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COMPARISON OF TWO CONTROL ALGORITHMS BASED ON DIFFERENT CANAL MODELS USING NUMERICAL SIMULATION AND EXPERIMENTS ON A LABORATORY CANAL

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Automatic control is one way to improve irrigation canal management and to save water volumes during normal canal operation. In order to develop control algorithms for irrigation canals there is a need for internal linear models to be used in the algorithms. The following simple linear models are used to approximate the canal dynamics in order to give a base to develop control algorithms: Muskingum, Hayami and Integrator Delay Zero (IDZ). These models are calculated using the geometry of the canal – therefore no identification is needed. Two types of controllers are developed using the selected models: PI and predictive control. They are tested numerically and implemented in a laboratory canal.

INTRODUCTION

Irrigation is one of the biggest water consumers while its efficiency is generally very low, in case of traditional operation up to 40% of the irrigation water can be lost. The water is directed from the main sources (rivers, reservoirs) to the users by irrigation canals. In case of traditional operation the system is not flexible, the users have to schedule their needs days before the use. The goal of automatic canal operation is to deliver the right amount of irrigation water in the right time, allowing on demand operation of irrigation canals. This does not only make the users comfortable but also allow them to use the least amount of water, just in the time and amount as they need it. Also while discharges and water levels are regulated, construction and maintenance costs can be saved due to the less fluctuations of the water levels.

This paper presents different discharge controllers. In this case the task of the controller is to manipulate an upstream gate in order to achieve the demanded discharge downstream. This task is made difficult by the flow dynamics, in particular the time delay, the time it takes for the water to arrive from upstream to downstream. Therefore the controller needs the combination of a model to account for the behaviour of the flow and a feedback control strategy. In practice a simple model is preferred to approximate such dynamics to allow for an easy implementation using feedback information from sensors.

In this study we are going to test three different canal models: the Muskingum model, the Hayami model and the Integrator Delay Zero (IDZ) model.

THE CANAL MODELS

The Hayami model

The Hayami model is derived from the diffusive wave equation, a simplified form of the Saint-Venant equations. It can be identified with first or second order linear time invariant systems with the help of the moment matching method. [1]

The Muskingum model

Though the Muskingum model was initially developed for flood propagation it can be used in controller design. It contains two equations, a continuity equation and a storage equation having two parameters K and χ that contain all the information about the reach. K is the storage time constant (with the dimension of time) for a reach that can be well approximated by the travel time: this is the time it takes for one wave to travel through the reach. χ is a dimensionless coefficient weighting the relative effects of inflow and outflow on the reach storage. [2]

The Integrator Delay Zero model

The integrator delay (IDZ) model assumes that the canal consists of two parts: a backwater part and a transportation section with uniform flow. In the parts affected by backwater, a simple reservoir model is used, and the parts with uniform flow are approximated by the kinematic wave model. It is able to represent the canal behaviour in low and high frequencies; the integrator delay accounts for low frequencies, whereas the zero represents the direct influence of the discharge on the water level in high frequencies. [3]

THE CANALS USED TO TEST THE MODELS

The UPC-PAC canal

The laboratory canal is 220m long with a serpentine shape. It is 1 m deep, 0.44 m wide, and contains 3 motorized vertical sluice gates, 9 water levels sensors, 4 rectangular weirs and a supervisory control and data acquisition system. The canal has zero slope in order to achieve the largest possible time delay. The facility occupies 22.5m x 5.4m surface area and it is possible to be arranged as a SISO (Single Input/Single Output) or MIMO (Multiple Input/Multiple Output) system. In the MIMO configuration, the canal is represented by a series of reaches interconnected with gates. By setting two gates (Gate3 and Gate5) to a completely open position the canal can be configured as a 220m long one pool. In this case the offtakes through weirs represent the disturbances in the control system. (Figure 1)

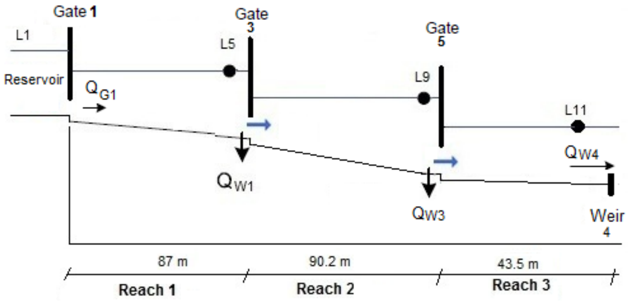

Figure 1. The UPC-PAC canal

During these tests the canal was configured as one pool, the control variable was the upstream discharge and the controlled variable was the downstream discharge. The gate movements were controlled by a secondary controller. The reference discharge used was 70 l/s. There is the constraint of a minimal gate movement (8mm); therefore the gate does not change its positions if the controller suggests the system to move less than this value. The discharge measurement errors are 2 l/s.

The Corning Canal

Corning canal is set to be a test canal for control algorithms by the Task Committee on Canal Automation Algorithms of the ASCE. The canal is a large and mild canal, with a slow response located in California. All gates are always submerged avoiding supercritical flow conditions. For this test the first pool of the Corning Canal is going to be used. The hydraulic and physical characteristics are summarized in Table 1. [4]

THE MODEL IDENTIFICATIONS

All the models were identified using the geometrical features of the canals. Hence, the design of the controllers do not need extensive measurement campaigns, they are simple to use even in case of lack of data.

Table 1. The geometry of the UPC-PAC and the Corning Canal

	n	b (m)	S_b	L (m)	S_m	$Q_r(m^3/s)$	Y_r (m)
UPC-PAC	0.016	0.44	0	220	0	0.07	0.647
Corning	0.02	7	0.0001	7000	1.5	11	2.1

where n is the manning coefficient, b is the channel width (m), S_b is the bottom slope (m/m), L is the length (m) of the canal pool, S_m is the side slope, Q_r is the reference discharge (m^3/s) and Y_r(m) is the reference depth (m).

The Hayami model

The Hayami model was calculated using the moment matching method [1] with some modifications. First the delay was calculated using formulas from [3] and one momentum was matched to calculate a first order model with delay. The transfer function of the Hayami model is the following:

$$G_H(s) = \frac{e^{-\tau s}}{1+K_1 s} \tag{1}$$

The Muskingum model

In case of the Muskingum model two parameters should be calculated, K and χ. K was calculated following Cunge[2], and χ was approximated knowing the nature of the canals. This parameter can change between 0.01 and 0.1 and it shows the influence of the downstream boundary conditions to the results – the lower the parameter the bigger the influence. In case of the UPC-PAC χ was chosen to be 0.01 since the canal has zero slope therefore the influence of the downstream boundary conditions is considerably big. In case of the Corning canal the parameter was chosen to be 0.1 since the canal is relatively short and deep. It is important to mention that the results have very small sensitivity to this parameter. The transfer function of the Muskingum model is:

$$G_m(s) = \frac{1-K\chi s}{1+K(1-\chi)s} \tag{2}$$

The Integrator Delay Zero model

The IDZ model was calculated using [3]. Since the model presented in the reference relates the water levels to discharges, the weir and gate formulas were used to calculate the discharge-discharge relationship. The transfer function of the IDZ model:

$$G_{IDZ}(s) = \frac{(ls+p)e^{-ms}}{ns+p} \tag{3}$$

The calculated parameters of the three models are shown in Table 2.

Table 2. The calculated parameters of the three models for both canals

Canal	τ	K_1	K	χ	p	l	n	m
UPC-PAC	-79.6	201.3	80	0.01	0.01199	1.15449	3.17492	79.48
Corning	-1562	1643	1562	0.1	0.00001165	0.00148	0.0892	1501

THE CONTROLLER DEVELOPMENT

In all cases the controlled variable is the downstream discharge and the control variable is the upstream discharge. The sampling time was 80s and 1500s in case of the predictive controller for the UPC-PAC and the Corning respectively. In case of the PI controller the sampling times were 10s and 180s respectively.

The predictive controller

The predictive control was formulated in an incremental manner so that the controller is able to reject the disturbances. The controllers were developed following [5]. The controller for the Muskingum model was published in [6].

The PI controller

The proportional integral (PI) and the proportional integral derivative (PID) controller still remain to be the most extensive option that can be found on industrial control applications. The PI controller in the Laplace domain has the transfer function

$$G_c = K_p\left(1 + \frac{1}{T_i s}\right) \tag{4}$$

where K_p is the proportional gain and T_i is the integral time.

In this paper, a PI controller is designed specifically for each model. All of them are tuned using the Astrom-Hagglum method in the frequency domain. The specification of 45-degree phase margin and 10dB of gain margin is the guideline. This value yields a response that is critically damped and has the best compromise of response and settling time.

Table 3. The test for UPC-PAC

Simulation time (s)	Setpoint (l/s)	Weir1 height (cm)	Weir3 height (cm)
0	60	90	90
1000	80	90	90
3000	100	90	90
5000	70	90	90
6500	70	90	55
0	70	90	90
500	70	90	55
2000	70	90	90
3500	70	55	90
5000	70	90	90

Table 4. The test for the Corning

Simulation time (h)	Setpoint (m^3/s)	Offtake (m^3/s)
0	11	0
12	12	0
24	13.5	0
36	9	0
48	11	0
0	11	0
12	11	2
24	11	0

Description of the tests

Two different tests were carried out: test 1 (first 5 rows of Table 3 and 4) is measuring the ability of the controller to follow the setpoint, while test 2 (last rows of Table 3 and 4) is measuring the response to the unknown disturbances, that are in this case offtakes of water.

The two tests were carried out on the UPC-PAC and on the Corning Canal. (In case of the UPC-PAC not only simulation, but also laboratory tests were carried out.) Altogether these are 4 tests. There are 6 controllers developed (however some of them proved to be unacceptable): predictive controller based on the Muskingum model (MUS-PR), predictive controller based on the Hayami model (HAY-PR), predictive controller based on the IDZ model (IDZ-PR), PI controller based on the Muskingum model (MUS-PI), PI controller tuned using the Hayami model (HAY-PI), PI controller based on the IDZ (IDZ-PI). The tests are described in Tables 3 and 4. The performances are compared using the plots and the following two performance indices (Table 6). The first one is the maximum absolute error:

$$MAE = \frac{\max \left| q_t - q_{sp} \right|}{q_t} \tag{5}$$

where q_t is the discharge at any time t, and q_{sp} is the setpoint. The second index is the integral of the absolute error (IAE):

$$IAE = \frac{\frac{\Delta t}{T} \sum_{t=0}^{T} \left| q_t - q_{sp} \right|}{q_{sp}} \tag{6}$$

where Δt is the measurement time step and T is the examined time period. The simulations were carried out using the 1D hydrodynamic software Simulation of Irrigation Canals (SIC) developed by Cemagref [7].

TEST RESULTS

Test in the laboratory canal

There have been 6 discharge-discharge controllers developed for the canal. Six simulations were carried out, but only 3 successful laboratory tests: the three other controllers showed unacceptable performance in the laboratory (MUS-PI, HAY-PI, HAY-PR). The explanation of this behaviour is that most of the controllers were destabilized by the physical canal constraints: the minimal gate movements, and the measurement errors. It is interesting to note that while the controllers based on Hayami model showed good results in simulations, they got unstable in practice.

The controllers IDZ-PI, IDZ-PR and MUS-PR were able to control the canal. In all these three cases the setpoints were reached within the range of the measurement error. All the three controllers are able to respond to unknown disturbances, tested as offtakes at two different locations. Only the controller based on the Muskingum model has under/overshoot, it is important in case of decreasing setpoint, because the new setpoint is reached by means of an undershoot and in this way more water volume can be saved.

Table 5. Test on the UPC-PAC (in brackets the prediction horizon)

	Following the setpoint		Reaction to perturbations	
	MAE	IAE	MAE	IAE
IDZ-PI	33.9	4.3	21.6	4.4
IDZ-PR(6)	31.0	5.3	17.3	3.1
MUS-PR(9)	32.9	7.1	20.1	6.9

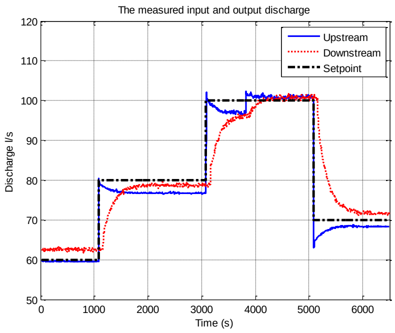

Figure 2. UPC-PAC-IDZ-PR, Test1

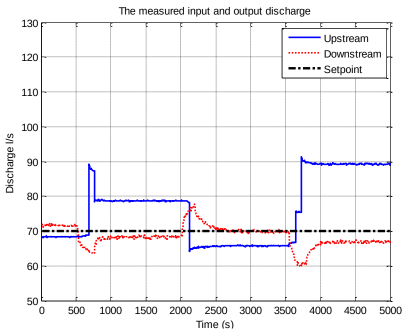

Figure 3. UPC-PAC-IDZ-PR, Test2

Tests in the Corning Canal

In the case of the Corning canal, all predictive controllers are able to control the canal, however the PI controllers based on the Muskingum model presented oscillatory behaviour. All controllers make the downstream discharge arrive to the setpoint in some hours. The performance of the PI and the predictive controllers are comparable. All the controllers reach the setpoint within 8 hours and they respond the disturbances within 5 hours. In case of the controllers based on the Hayami model, the setpoint is reached through under/overshoot that results in case of decreasing setpoint saving of water volumes.

Table 6. Tests in the Corning Canal (in brackets the prediction horizon)

	Following the setpoint		Reaction to perturbations	
	MAE	IAE	MAE	IAE
COR-HAY-PR(7)	33.4	3.2	15.3	2.0
COR-IDZ-PR(4)	33.4	3.6	17.5	1.8
COR-MUS-PR(4)	33.4	3.7	15.2	2.2
COR-HAY-PI	33.2	3.2	13.2	2.9
COR-IDZ-PI	34.0	3.1	13.1	0.8
COR-MUS-PI	-	-	-	-

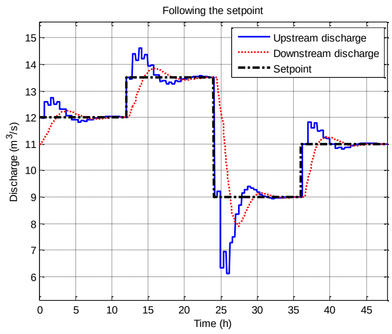

Figure 4 COR-HAY-PR, Test1

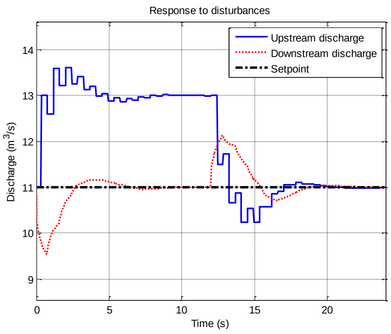

Figure 5 COR-HAY-PR, Test2

CONCLUSION

The predictive as well as the PI controllers showed a satisfactory performance. The controllers showed slightly different behaviours depending of the internal model. These simple models were able to drive predictive controllers and give a base for PI controller tuning.

Acknowledgments

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