was one of the first to be commercialized for tuning of PID controller in industry. It has since remained attractive owing to its simplicity and robustness. The objective of the method is to determine the critical point, from a single experiment, i.e., the process frequency response with a phase lag of $-180°$. It can be shown that under relay control as in Fig. 9.1, the process will oscillate with the period T_u and that the critical gain k_u is approximately given by:

$$k_u = \frac{4d}{\pi a}, \tag{9.1}$$

where d is the relay amplitude and a is the amplitude of the process output [2].

Typical responses are as in Fig. 9.1. The relay is a simple nonlinear element that changes the input to $+d$ when the output error $e = y - r$ becomes negative,

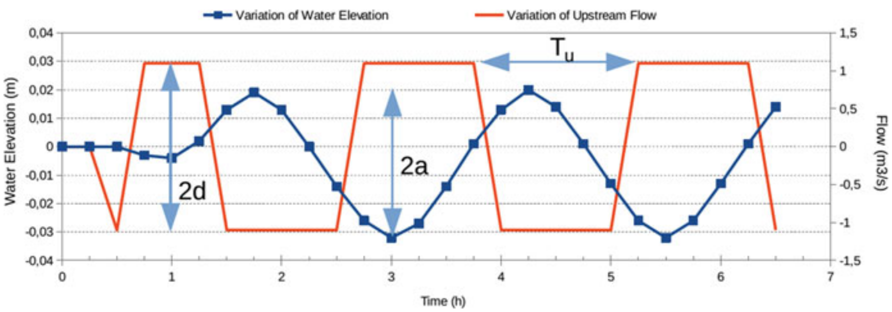

Fig. 9.1 Relay experiment result on the first pool of ASCE test case canal 2

and to $-d$ when the error becomes positive. It is therefore very easy to implement on a real canal, since the gate opening has to be opened or closed of a given value $\pm d$ according to a measured water level y.

9.2.2 Application of ATV Method on One Canal Pool

We will apply the ATV method on a canal pool supposed to be approximated by an Integrator Delay (ID) model proposed by Schuurmans et al. [17]. This simplified model used for the design of water level controllers for irrigation and drainage canals describes the essential characteristics of the processes relevant for canal control (such as water movements and control structures).

This model has two parameters A and τ respectively the inverse of the integrator gain and the delay of the canal pool. The canal pool is then represented, in the frequency domain, by:

$$y = \frac{e^{-\tau s}}{As} u, \tag{9.2}$$

with y the downstream water elevation, u the upstream discharge of the pool and s the Laplace transform variable.

Litrico et al. [9] showed how to compute the ultimate cycle parameters obtained via a relay experiment for an ID model given by (9.2).

Let us examine the system behavior in steady state with persistent limit cycle. We suppose, without loss of generality, that the error becomes negative at $t = 0$. Due to the integrator and since this output error comes from an input negative step of amplitude d, the error is decreasing as a negative ramp of slope $-d/A$. Then, at $t = 0$ the relay leads to a input positive step of amplitude d. At $t = \tau$, this positive step influences the output, which has reached the value $-d \times \tau/A$. Then the output increases as a positive ramp of slope d/A, during a time equal to 2τ. This is depicted in Fig. 9.2. Therefore, the amplitude of the output is equal to

$$a = d \times \frac{\tau}{A}, \tag{9.3}$$

and, using (9.1), the ultimate cycle parameters are given by

$$k_u = \frac{4A}{\pi \tau}, \tag{9.4}$$

and

$$T_u = 4\tau. \tag{9.5}$$

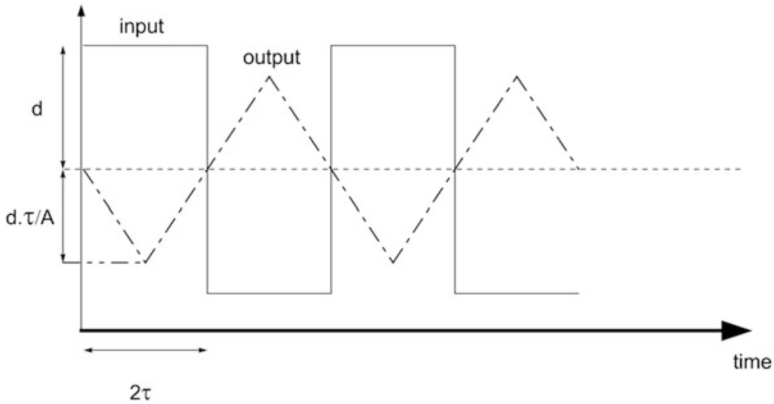

Fig. 9.2 Relay experiment for an ID model

Therefore the relay experiment enables to identify the ID model parameters τ and A

$$\tau = \frac{T_u}{4}, \tag{9.6}$$

$$A = \frac{\pi T_u k_u}{16}. \tag{9.7}$$

9.2.3 Tuning Rule of the PI Controller

Many different rules have been proposed to tune PI or PID controllers from ultimate cycle parameters. Most of them are based on pre-specified rules (such as Ziegler-Nichols rule [19]). Litrico et al. [9] proposed a way to be able to choose the controllers parameters according to time performance and robustness specifications by defining the proportional and the integral parameters, respectively k_p and T_i, from gain and phase margins:

$$k_p = k_u \frac{\pi^2}{8} 10^{-\frac{\Delta G}{20}} \sin\left(\frac{\pi}{180}\Delta\Phi + \frac{\pi}{2}10^{-\frac{\Delta G}{20}}\right), \tag{9.8}$$

$$T_i = \frac{T_u}{2\pi} 10^{\frac{\Delta G}{20}} \tan\left(\frac{\pi}{180}\Delta\Phi + \frac{\pi}{2}10^{-\frac{\Delta G}{20}}\right), \tag{9.9}$$

with ΔG the gain margin in dB and $\Delta\Phi$ the phase margin in degrees.

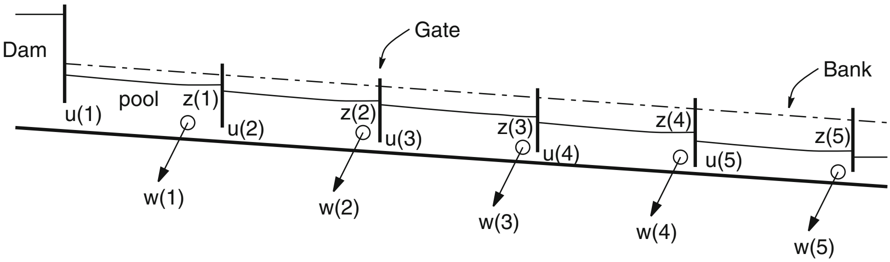

Fig. 9.3 Example of multi-pool canal

9.2.4 Case of Multiple Pools

In the case of multiple pools (cf. Fig. 9.3) controlled with distant downstream PI controllers, one may use a relay experiment to tune successively each pool. This will lead to decentralized PI controllers for the canal pool. However, it is well-known that pool interactions decrease the overall performance of decentralized controllers for an irrigation canal [16]. In a classical decentralized framework, each controller is supposed to be SISO, one control action U aiming at controlling one and only one controlled variable y. This framework is efficient and adapted to situations where indeed each control action U has an influence on only the controlled variable y that it is supposed to control. But in reality, and this is the case in our multi-pool system, each control action U has hydraulic effects on several controlled variables y. This is called coupling effects. There is a mathematical way of assessing the importance of this coupling, using the RGA (Relative Gain Array) index [14]. This coupling effect is becoming stronger when changing from local upstream control logic, to local downstream logic, and even more to distant downstream logic. In our distant downstream control logic, two coupling effects can be denoted:

- If we consider control action variable in term of gate opening W, if gate no. 1 (control action variable U_1) is opened, then water level y_1 will increase after a certain time due to the hydraulic delay in pool no. 1, and since this increase affects the discharge going through gate no. 2, water level y_2 will, in turn, increase.
- If gate no. 2 (control action variable U_2) is opened, then nearby upstream water level y_1 will decrease rapidly.

Several existing decoupling techniques are described in Malaterre and Baume [14] which lead to two strategies for compensating the coupling effects described above.

The first one consists in using discharges Q instead of gate openings W as control action variables (U_i). The direct consequence is that if a given target discharge is maintained through a gate, then the downstream pool is no longer subject to perturbations occurring on the upstream pool.

The second one is the fact that each calculated control action variable U_i, or a portion α of it, is added to the next upstream one U_{i-1}. Hydraulically, this means that if U_i is operated to compensate for a perturbation in its downstream pool i, then we know that this operation will have an interaction effect on y_{i-1}. Of course U_{i-1} will in turn correct the effect of this perturbation (after some delay inherent to the system's characteristics) when its effect is felt on y_{i-1}. But we can anticipate this action by adding directly the correction to U_{i-1}:

$$U_{i-1} = F_{i-1} y_{i-1} + \alpha U_i, \tag{9.10}$$

where F_{i-1} is the transfer function of the PI controller linking y_{i-1} to U_{i-1} and $\alpha \in [0, 1]$. Theoretically α must be equal to 1, but for stability and robustness reasons, it is sometimes reduced close to lower values such as 0.8.

This correction will cancel or at least reduce the effect of U_i on y_{i-1}. This second decoupling technique cannot be as good as the first one proposed above since the delay time on pool $i-1$ implies that the additional correction αU_i at gate $i-1$ will not be felt instantaneously on the controlled variable y_{i-1}.

This decoupler is easy to understand and to design when the control action variable U_i is a discharge Q. In case of a control action variable U_i in terms of gate opening W, it is necessary to use a calculation of the outgoing discharge for calculating the decoupler. Litrico and Malaterre [8] proposes a method using the results of the relay experiment for this purpose. But here, since the experiment described below uses feedforward control which is in term of discharge, discharge conversion into gate opening is required.

9.3 Test Case on ASCE Canal 2

9.3.1 Description of ASCE Canal 2

The ASCE Task Committee on Canal Automation Algorithms (1993–1998) has defined benchmark canals and scenarios for two canals [4]. The aim was to provide researchers with benchmarks that would allow performance comparison between different canal regulation algorithms. Each canal is composed of eight pools separated by cross-gates. The main differences between the two canals are their slopes and in-line volumes. Canal 1 is a steep, fast canal with little storage, and Canal 2 is a flat canal with more storage volume and longer pools. Canal 2 is based on the upstream portion of the Corning canal in California.

Two test scenarios are considered for each canal. For the first one (the tuned test), the control parameters are tuned with the correct canal description, and they are then tested on the same canal system. For the second one (the untuned test), the same control parameters as previously tuned are applied to a canal system with modified Manning and gate discharge coefficients. This second test aims at verifying the robustness of the algorithm.

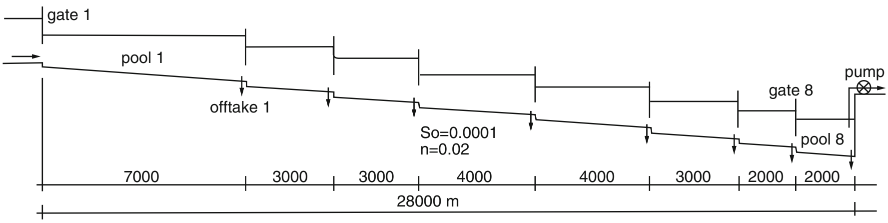

Fig. 9.4 Profile for test canal 2 (taken from [11])

Table 9.1 Hydraulic conditions in the tests 1 and 2 for ASCE test case canal 2

Test	Period	Offtakes no.								Pump
		1	2	3	4	5	6	7	8	
1	Initial withdrawals	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.0
	0–12 h	–	–	–	–	+1.5	+1.0	–	–	–
	0–24 h	–	–	–	–	–	−2.0	–	–	–
2	Initial withdrawals	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.3	0.7
	0–12 h	+1.5	+1.5	+2.5	–	–	+0.5	+1.0	+2.0	+2.0
	0–24 h	−1.5	−1.5	−2.5	–	–	−0.5	−1.0	−2.0	−2.0

In this study, we will focus on the regulation of the eight pools of Canal 2. The control objective is to regulate the downstream level in each canal by modifying upstream discharges and thus the corresponding gate openings. Pools lengths are visible in Fig. 9.4. The bottom width is 7 m, the bottom slope is 0.0001, the Manning's n is 0.02 and the drop at each gate is 0.2 m. Gate movement, between two regulation time steps, is restricted with a minimum gate movement allowed equal to 0.5 % of the gate height.

9.3.2 Description of the Tests

Each test is divided into two parts, 12 h long: 0–12 h (where a feedforward component can be used since the offtake discharge changes are known), and 12–24 h (where the offtake discharge changes are supposed to be unknown and therefore cannot be used by the controller). The time step of the controllers ΔT_r is fixed at 15 min. The first test starts with a heading flow of 11 m^3/s and has a relatively small scheduled flow change at 2 h, followed by a similar unscheduled change at 14 h. The second test represents multiple variations showing dramatic changes with heading flow varying between 2.7 and 13.7 m^3/s. Complete hydraulic conditions of the tests are described in Table 9.1.

For testing the robustness of the controllers, the tests are performed in tuned and untuned conditions. The latter involves unknown changes of some hydraulic parameters of the canal:

- Manning's n value of 0.026 instead of 0.02.
- Check gate discharge is 10 % less than in the tuned conditions.
- Real scheduled offtake discharge changes is 5 % higher than as scheduled.

9.3.3 Performance Indicators

The original objective of the control algorithms for these tests is to keep the water level in the canal constant so that the flow to offtakes will remain constant. Therefore, the main performance criteria proposed by Clemmens et al. [4] are related to maintaining constant water levels at the offtakes, located at the downstream end of each pool. The following indicators are used:

Maximum Absolute Error (MAE)

$$MAE = \frac{\max\left(\left|y(t) - y_{target}\right|\right)}{y_{target}}, \tag{9.11}$$

where $y(t)$ = observed (computed from simulation) water level at time t; and y_{target} = target water level (being the initial water level at time 0).

Integral of Absolute Magnitude of Error (IAE)

$$IAE = \frac{\frac{\Delta t}{T} \sum_{t=0}^{T} \left|y(t) - y_{target}\right|}{y_{target}}, \tag{9.12}$$

where Δt = regulation time step; and T = time period for the test.

Steady-State Error (StE)

$$StE = \frac{\max\left(\left|\bar{y}_{10,12} - y_{target}\right|, \left|\bar{y}_{22,24} - y_{target}\right|\right)}{y_{target}}, \tag{9.13}$$

where $\bar{y}_{h_1,h_2}$ = average water depth between time h_1 and h_2.

Integrated Absolute Discharge Change (IAQ)

$$IAQ = \sum_{t=t_1}^{t_2} \left(\left|Q_t - Q_{t-1}\right|\right) - \left|Q_{t1} - Q_{t2}\right|, \tag{9.14}$$

where Q_t = check gate discharge at time t.

9.3.4 Experimental Design on ATV-PID

The method we will develop in this chapter, combining a series of PID controllers (PI only in our case, to be more precise) tuned by the ATV method will be referred as the ATV-PID method. Several options are possible depending on the type of control action variables, on the feedforward component, on the report from one gate to another, on the order of tuning, etc. The simulations have been performed with SIC^2 version 5.33 developed at Irstea, Montpellier [3]. This software is specially well adapted to the simulation of the automatic control of an open-channel system, and includes a library of preprogrammed algorithms such as the ATV, the PID, the combined ATV-PID that we will use in this chapter and much more. It also offers open interfaces with Matlab, Scilab, WDLangage and Fortran that we will also use for advanced options. At the same time, Scilab [18] was used for driving automatically in batch mode all the simulations and calculating the performance indicators. Simulations use a calculation time step ΔT and a gate movement duration ΔT_o of 1 min. This choice was made for:

- representing a realistic duration of a gate movement,
- reproducing faithfully high frequency waves occurring after a gate movement.

The control time step for the ATV relay experiment is also fixed at 1 min in order to accurately determine the period and the amplitude of the process outputs.

Considering the different issues on coupling effects described in Sect. 9.2.4, the authors propose to analyze the performance of the ATV method on tests 1 and 2 of the ASCE test case canal 2 with different decoupling options.

The first option is the choice of the control action variable at the check gates:

- the flow with check gates acting as pumps hereafter noted option P. This choice allows to verify if the ID model could be representative of the dynamic flow in this case study. Indeed, in the case of pumps, the assumptions underlying the integral-delay model are satisfied.
- the flow with discharge inversion for calculating the opening of the check gates at each control time step hereafter noted option Q. For this purpose, we use here the method of the characteristics used by Litrico et al. [10]. This method takes into account the deviations of the upstream and downstream water levels and their impacts on the gate discharge due to change of hydraulic conditions at the gate due to its movements.
- the gates opening W (except for the head of the canal where the flow Q is used) hereafter noted option W.

For configurations using control action variables Q and W, gate movements are restricted by the minimum gate movements described in Sect. 9.3.1, as imposed by the benchmark specifications. The idea of this minimum gate movement is twofold. First, the actuators do not have an infinite precision. Second, in order to limit the number of operations of the gates and the solicitation of the motors, if the gate movement required by the controller is less than this minimum value, then the gate will not be moved. For the control action variables P, we did not impose an equivalent minimum discharge change, since this P option is more seen as a reference option for comparison, rather than a realistic option. But, for this P pump option we observed that the canal pools could be dried at some moments due to the very important discharge changes that can be applied at the control structures, contrary to the options where a gate opening is applied. This is why, for this P option, we added a security threshold preventing from drying the pools. When a water level upstream of a pump is dropping to much, below half of the corresponding target water depth, then the downstream pump is stopped during at least 5 min.

The second option is related to the use of the decoupler transferring the value of the control action variable of one structure to the next upstream control structures using (9.10). Several coefficients α are tested: 0, 0.8, and 1.

The last option is related to the way the ATV-PID method is applied on a multiple-pool canal. Each PI controller of a pool is tuned one after the other, but there are many possibilities for the order in which this is done. Just after a PI controller of a pool is tuned, this one is switched into automatic PI mode and regulates the water level at the downstream end of this pool. Therefore, due to coupling issues, it is easy to understand that the order used for tuning the controllers of each pool can change the result of this tuning. The dynamic of a pool with or without the adjacent pools in PI mode is not the same, except for the pump option P, where the coupling effects are completely removed. Two possibilities are then explored: tuning from downstream to upstream (hereafter denoted $Dn \rightarrow Up$), and tuning from upstream to downstream (hereafter denoted $Up \rightarrow Dn$). For taking into account the possible change of dynamics involved when all the PI controllers are activated, compared to the case when some are not, we choose to test an option with so-called *meta-cycles*. In the first meta-cycle, the PI controllers are activated, one after the other, after their first ATV tuning, in a given order ($Dn \rightarrow Up$ or $Up \rightarrow Dn$). The PI controllers not tuned yet are not set to PI mode and therefore the corresponding gates are not moved during the tuning procedure. In the second meta-cycle, ATV tuning is performed again for each pool, one after the other (in the same order than during the first meta-cycle) with all the other PI controllers activated. These PI controllers have first the parameters calculated in the first meta-cycle and are progressively updated by the parameters calculated during the second meta-cycle. We observed, in our example, that the parameters obtained with only one meta-cycle, or with two, are almost the same, at least for the best options that we will select. This is probably due to the satisfactory way of handling the coupling effects. This validates the approach proposed in this chapter, both for an initial tuning when no PI has been tuned yet, and for subsequent tuning procedures, in real field conditions when some or all PI have already been tuned and activated.

Auto-tuning experiments are performed on the ASCE test-case canal 2 with steady conditions corresponding to the beginning of both tests and for tuned conditions as described in Sect. 9.3.2. Litrico et al. [9] advised to use a relay included in the range 10–20 % of the initial discharge. The relay chosen for the test 1 is equal to 10 % of the initial discharge on each check gates (a bigger value carrying too large oscillations in the pools), and for test 2, it is equal to 15 % of the initial discharge (Lower values resulting in impossibilities to perform the relay experiment because of the minimum gate movement).

Considering the choice of the gain and phase margins used for tuning the PI controllers, Litrico et al. [9] had tested a range of ΔG between 6 and 14 dB with keeping a constant phase margin ratio $\Delta\Phi/\Delta\Phi_{max} = 0.7$ with $\Delta\Phi_{max}$ determined by the formula $\Delta\Phi_{max} = 90(1 - 10^{\frac{\Delta G}{20}})$. For both control action variable P and Q configurations, different values have been tested for the gain margin and we used each time the formula above for calculating the phase margin. Starting from $\Delta G =$ 10 dB, we increased this value with a step of 5 dB until the ATV experiment does not lead to oscillating or unstable controllers (e.g., PI controllers with long-lasting oscillations). Finally, the gain and phase margin were respectively 20 dB and 56.7° for configurations with control action variable P and Q, and 15 dB and 51.8° for configurations with control action variable W.

Combining decoupling options and hydraulic conditions, the experiment totals 36 sets of PI parameters. The simulations of the hydraulic behavior and the regulation algorithms are performed under SIC^2 where the ATV-PID method used here is fully implemented. The first decoupler (i.e., use of the characteristics method for discharge inversion calculation for the gate opening) is also available in SIC^2. For the second decoupler, a module written in Windev script language (called WDLangage) is used inside SIC^2 (see Fig. 9.5 for an overview of SIC^2 interface showing the canal and the controllers). For the control action variable W, the SIC^2-Scilab interface was used for calculating discharge conversions used by the second decoupler.

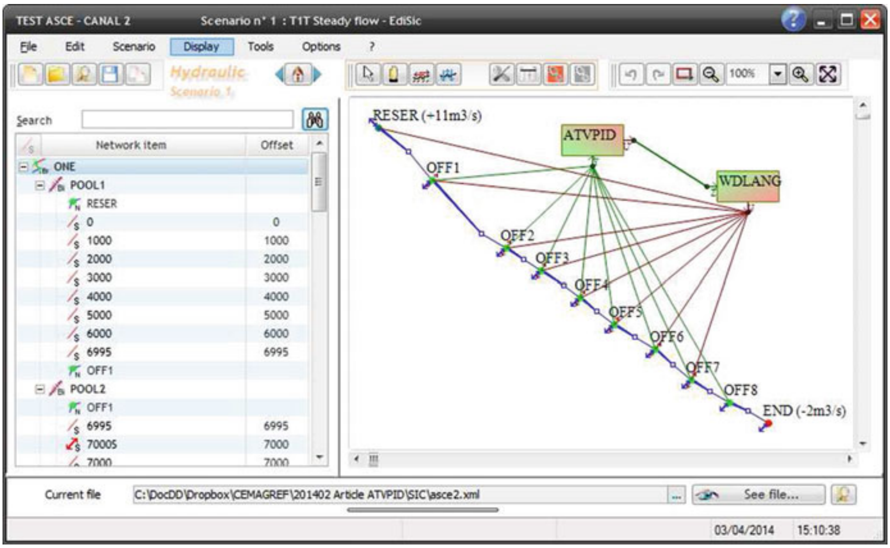

Fig. 9.5 Implementation of ATV-PID experiment within SIC^2

9.3.5 Performing the Tests

The tests are performed for a period of 24 h with a 1 min ΔT simulation time step and 15 min ΔT_r regulation time step. The scheduled flow change at time $t = 2$ h requires the use of a feedforward controller. Keeping in mind the philosophy of simplicity of use, we choose to use a pure delay controller calibrated from the parameters τ (pure delay) and A (backwater area) of the Integrator Delay models identified by the ATV relay experiment with (9.6) and (9.7).

When a discharge variation ΔQ occurs at the downstream end of a reach, a variation of the water level ΔY_c is expected. This variation can be estimated by the characteristic method which corresponds to the equation:

$$\Delta Y_c = -\frac{\Delta Q}{T(C - V)}. \tag{9.15}$$

With T, the top width of the canal, C the wave celerity, and V the mean velocity. Considering that the water level at the downstream end of the reach is equal or close to the target level, T and C remain almost constant and V only depends on the local scheduled discharge Q.

In order to counterbalance this water level variation, one can use the Integrator Delay model to calculate the delay we have to use for the anticipation feedforward action to get an opposite water level variation before the discharge variation occurs at the downstream end of the reach. The link between the delay and the water level variation is shown in Fig. 9.6. The anticipation to apply at the upstream check gate for the feedforward controller is then equal to $\tau + \Delta t_{ff}$, where Δt_{ff} if given by

$$\Delta t_{ff} = \frac{A.\Delta Y_c}{q}, \tag{9.16}$$

with A the integrator parameter of the ID model, q the downstream discharge change ($q = \Delta Q$ for a classical 100 % feedforward loop) and ΔY_c the anticipated water level change calculated with (9.15). That means that if a flow change ΔQ_i is scheduled at time t at the offtake located at the downstream end of the pool i, ΔQ_i will be applied at the upstream check structure at time $t - (\tau + \Delta t_{ff})$.

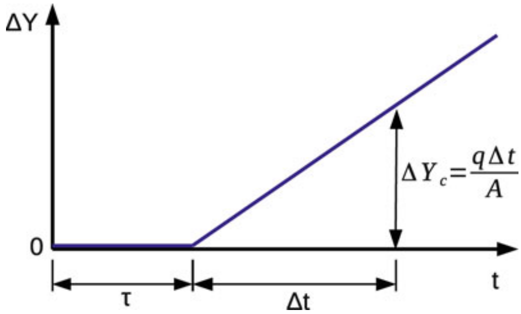

Fig. 9.6 Link between the Integrator Delay model and the water level variation ΔY_c

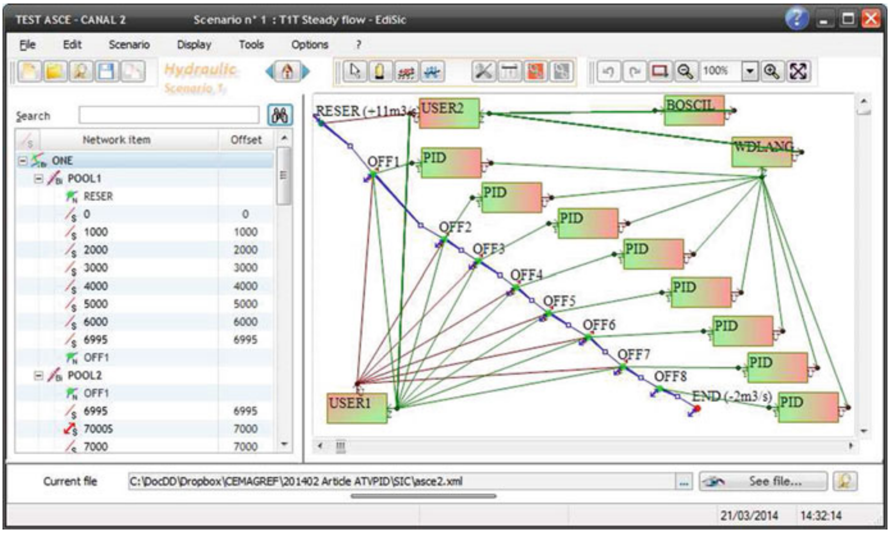

Fig. 9.7 Implementation of PI tests within SIC^2

The feedforward controller is calculated offline in Scilab and applied into SIC^2 with the so-called BOSCIL method which allows to use an open loop controller reading the control variables in file containing a matrix in Scilab format. In addition, we develop specific regulation modules in Fortran in order to be able to use the inversion discharge calculation embedded in SIC^2 but with changing the discharge coefficient to take into account the untuned conditions. See Fig. 9.7 for an overview of the regulation framework interfaces in SIC^2.

On one side, the tests in tuned conditions are performed with the PI set of parameters obtained in tuned conditions. On the other side, the tests in untuned conditions are performed with the same set of parameters obtained in tuned conditions.

9.3.6 Results

Performance indicators have been calculated for the four tests (tests 1 and 2 in tuned, and untuned conditions), for the 18 combinations of decoupler configuration, and for each 12-h period of the tests. For each indicator, maximum and average value of the indicators encountered in the eight pools of the canal are calculated.

All these indicators has been sorted and compared to results of other controllers which have been tested on the ASCE benchmark test-case on Canal 2. These references are:

- PILOTE: A Linear Quadratic Gaussian optimal controller using gate opening as control action variable [12].
- PIR: This controller is based on Dynamic Regulation coupled with a PI controller using a Smith Predictor and the second decoupler used herein. To simplify the coupling of reaches, the discharges to be adjusted at the check gates are used as control action variables [5].
- CLIS based on an inverse solution method of the Saint Venant equations [11].

The current experiments show that the results are very sensitive to the time taken for the operations at the check gates and at the offtakes. A given gate opening at a given regulation time t can be done in an operation time duration ΔT_o of 10 s or of 5 min for example. To simplify, we decided to take this time ΔT_o equal to the numerical simulation time step ΔT. These times steps ΔT_o and ΔT are not specified in the benchmark conditions. Only the regulation time step ΔT_r is specified, meaning the frequency at which a new gate operation can be done. For this benchmark on ASCE Canal 2 it is equal to 15 min. A long numerical simulation time step ΔT will not be able to reproduce high frequencies waves occurring after a gate movement. Especially, we observe in case of the use of Q control action variable that the error between the desired and obtained discharge considerably increases during the ΔT_r time step as the simulation time step ΔT decreases. Since results for PILOTE and CLIS has been produced respectively with a 15 min and 5 min simulation time step ΔT and the one of PIR is not defined, the comparison with these reference should be taken with caution. The tests using a 1 min simulation time step ΔT correspond to more stringent conditions with regards to the performance indicators and also to a more realistic field situation considering that the changes in gate opening or discharge last 1 min.

Detailed Results on Test 1

In Test 1 with tuned or untuned conditions (see Figs. 9.8 and 9.9), PILOTE, CLIS, PIR, and configurations with P as control action variable are often at a good position in the rankings of MAE, IAE, and StE performance indicators. In untuned conditions configurations with W as control action variable are also well ranked for MAE or IAQ indicators. In the rankings of the Integrated Absolute Discharge Change (IAQ), the best configurations are the ones that are generally at the bottom end on the others indicators. It can be explained by the fact that IAQ is an indicator relative to the wear and tear of the check gates and then the best configurations in IAQ are under-reacting controllers.

On the scheduled period (0–12 h), there is no significant differences between configurations using different values of α for the upstream report. We see here that the feedforward controller does most of the job on the scheduled period by bringing the necessary volume of water at the good time. The feedback controller only has to adjust the water level without the need to communicate such big changes in water discharge to the upstream check structures. On the contrary, on the unscheduled

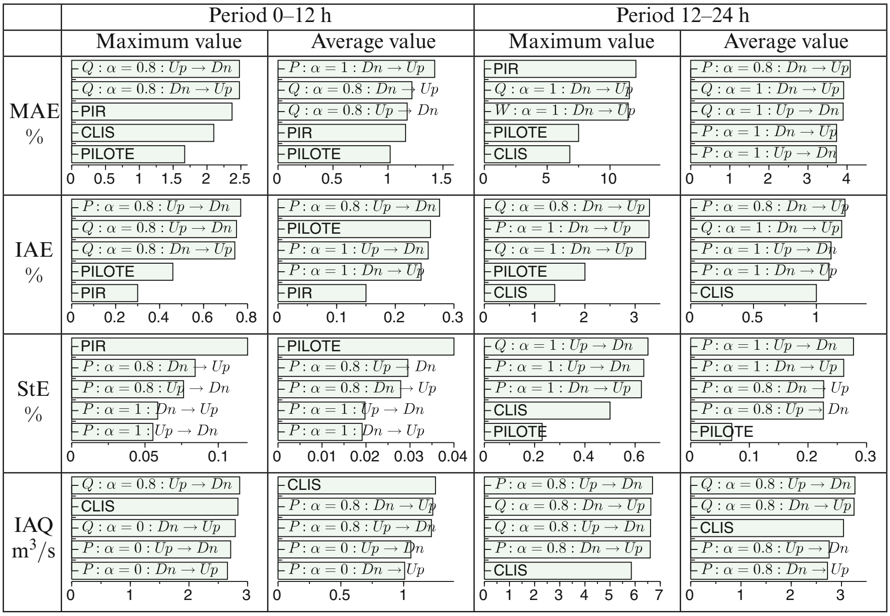

Fig. 9.8 Benchmarking of performance indicators for test 1 in tuned conditions

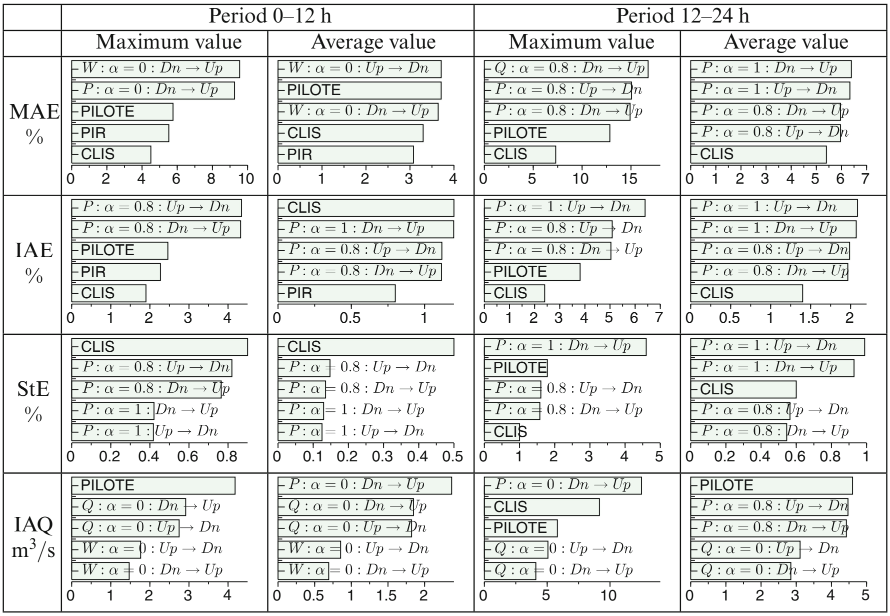

Fig. 9.9 Benchmarking of performance indicators for test 1 in untuned conditions

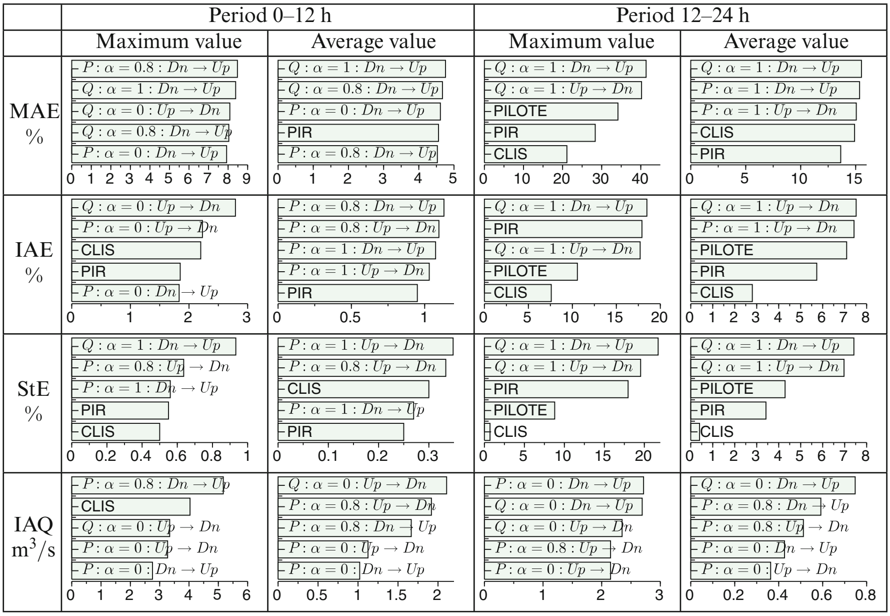

Fig. 9.10 Benchmarking of performance indicators for test 2 in tuned conditions

period (12–24 h), only upstream report with α equal to 0.8 or 1 are on the hit list for MAE, IAE, and StE showing that big deviations in water discharges caused by the feedback controller need to be communicated to the upstream check structures in order to perform well.

Detailed Results on Test 2

The Test 2 offers much larger variations in flow changes. In this test (see Figs. 9.10 and 9.11), one can notice the good reliability of the configurations P and Q both in tuned and untuned conditions on the scheduled period (0–12 h) whatever the upstream report α is. That validate the fact that most of the performance here is due to the feedforward controller which is independent from the upstream report.

Global Ranking

Given the multitude of different results, it is difficult to distinguish which configuration to use in order to maximize most of the performance indicators. For that purpose, we choose to use a scoring method on each of the 64 calculated performance indicators. The first ranked configuration gets 10 points and the worst configuration gets 0 points while the score of all the others configurations

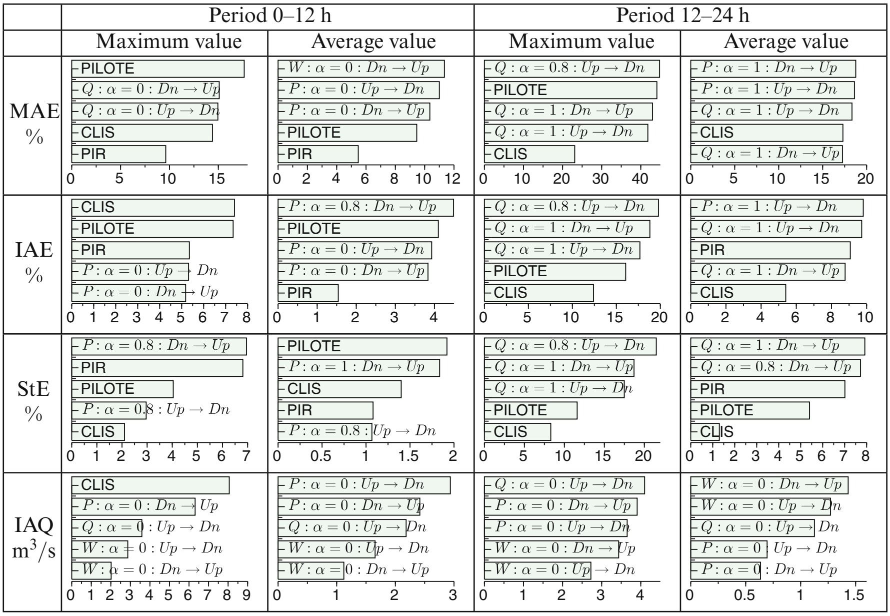

Fig. 9.11 Benchmarking of performance indicators for test 2 in untuned conditions

is calculated proportionally between these two extremes given there respective indicator values. Finally, scores are summed in order to get the global score and the global ranking. The results for the tested configurations is given in Table 9.2.

At first sight, ATV-PID is a controller that under-performs compared to more sophisticated controllers such as CLIS, PILOTE and PIR. Regarding control action variable, P is the best choice, followed by Q and W. That proves the relevance of the ID model used in the ATV method to synthesize the PI controller in the P option, when the hypothesis underlying the ID model are fully valid. The more there exists a deviation between the required discharge change and the obtained one at a gate, the more the controller under-performs.

Regarding upstream report, $\alpha = 0.8$ configurations are at the top-ranking for P and Q configurations, confirming that $\alpha = 1$ configurations raise oscillatory issues. This aspect can be explained by the over-reaction due to the PI controller. For example, if an increase of discharge is done on a check gate, this increase is entirely transmitted to the upstream check gate that will deliver the necessary discharge to fill the gap at the downstream part of the reach. But, because of the delay this gap is not fulfill instantaneously, and the PI controller will aim at compensating for the decrease of water level by increasing the discharge as well. Without surprise, configurations with no upstream report is at the rear of the pack except for W configurations where the solution used here to perform the upstream report does not seem to be efficient. This point will be further investigated in future works.

Table 9.2 Global scores of tested decoupler configurations

Rank	Control action variable	Upstream control transfer	ATV direction	Score
1	CLIS			578
2	PILOTE			544
3	Discharge in Pump mode (P)	$\alpha = 0.8$	Down to up	524
4	Discharge in Pump mode (P)	$\alpha = 0.8$	Up to down	518
5	PIR			509
6	Discharge in Pump mode (P)	$\alpha = 1$	Down to up	492
7	Discharge (Q)	$\alpha = 0.8$	Down to up	484
8	Discharge (Q)	$\alpha = 0.8$	Up to down	481
9	Discharge in Pump mode (P)	$\alpha = 1$	Up to down	481
10	Discharge (Q)	$\alpha = 1$	Down to up	469
11	Discharge (Q)	$\alpha = 1$	Up to down	464
12	Discharge in Pump mode (P)	$\alpha = 0$	Up to down	416
13	Discharge in Pump mode (P)	$\alpha = 0$	Down to up	401
14	Discharge (Q)	$\alpha = 0$	Up to down	366
15	Discharge (Q)	$\alpha = 0$	Down to up	355
16	Opening (W)	$\alpha = 0$	Down to up	262
17	Opening (W)	$\alpha = 0$	Up to down	247
18	Opening (W)	$\alpha = 0.8$	Down to up	236
19	Opening (W)	$\alpha = 1$	Down to up	222
20	Opening (W)	$\alpha = 0.8$	Up to down	216
21	Opening (W)	$\alpha = 1$	Up to down	171

Results for $Dn \rightarrow Up$ and $Up \rightarrow Dn$ configurations generally show no significant differences in the performances indicators but there is always a little advantage for $Dn \rightarrow Up$ configurations with upstream report $\alpha \neq 0$.

Except for StE indicators where the minimum gate movement is in cause, P compared to Q control action variable configurations shows that even with the use of the characteristics method, there could be still scope for improvement in the method used to calculate the gate opening from the discharge equation.

The results can also be examined in relation to the sensibility of the controllers to untuned conditions. In order to asset this issue, we have calculated the average evolution of all the performance indicators for each controller configuration. Results for Test 1, Test 2 and both tests detailed for scheduled and unscheduled periods are presented in Table 9.3.

One can notice that performance indicators downgrading is largely less important in the scheduled period (0–12 h) than in the unscheduled one (12–24 h) for all configuration. That shows that feedforward controllers are more robust to changes of hydraulic conditions. Nevertheless the underestimation of 5 % of scheduled offtakes in untuned condition tested here could not be considered as a hard test of robustness. The less sensitive configurations are the ones with W as control action variable with no upstream discharge reporting ($\alpha = 0$). But this configuration cannot be

Table 9.3 Average evolution of performance indicators between tuned and untuned conditions

Configuration	Test 1		Test 2		All tests	
	0–12 h	12–24 h	0–12 h	12–24 h	0–12 h	12–24 h
CLIS	+63 %	+87 %	+36 %	+132 %	+49 %	+110 %
PILOTE	+154 %	+273 %	+51 %	+68 %	+103 %	+171 %
$P : \alpha = 0.8 : Dn \rightarrow Up$	+185 %	+219 %	+112 %	+146 %	+149 %	+183 %
$P : \alpha = 0.8 : Up \rightarrow Dn$	+185 %	+220 %	+86 %	+142 %	+136 %	+181 %
PIR	+111 %	+315 %	+40 %	+105 %	+75 %	+210 %
$P : \alpha = 1 : Dn \rightarrow Up$	+208 %	+280 %	+76 %	+153 %	+142 %	+217 %
$Q : \alpha = 0.8 : Dn \rightarrow Up$	+227 %	+311 %	+77 %	+152 %	+152 %	+231 %
$Q : \alpha = 0.8 : Up \rightarrow Dn$	+231 %	+317 %	+69 %	+132 %	+150 %	+224 %
$P : \alpha = 1 : Up \rightarrow Dn$	+202 %	+275 %	+89 %	+153 %	+145 %	+214 %
$Q : \alpha = 1 : Dn \rightarrow Up$	+246 %	+338 %	+73 %	+150 %	+159 %	+244 %
$Q : \alpha = 1 : Up \rightarrow Dn$	+245 %	+333 %	+66 %	+132 %	+155 %	+233 %
$P : \alpha = 0 : Up \rightarrow Dn$	+128 %	+138 %	+83 %	+85 %	+105 %	+112 %
$P : \alpha = 0 : Dn \rightarrow Up$	+124 %	+137 %	+82 %	+96 %	+103 %	+116 %
$Q : \alpha = 0 : Up \rightarrow Dn$	+84 %	+148 %	+66 %	+137 %	+75 %	+143 %
$Q : \alpha = 0 : Dn \rightarrow Up$	+87 %	+150 %	+43 %	+78 %	+65 %	+114 %
$W : \alpha = 0 : Dn \rightarrow Up$	−3 %	+4 %	−7 %	+18 %	−5 %	+11 %
$W : \alpha = 0 : Up \rightarrow Dn$	−20 %	−13 %	−12 %	+7 %	−16 %	−3 %
$W : \alpha = 0.8 : Dn \rightarrow Up$	+91 %	+126 %	+27 %	+34 %	+59 %	+80 %
$W : \alpha = 1 : Dn \rightarrow Up$	+150 %	+193 %	+41 %	+46 %	+95 %	+120 %
$W : \alpha = 0.8 : Up \rightarrow Dn$	+73 %	+104 %	+22 %	+26 %	+48 %	+65 %
$W : \alpha = 1 : Up \rightarrow Dn$	+109 %	+112 %	+33 %	+32 %	+71 %	+72 %

considered as robust regarding the poorness of its results in tuned conditions. Best tested configurations are more sensitive to untuned conditions than CLIS, PILOTE and PIR but this conclusion should be nuanced by the fact that the simulation time step used here ($\Delta T_o = \Delta T = 1\,mn$) corresponds to a priori more difficult conditions.

9.4 Linking Transport of and Transport over Water

Main issues in transport of water are to deliver the requested amount of water at the good locations, at the good moment and in the good quantity while, at the same time, minimizing water losses at canal downstream end. Distant downstream control is a very efficient way to reach these objectives because it has the ability to control the discharge delivered from the upstream cross devices and therefore to reduce water losses directly from the source.

The ATV method presented here was applied to this distant downstream control logic. It is easy to implement on a real canal [8]. The combination of this method with the two decouplers using gate equation inversion with the characteristics method (Q) and upstream discharge reporting ($\alpha = 0.8$) shows in the study that the performances are respectable and robust compared to other more complicated controllers.

Since this regulation method used for transport of water consists in keeping constant water level at the downstream end of the pools, it is also of interest when considering transport over water. Usually in transport over water systems such as navigable rivers, the upstream discharge is not under control and the regulation is done by using a local upstream controllers at each check structure which could be a regulated gate or a simple weir. In these systems, major perturbations are caused by locks when boats move from one pool to another.

It is also possible to use ATV-PID design and tuning method for performing upstream local control but the interest of this in front of a large static weir which will be able to perform a robust control is not obvious. Except if the targeted water level is changing over the time, due to flow or navigation conditions. On the opposite, in the case of the existence of a reservoir at the upstream end of the canal, a distant downstream control should be an efficient solution for both transport of and over water with a good efficiency on saving the water reservoir. ATV-PID will be then specially appropriate on systems where physical parameters (such as bed geometry or roughness) are not well-known or where they can significantly change. Indeed, even if the results show a relative low robustness of the controller compared to more sophisticated controllers, the advantage of the ATV-PID controller is that it can be easily re-calibrated whenever the manager observes a performance loss.

9.5 Conclusions and Future Research

This chapter considered the use of an auto-tuned PI controller (ATV-PID) on a multi-pool open channel system where the PI controller is tuned from an Integrator Delay model determined by a relay experiment on each pool. A feedforward controller has also been calibrated from this relay experiment and use the parameters of the identified ID model to counterbalance the water level variation expected by the discharge variation at the downstream end of the pool and calculated from the characteristics method.

Different decoupling options have been explored to tackle interactions between pools which consist in the use of discharge as control action variable instead of gate opening and the use of a report of discharge variation occurring at one check gate to the next upstream check gates. Different combination of decoupling configuration have been tested on the test canal 2 proposed by the ASCE Task Committee on Canal Automation Algorithms. Four tests separated in a scheduled and unscheduled periods have been performed representing different hydraulic conditions and unknown changes in physical parameters in order to assess the robustness of the controller. All configurations have been assessed with performance indicators and have been compared with results from previous researches.

Results show that ATV-PID method can lead to comparable performance as other more sophisticated such as PIR with a determinant advantage that ATV-PID only need a minimum of information concerning the system to be directly implemented on the field and have the ability to be recalibrated as often as necessary. The best results have been obtained with configuration using discharge (pump mode P) as control action variable and an upstream report of 80 % of the discharge. This option is not very realistic. The main issue is therefore how to get, with a real gate, the closest discharge to the one asked by the controller. The method Q offers a good alternative, inverting the gate equations and anticipating with water level fluctuations generated by the corresponding gate movement using a simple formula obtained from the method of characteristics. This option proved to provide good results close to the ones obtained with the P mode and with more sophisticated MIMO methods, when combined with a 80 % upstream report and a feedforward loop. This method is easy to implement, both on a simulation software for testing and validation, and also on SCADA or RTU units for field use. This therefore fits the objectives we were assigning to the control algorithms and strategy to tune them in the introduction section. It will always be possible in a second step to switch to more advanced methods, when the manager are already convinced by this first simple and performant enough approach. All the equipments (sensors, actuators, RTU, SCADA) used for this series of PI controllers will be able to support the implementation of any other method by just changing some source code lines in the SCADA software.

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