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LPV Modelling and Identification of an Open-flow Canal for Control

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Abstract— **Open-flow canals are large distributed systems characterized by non-linear, time-varying and dependent with the operating point behavior. These systems can be suitably represented for control by linear parameter varying (LPV) models. In this paper, two ways of obtaining an LPV model for a single reach open canal are proposed and compared: an LPV integrator delay zero (IDZ) model based on hydraulic laws and an LPV model based on identification techniques. The first approach is a white-box modeling approach while the latter is a grey-box methodology using experimental data. Finally, they will be applied and compared in a test-bench canal.**

I. INTRODUCTION

The design of control systems is currently driven by a large number of requirements posed by increasing competition, environmental requirements, energy and material costs and the demand for robust, fault-tolerant systems. These considerations introduce extra needs for effective process modelling techniques. Many systems are not amenable to conventional modelling approaches due to the lack of precise, formal knowledge about the system, due to strongly non-linear behaviour, high degree of uncertainty, dependence of the parameters with the operating point, time varying characteristics, etc .

Open-flow canals are large distributed parameter systems described by Saint-Venant's partial-differential equations [1]. So far mainly linear time-invariant (LTI) models have been considered for control neglecting their non-linear behaviour and the dependence of the parameters with the operating point. This is the case of Hayami model [2], Muskingum model [3], integrator delay zero (IDZ) model [4] or black-box models identified using parameter estimation [5]. However, when operating in large operating conditions using this type of models, influence on the operating point in parameters is neglected. In order to consider such variations linear-parameter varying (LPV) or quasi-LPV models can be used. They are based on a linear lumped parameter in which the parameters are not constant but a function of external parameters or of system states and/or the operating point [6].

There are two possible forms to obtain an LPV model:

1) Physical modelling. The model is obtained by physical laws taking into account that the model parameters vary according the system states, the operating conditions and/or external factors.

2) Identification. In this case, one-shot LPV identification algorithm can be used as was proposed in [7].

The aim of this paper is to propose these two methodologies for obtaining an LPV canal control model based on the IDZ model proposed by [4]. This is nowadays a quite accepted model in the canal control community that has been rigorously derived by approximating the Saint-Venant's equations around a given operating point. First, an LPV IDZ model obtained through physical modelling is obtained. Then, an LPV identification is carried out using also an IDZ model structure for the canal plant. Both approaches are compared and tested using a test bench canal.

The paper is organised as follows. In Section II, a test-bench canal used to compare the two modelling approaches is presented. In Section III, a physical LPV model based on the IDZ model is introduced. In Section IV, LPV identification is carried out using the IDZ model structure. In Section V, the two previous modelling/identification approaches are compared and validated on the test-bench canal. Finally, the main conclusions are given in Section VI.

II. TEST-BENCH CANAL DESCRIPTION

A single pool equipped with an upstream sluice gate and a downstream spillway composes the test bench canal used in this paper (Figure 1). An electromotor is driving the gate position and two sensors located upstream and downstream of the gate are measuring the levels. Upstream of this gate there is a dam. The total length of the pool is L=2km, a gate discharge coefficient C_{dg}= 0.6, a Manning roughness coefficient n=0.014, gate width b = 2.5m and canal width B=2.5m, a downstream spillway of height y_s = 0.7m with a spillway coefficient C_{ds}= 2.66, and a bottom slope I_0= 5.10^{-4}.

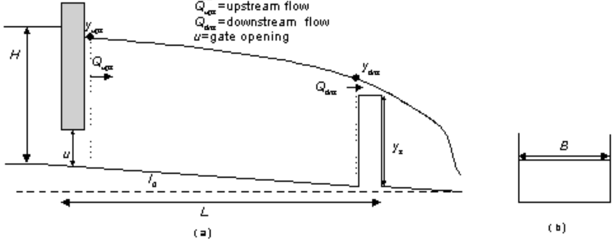

Figure 1. Canal scheme.(a) Longitudinal and (b) cross section.

In this paper, the "real" canal behavior is accurately reproduced by a simulator developed in [8]. This simulator solves numerically Saint-Venant's equations [1], which describes the dynamics of this test-bench canal by the conservation of mass and momentum principles in a one-dimensional free surface flow. This pair of partial-

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differential equations constitutes a non-linear and hyperbolic system that for an arbitrary geometry lacks of analytical solution. It has to be solved numerically and therefore the simulations are time-consuming for on-line applications.

III. LPV IDZ MODEL DERIVATION

A. *LPV IDZ model derivation*

The complete dynamics of the single-pool irrigation canal presented in Figure 1 is classically modeled with the Saint-Venant Equations. However, as discussed in Section I, for control purposes let us consider the IDZ model proposed in [4]. According to this modelling approach, the single reach canal reach dynamics (relation between downstream level, y_{dns}, and downstream flow, q_{dns}, and upstream flow, q_{ups}) for low frequencies can be approximated by

$$y_{dns}(s) = P_1(s)q_{ups}(s) + P_2(s)q_{dns}(s) \tag{1}$$

where: $P_1(s) = \dfrac{e^{-\tau_d s}}{A_d s}$ and $P_2(s) = \dfrac{-1}{A_d s}$ with τ_d is the downstream transport delay and A_d is the downstream backwater area, both depending on the operating point. Additionally, a linearised relation is assumed between the upstream flow q_{ups} and the opening gate u :

$$q_{ups}(s) = \varphi u(s) \tag{2}$$

where φ is a constant that also varies with the operating point. Finally, taking into account the linearised relation between the downstream flow q_{dns} and level y_{dns} in the spillway, the following relation can be established

$$q_{dns}(s) = \lambda\, y_{dns}(s) \tag{3}$$

where λ is a constant that varies with the operating point too.

Combining equations Eqs.(1)-(3), the following first order plus time delay (FOPDT) model can be obtained

$$\begin{aligned} y_{dns}(s) = G(s)u(s) = \frac{P_1(s)}{(1 - \lambda P_2(s))}u(s) = \\ \frac{e^{-\tau_d s}}{(A_d s + \lambda)}u(s) = \frac{k}{(Ts+1)}e^{-\tau_d s}u(s) \end{aligned} \tag{4}$$

at each operating point with a gain $k = \dfrac{\varphi}{\lambda}$ and a time constant $T = \dfrac{A_d}{\lambda}$. This result is in agreement with some previous works where a first order plus time delay model has been proposed without assuming a IDZ model as a starting point [9].

Besides, for a canal in uniform flow, the downstream time delay τ_d is equal to $L/(v+c)$ where L is the length of the pool, v is the water velocity and c is the celerity. The relation among the upstream gate level (y_{ups}), the upstream pool flow (q_{ups}) and the downstream pool flow (q_{dns}) is the following:

$$y_{ups}(s) = P_3(s)q_{ups}(s) + P_4(s)q_{dns}(s) \tag{5}$$

where: $P_3(s) = \dfrac{1}{A_u s}$ and $P_4(s) = \dfrac{-e^{-\tau_u s}}{A_u s}$ with τ_u being the upstream transport delay and A_u the upstream backwater area. According to [4], the theoretical value of the upstream time delay is evaluated by computing the integral:

$$\tau_d = \int_0^L \frac{dx}{v(x) + c(x)} \tag{6}$$

This corresponds to the minimum time required for a perturbation to travel from upstream to the downstream of the pool. Analogously, the upstream time delay τ_u can be evaluated by

$$\tau_u = \int_0^L \frac{dx}{c(x) - v(x)} \tag{7}$$

and corresponds to the maximum time required for a perturbation to travel from upstream to downstream of the pool. In both cases, we recover the classical value in the uniform case when v and c are constant: $\tau_d = L/(v+c)$ and $\tau_u = L/(c-v)$. In the uniform case, the coefficient A_d of the $P_1(s)$ and $P_2(s)$ transfer functions reflects the way in which the downstream water level varies when the upstream and downstream discharge varies. It can be evaluated by computing the variation of the volume of the pool V_{pool} with respect to the downstream water elevation:

$$A_d = \frac{\partial V_{pool}}{\partial y_{dns}} \tag{8}$$

It is clear, then, that this coefficient depends on the way the volume changes, which is difficult to account for in a simple way [4].

Taking into account that the operating point can be characterized by the gate opening u, model (4) can be seen as a FOPDT LPV model [9][1]:

$$y_{dns}(s,\theta) = G(s,\theta)u(s) = \frac{k(\theta)}{(T(\theta)s+1)}e^{-\tau_d(\theta)s}u(s) \tag{9}$$

where the scheduling variable is taken as the gate opening, that is in the following $\theta = u$. Similar result could be obtained by using as scheduling variable the downstream level. Model (9) can be used to design a controller that considers the canal dynamics for the whole set of operating points.

The FOPDT LPV behavior (9) is in agreement with what can be observed from step responses obtained by

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[1] In the following, for simplicity and with abuse of notation, transfer functions are used for LPV systems, although computations are performed entirely in the time domain using the state space representation.

simulations at each operating point over the test canal [10], as it can be seen in Figure 2.

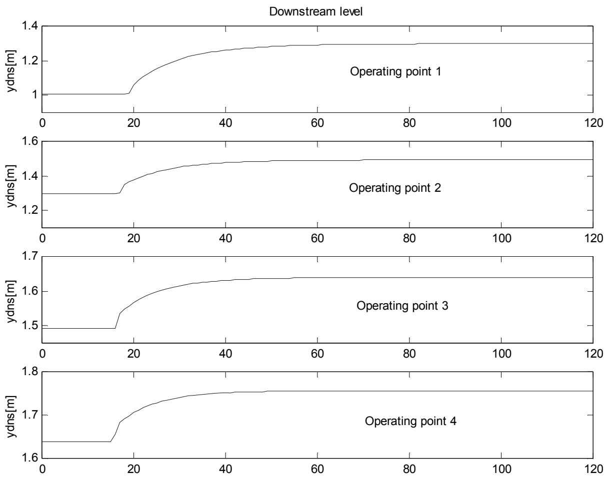


Figure 2. Step time responses for the four operating points: 1 (θ from 0.1 to 0.3m), 2 (θ from 0.3 to 0.5m), 3 (θ from 0.5 to 0.7m) and 4 (θ from 0.7 to 0.9m).

Next, it is discussed how LPV parameters (k, $\tau_d(\theta)$, $T(\theta)$) can be expressed in terms of the operating point θ from physical reasoning and experiments.

The dependency of the steady state gain k with the operating point θ considering

$$k(\theta) = \frac{dy_{dns}}{du} \tag{10}$$

in steady state is described in [9]. Using the LTI IDZ model [4] Eq. (2)-(3), Eq. (10) and taking into account that the factor $\lambda(\theta)$ as well as the factor $\varphi(\theta)$ vary with the operating point θ, the following constant gain for the LPV model is obtained:

$$k(\theta) = \frac{\Delta q_{dns} / \lambda}{\Delta q_{ups} / \phi} = \frac{\phi}{\lambda} \tag{11}$$

On the other hand, the delay $\tau_d(\theta)$ associated to the model (9) can be derived by physical laws $\tau_d = \dfrac{L}{v+c}$, that is equivalent to $\tau_d(\theta) = \dfrac{k_1}{(1+k_2\theta)}$.

where k_1 and k_2 are functions of the operating point (θ) and the geometry of the canal, see [10].

Finally the time constant $T(\theta)$ according to the physical relation with the delay can be approximated as was proposed in [10] as

$$T(\theta) \approx \kappa \tau_d(\theta) \tag{12}$$

where κ is an empirical constant that depends on the canal geometry.

In the same way as in [4], considering that the test-bench canal is rectangular and assuming that this pool is small, the downstream area of the pool is assumed as a storage area. That is, $A_d = k_d BL$ where B is the canal width, L is the canal length and k_d is a constant that takes into account only the downstream area ($0 < k_d < 1$), see Figure 3. Then, using the linear approximation (3), the time constant $T = \dfrac{A_d}{\lambda}$ (see Eq. (4)) can be approximated by $T \approx \dfrac{k_d BL}{q_{dns} / y_{dns}}$. Furthermore, considering $q_{dns} = vA_w$ where A_w is the wet area at the end of the pool that is given by $A_w = By_{dns}$, the time constant can be expressed as follows

$$T = \frac{k_d BL}{vA_w / y_{dns}} = \frac{k_d BL}{vBy_{dns} / y_{dns}} = k_d \frac{L}{v} \tag{13}$$

This time constant is an LPV parameter because depends on the operating point θ: $T(\theta) \approx k_d \dfrac{L}{v(\theta)}$. In the test-bench canal the time constant that comes from the IDZ model is showed in Figure 3.

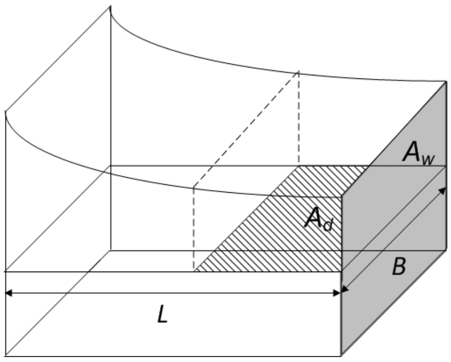


Figure 3. Downstream and wet areas of a small pool or a pool with very small slope.

Then, expression (13) is equivalent to (12) where

$$k_d = \kappa \frac{v}{v+c} \tag{14}$$

B. Discretization of the LPV IDZ model

To allow comparing the LPV IDZ model derived above with the LPV model obtained using the identification approach presented in next section, the LPV IDZ model is discretised by ZOH transform and a sampling time T_s (in case of the test-bench canal, equal to 1 min since canal constant time T is 10min). Then, the following discrete-time LPV model is obtained [10]

$$G_{LPV}(z,\theta)=\frac{\Delta y(z,\theta)}{\Delta u(z,\theta)}=\frac{b_0(\theta)z^{-1}}{(1-a_1(\theta)z^{-1})}z^{-d(\theta)} \qquad (14)$$

where

$$a_1(\theta)=e^{\frac{-T_s}{T(\theta)}},b_0(\theta)=k(\theta)(1-a_1(\theta)),d(\theta)=round\left(\frac{\tau(\theta)}{T_s}\right) \qquad (15)$$

Additionaly, to facilitate the comparative study with the model obtained with LPV identification approach, the discrete LPV parameters are appropiately approximated by second order polynomial using truncated Taylor series approximation. Then, the approximated LPV parameters are

$$\begin{aligned} a_1(\theta) &= e^{\frac{-T_s}{T(\theta)}} = e^{\frac{-T_s(1+k_2\theta)}{1.45k_1}} \\ &\underset{e^{-x}\approx 1-x+\frac{x^2}{2}}{\approx} 1-\left(\frac{T_s(1+k_2\theta)}{1.45k_1}\right)+\frac{1}{2}\left(\frac{T_s(1+k_2\theta)}{1.45k_1}\right)^2 \qquad (16) \\ &= a_{13}\theta^2+a_{12}\theta+a_{11} \end{aligned}$$

where

$$\begin{aligned} a_{11} &= \left(1-\frac{T_s}{k_{1m}}+\frac{1}{2}\left(\frac{T_s}{k_{1m}}\right)^2-\frac{1}{6}\left(\frac{T_s}{k_{1m}}\right)^3\right) \\ a_{12} &= \left(-T_s\frac{k_{2m}}{k_{1m}}+k_{2m}\left(\frac{T_s}{k_{1m}}\right)^2-\frac{k_{2m}}{2}\left(\frac{T_s}{k_{1m}}\right)^3\right) \\ a_{13} &= \left(\frac{k_{2m}}{2}\left(\frac{T_s}{k_{1m}}\right)^2-\frac{k_{2m}^2}{2}\left(\frac{T_s}{k_{1m}}\right)^3\right) \qquad (17) \end{aligned}$$

with $k_{1m}=\frac{\sum_{l=1}^{j}k_1(\theta)_l}{j}$ and $k_{2m}=\frac{\sum_{l=1}^{j}k_2(\theta)_l}{j}$, l is the operating point.

As the gain of the LPV physical model can be approximated by a linear equation that depends on the operating point θ, Eq. (15) for the a_1 parameter, b_0 parameter can also be approximated by second order polynomial according to

$$b_0(\theta)=k(\theta)(1-a_1(\theta))\approx b_{03}(\theta)^2+b_{02}\theta+b_{01} \qquad (18)$$

Finally, the delay can be approximated by

$$\begin{aligned} \tau(\theta) &= \frac{k_1}{(1+k_2\theta)} = k_1-k_1k_2\theta-k_1k_2^2\theta^2-k_1k_2^3\theta^3 \\ &+\frac{k_1k_2^4\theta^4}{(1+k_2u)} \approx k_1-k_1k_2\theta-k_1k_2^2\theta^2 \qquad (19) \\ &= \tau_{13}\theta^2+\tau_{12}\theta+\tau_{11} \end{aligned}$$

what allows to obtaing the discrete-time delay as

$$d(\theta)=\text{round}\left[\frac{\tau(\theta)}{T_s}\right]=\text{round}\left[\frac{\left(\tau_{13}\theta^2+\tau_{12}\theta+\tau_{11}\right)}{T_s}\right] \qquad (20)$$

In the case of the test-bench canal, the relative error between the parameter values given by physical expressions and their second order polynomial approximations can be determined. By considering that $\theta\in[0.1,0.9]$ m and selecting j equally spaced operating points, the relative error is given by

$$error(\%)=abs\left(\frac{\sum_{l=1}^{j}(p(l)-\hat{p}(l))}{\sum_{l=1}^{j}(p(l))}\right)\times 100 \qquad (21)$$

where p is the parameter given by physical expression and $\hat{p}$ is given by the polynomial approximation. Applying such formula to parameters a_1, b_0 and d, the relative error is 0.7358%, 4.1221% and 4.563%, respectively. This proves the “goodness” of these approximations.

IV. LPV IDZ MODEL IDENTIFICATION

A. *LPV IDZ model identification*

The input signal used to calibrate and validate the LPV model (see Eq. (9)) has been a set of steps that sweeps all the operating points (gate opening from 0.1 to 0.9 m). The structure of the LPV model used for the identification is given by

$$G_{LPV}(q^{-1},\theta)=\frac{y(k)}{u(k)}=\frac{b_0(\theta)q^{-1}}{(1-a_1(\theta)q^{-1})}q^{-d(\theta)} \qquad (22)$$

where:

$$\begin{aligned} a_1(u) &= a_{11}+a_{12}u+a_{13}u^2 \\ b_0(\theta) &= b_{01}+b_{02}\theta+b_{03}\theta^2 \end{aligned}$$

according to Eq. (14) and (16)-(18).

The discrete-time delay is identified following the procedure presented in the following section. Once the delay has been identified, it is removed from the input/output data in order to estimate parameters a_{1j} and b_{0j}.

The parameter of the LPV model (22) have been estimated applying the Least Mean Square (LMS) algorithm extended to LPV models proposed in [7]. The resulting values are shown in Table 1.

TABLE I. ESTIMATED PARAMETERS BY LPV IDENTIFICATION

	1	θ	θ^2
a_1	-0.9257	0.0878	-0.0429
b_0	0.1200	-0.0500	-0.0079

B. LPV IDZ delay identification

The delay of the test-bench canal in case of the LPV physical model has been derived, as it was proposed in [9], using physical modeling (see Section III.A). On the other hand, in case of the identification based LPV model, the delay is estimated by classical correlation method that is based on the impulse response with regard to the gate movement [11]. Considering that the input signal is a white noise and carrying out the study of the independence between the input and output process signals, an interval for the delay is estimated using confidence intervals (usually, 99% or 95%) [12].

Since the delay depends on the operating point, it should be estimated in some points in order to characterize its dependence. In the test-bench canal, the delay is estimated around different operating points (gate opening in the range 0.1 to 0.9 m). Figure 4 is obtained by the interpolation of the obtained estimated delays over every operating point using second order polynomial suggested by Eq. (19-20). In this figure, the delay obtained using physical modeling is compared with the one obtained using the identification procedure proposed in this section and with the one experimentally measured as described in Section III.

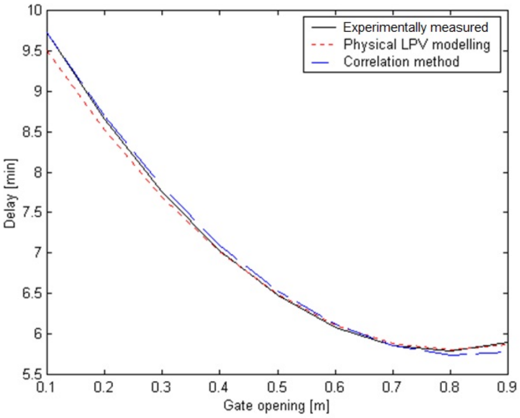


Figure 4. Experimentally measured delay vs. estimated LPV delay (by physical modelling and correlation method).

V. COMPARISON AND VALIDATION OF DIFFERENT APPROACHES

In this section, the different proposed LPV discrete-time models obtained by the two approaches considered in the previous sections are tested and validated by comparing the experimentally measured parameters of the system and the estimated parameters using identification techniques.

An LPV model obtained by identification establishes a non-linear global relation between the past inputs and outputs and the predicted output of the following way [13]:

$$y(k) = F(y(k-1),\ldots,y(k-n_a),u(k-1-d),\ldots,u(k-1-n_b-d)) \quad (23)$$

In case of an LPV FOPDT structure given in Eq. (22) model (23) is particularised as

$$y(k) = a_1(\theta)y(k-1) + b_0(\theta)u(k-d(\theta)) \quad (24)$$

An approximation of model Eq. (23) around a generic equilibrium state corresponding to a given operating point ($F(y_{0j},\ u_{0j}\,,\ p_j)=0$) with local validity can be obtained by input/output linearization

$$\dot{y} = y_{0j} + \left.\frac{\partial F}{\partial y}\right|_{y_{0j},u_{0j},p_j}(y-y_{0j}) + \left.\frac{\partial F}{\partial u}\right|_{y_{0j},u_{0j},p_j}(u-u_{0j}) =$$

$$y_{0j} + \boldsymbol{A}_j(y-y_{0j}) + \boldsymbol{B}_j(u-u_{\boldsymbol{0j}}) \quad (25)$$

In case of the global model (23) has the form (24), the incremental local model can be obtained applying (25) and yielding

$$\Delta y(k) = a_1^*(\theta)\Delta y(k-1) + b_0^*(\theta)\Delta u(k-d(\theta))$$

where: $a_1^*(\theta) = a_1(\theta)$, $b_0^*(\theta) = b_0(\theta) + \frac{\partial b_0(\theta)}{\partial \theta}\theta$. This establishes a relation between global and local incremental models that will allow comparing the obtained LPV models.

In particular, considering that $a_1(\theta) = a_{12}\theta^2 + a_{11}\theta + a_{10}$ and $b_0(\theta) = b_{02}\theta^2 + b_{01}\theta + b_{00}$, then

$$b_0^*(\theta) = 3b_{02}\theta^2 + 2b_{01}\theta + b_{00} \approx 2b_{01}\theta + b_{00} \quad (26)$$

because the term b_{02} can be neglected (see Table 2).

TABLE II. ESTIMATED AND PHYSICAL MODELLING PARAMETERS OF THE LPV MODEL

	1	θ	θ^2
Estimated parameters			
a_1	-0.9489	0.1216	-0.0453
b_0	0.1282	-0.1161	0.0527
Physical modelling parameters			
	1	θ	θ^2
a_1	-0.9469	0.1510	-0.0809
b_0	0.1363	-0.1100	0.0387

The correctness of two obtained LPV models is evaluated by error functions between the experimentally measured and estimated values of the parameters $a_1(\theta)$, $b_0(\theta)$ and $d(\theta)$ at each operating point. In Figure 5, it can be observed that the error between the experimentally measured and estimated parameters is small for the two models since a low error (see Eq. (21)) for all the parameters is achieved. This relative error for the delay d is of 2.9781% and 3.0653%, in the cases of physical modeling and correlation method, respectively. For the parameter a_1, it is approximately of 0.9531%, and 0.5671%, for the case of LPV identification and physical modeling, respectively. For the parameter b_0 it is of 7.4761% and 9.2219%, respectively.

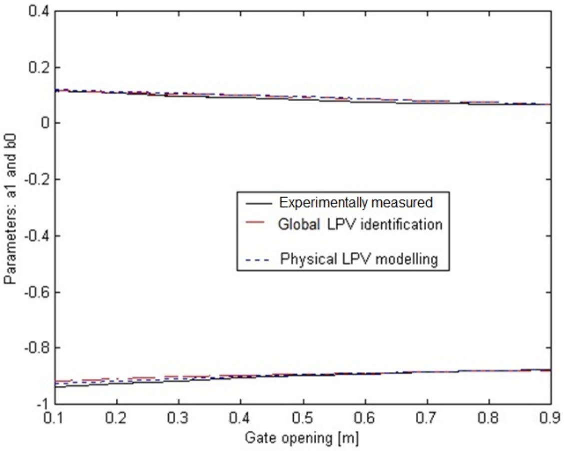
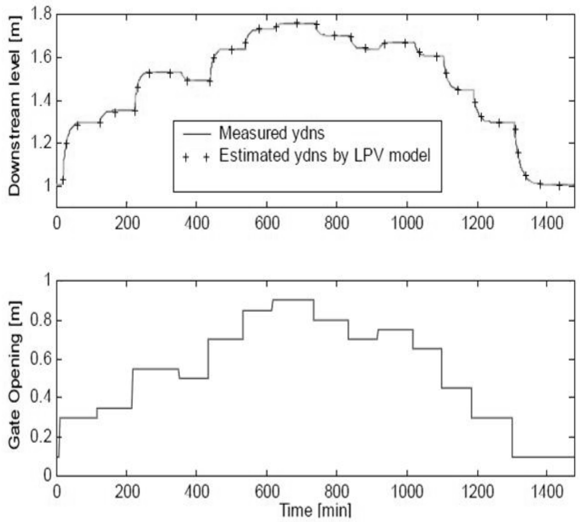


Figure 5. Estimated parameters (a_1 and b_0) by the three approaches vs. experimentally measured parameters.

Figure 6 shows the comparison between the measured and estimated temporal canal response by the proposed LPV model in a scenario that sweeps all the operation range. As it can be noticed, the estimated and measured level evolution are very similar. The Mean Square Error (MSE) is of the order of 10^{-6}.



(down)

Figure 6. Comparison between the measured and estimated rich temporal responses.

VI. CONCLUSIONS

Because open flow canals are systems whose parameters depend on the operating point when approximated by an LTI model for control purposes, it is convinient to catch such dependence using an LPV model. In this paper, this type of model is obtained for a test-bench canal using two approaches: LPV physical modeling and LPV identification. An LPV IDZ model has been proposed based on the physical model. In this case, hydraulic laws allow deriving the parameters dependence with operating point. Such dependence has been obtained for a particular test-bench canal, but for a general canal such dependence is hard to obtain. On the other hand, using LPV identification, an LPV model has been obtained without using the hydraulic knowledge but only selecting the structure and the parameter dependence with the operating point obtained from the LPV physical model. This aspect is especially important using LPV identification because of the functions that describe the parameter dependence with the operating point should be provided at the beginning of the identification process. In particular, in this paper these functions are assumed second order polynomials that only can be supported with the knowledge of the physical LPV model. The LPV one-shot identification has the advantage that in one shot the parameters of the model can be estimated without requiring regime decomposition, and implies that the transition of the parameters of the models can be abrupt.

The two obtained LPV models are tested and compared, obtaining in all the cases satisfactory results. Moreover, it is also concluded that the models are consistent when comparing parameter values and temporal responses.

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