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System identification for control of a main irrigation canal pool

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Abstract: In this paper, a system identification for control procedure of a main irrigation canal pool characterized by exhibiting large variations in their dynamical parameters when it discharge regimes change is developed. This procedure delivers not only a nominal model, but also a reliable estimate of the canal pool parametric uncertainty associated with the model. The complete identification for control procedure from experiment design to model validation taking into account prior physical information is presented. It is shown that a linear second order model with an ARMAX structure and a time delay describes adequately the main nominal dynamical behavior of this canal pool. Application of system identification for control in control system design of water distribution in main irrigation canal pools responds to the current necessity of introducing more effective and robust control systems.

1. INTRODUCTION

In spite of the important and recognized role of automatic control in the increase of irrigation systems efficiency over the last decade, only a limited number of main irrigation canals have been really automated (Litrico and Fromion, 2006). This is due to the fact that the design of a control strategy leading to a practical and effective controller of water distribution in main irrigation canals is a difficult task because these systems are distributed over long distances, with dynamic behaviour characterized by important varying time delays, strong nonlinearities, numerous interactions between different consecutive sub-systems and the existence of others hydraulic parameters that change over time during their exploitations (Malaterre, 1995; Weyer, 2001).

A large portion of the effort devoted to design control systems for irrigation canals is related with obtaining their mathematical models. One of the most accepted and used models for simulation of the physical dynamics of a real main irrigation canal pool is the system described by the Saint-Venant equations. This is because of its capacity to represent the characteristics of real interest. However this model is based on nonlinear hyperbolic partial differential equations, which have analytical solution only in very special cases, requiring the use of numerical methods to solve it properly (Euren and Weyer, 2007; Rivas Perez, 1990). For this reason linearizations and simplifications of the Saint-Venant equations are recurrently studied by the irrigation control research community (Schuurmans, 1997; Rivas Perez et al., 2003; Weyer, 2001).

Recently system identification methods are being successfully applied to obtain linear models of main irrigation canal pools (Litrico, 2001; Rivas Perez, Feliu Batlle and Sanchez Rodriguez, 2007, Weyer, 2001). This class of models is usually sufficient to capture the main dynamic properties of a canal pool for control design. Indeed, these models do not necessary have a physical meaning, they only focus on accurate reproduction of the real irrigation canal pool dynamic behaviour.

Experiments developed by some authors confirm that main irrigation canal pools may exhibit large variations in their dynamical parameters when the discharge regimes change in the operation range $(Q_{\min}, Q_{\max})$ and/or other hydraulic parameters change, e.g. the friction coefficient, the pool geometry, the downstream water elevation, etc. (Feliu Batlle, Rivas Perez and Sanchez Rodriguez, 2007; Litrico and Fromion, 2006). Then any mathematical model to be obtained for this class of main irrigation canal pools has to take accounts these parameter variations. Consequently, the control system methods are usually based on a nominal model, while the parameters of the main irrigation canal pool model vary with the change of hydraulic conditions, originating a set of models (model uncertainties). It is well known that the ultimate goal of a controller for a main irrigation canal pool is to function under different hydraulic conditions guaranteeing a minimum level of time-domain performance (Litrico, Fromion and Baume, 2006). This is the robust performance design problem.

Identification for control is an area which has received a renewed interest since the beginning of the 1990s and still attracts a growing number of researchers (Garulli, Tesi and Vicino, 1999; Jansson, 2004; Reinelt, Garulli and Ljung, 2002). One of the main objectives of this research area is to estimate models that are suitable for robust control design techniques (Garulli, Tesi and Vicino, 1999). To this purpose, the identification procedure must determine not only a nominal model, but also a reliable estimate of the uncertainty associated to the model, i.e. a set of models to be considered in the control system design process.

Different mathematical models of main irrigation canal pools have been proposed in the literature. Some of them have been obtained in the time domain by applying specific system identification techniques (Euren and Weyer, 2007; Rivas Perez, Feliu Batlle and Sanchez Rodriguez, 2007; Weyer, 2001). These models present the drawbacks that they cannot be applied in robust control system design for main irrigation canal pools, because they do not have a reliable estimate of the model uncertainties originated when the canal pool is operating under different hydraulic conditions. Considering that for robust control system design it is very important to have not only a nominal model of the irrigation canal pool but also a reliable estimate of model uncertainties, in this paper a complete system identification for control procedure of a main irrigation canal pool is developed.

The paper is organized as follow. In Section 2 a brief presentation of Aragon's Imperial Main Canal (AIMC) is offered. The results of the experiment design and nonparametric identification of such canal are presented in Section 3. Section 4 is devoted to the model structure selection and parameters estimation. The model validation procedure is developed in Section 5. A discussion and conclusions are presented in the last section.

2. THE ARAGON'S IMPERIAL MAIN CANAL

The Aragon's Imperial Main Canal belongs to the Ebro Hydrographical Confederation. This canal gets its water diverted from the Ebro river. The water passes through the known as Casa de Compuertas (House of Gates) that controls the 30 m^3/s of discharge in the origin, although sometimes this value can be superior as a result of a high flow in the Ebro river. It has a length of 108.0 Km, a variable depth between 3.0 and 4.0 m., a trapezoidal cross section and 10 pools of different lengths separated by undershoot flow gates.

Different pools of this canal are characterized by large time varying parameters when the discharge regimes change in the operation range $(Q_{\min}, Q_{\max})$. For this reason, the installed simple PI controllers do not guarantee an effective control of water distribution, existing large water losses. In order to improve the operation and management of the whole canal and minimize the existing water losses, the implementation of a robust integral control system of water distribution has been considered. Therefore a first step in this study is obtaining simplified mathematical models of the canal pools that must describe accurately their dominant dynamic behaviors, and facilitate the ulterior robust control system design. This paper deals with the identification for control of the dynamics of only the first canal pool.

3. EXPERIMENT DESIGN AND NONPARAMETRIC IDENTIFICATION

The data and results reported in this paper are from the first pool of the Aragon's Imperial Main Canal, which is known as the Bocal and has a complex hydraulic infrastructure. It is a cross structure canal pool of 8.0 km. long, a variable depth between 3.7 and 3.1 m., a variable width between 15.0 m. and 30.0 m., and 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 (Kovalenko, 1983; Malaterre, 1995). The downstream end water level is controlled by means of 10 undershoot gates located in the House of Gates on the side of the canal. The available measurements are the upstream (Ebro river) and downstream end water levels and the gates positions, which are given in cm. Fig. 1 shows an equivalent diagram of the Bocal, in which the 10 control gates, are represented by means of an equivalent gate.

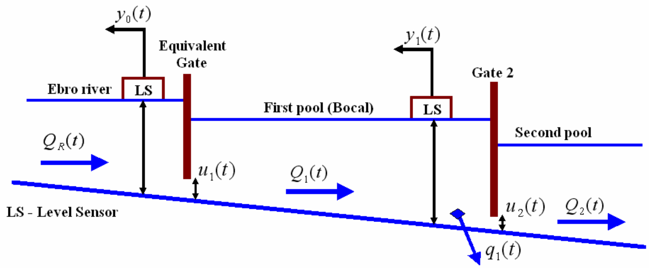

Fig.1. Equivalent diagram of the main canal pool "Bocal".

Considering that the downstream end water level is the controlled variable and the upstream gates positions (gates openings) are the manipulated variables, a mathematical model for control will consider the downstream end water level $y_1(t)$ as output variable and the total gates positions $u_1(t)$ as input variable. The fundamental perturbation variables $v_1(t)$ are the unknown offtake discharges $q_1(t)$, as well as the effects of the adjacent pools (upstream and downstream) interactions. Water levels and gates positions were uniformly sampled with a period of 60 s.

It is not necessary to know the water level variations along the whole pool to control water distribution in main irrigation canal pools, but only at specific points which depend on the canal operation method that is being used. In this case, since the water distribution is done by gravity offtakes, a good distribution is obtained by maintaining a constant water level at the offtake (Litrico, 2001). Considering this, a linear model with concentrated parameters and a time delay can adequately characterize the dynamical behaviour of an irrigation canal pool at specific points. The true main irrigation canal pool G can be represented by:

$$G = \hat{G}_0 + \Delta G, \tag{1}$$

where $\hat{G}_0$ is a nominal model (nominal plant) that can be exactly represented within a linear parameterized family for input/output behaviour, and ΔG is a model error (model parametric uncertainties). The nominal linear model is obtained when the main canal pool operates under normal hydraulic conditions and it presents the structure

$\hat{G}_0 = B.\theta_{nom}$, where B denotes the vector of chosen basis functions, and θ_{nom} the nominal parameter vector, to be estimated from data. The model set with real parametric uncertainties is given by (Reinelt, Garulli and Ljung, 2002):

$$U_p := \{G(\theta);\ G(\theta) := B.\theta, \\ (\theta-\theta_{nom})^T E^{-1}(\theta-\theta_{nom}) \leq \rho\}, \tag{2}$$

where, using Least Squares techniques, E is the covariance matrix of the parameter and ρ is linked to the probability level of estimation. The dynamics of the model set U_p depends on those of the basis B which hinges on a-priori knowledge. The identification for control procedures developed in this paper will deliver the main canal pool nominal model and the real parametric uncertainties which originate the model set represented by the expression (2).

3.1. Experiment with a gate step command

The objective of this experiment consists of obtaining initial estimations of the order and time delay of a mathematical model that characterizes the dynamic behavior of the Bocal, and then use these results to design a more informative experiment where the gates positions follow a binary signal. This experiment consists of maintaining the downstream gate in a fixed position, and then applying a step signal to the upstream gates. A total of 4 upstream gates received a simultaneous increment in their opening magnitudes of 25.0 cm. That is to say, an increment in the total gates opening magnitude of 100.0 cm was carried out. Data of the upstream and downstream end water level variations, as well as of the increment of the total gates opening magnitude were registered and stored.

The Bocal experimental response to a step command is drawn in Fig. 2. Such response shows that the Bocal dynamic behavior can be represented by a second order system with a time delay given by:

$$T_1T_2\frac{d^2\Delta y_1(t)}{dt^2} + (T_1+T_2)\frac{d\Delta y_1(t)}{dt}, \\ +\Delta y(t) = K\Delta u_1(t-\tau) \tag{3}$$

where $\Delta y_1(t)$ is the downstream end water level variation; $\Delta u_1(t)$ is the upstream gates position variation; K is the static gain; T_1, T_2 are time constants; τ is the 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. Linear model (3) may be represented by the following transfer function:

$$G(s) = \frac{\Delta y_1(s)}{\Delta u_1(s)} = \frac{K}{(T_1 s+1)(T_2 s+1)}e^{-\tau s}. \tag{4}$$

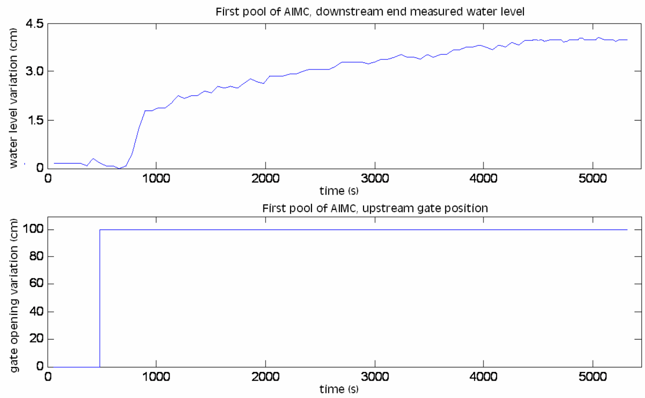

Fig. 2. Step test of the main canal pool "Bocal".

$$T_1T_2\frac{d^2\Delta y_1(t)}{dt^2} + (T_1+T_2)\frac{d\Delta y_1(t)}{dt}, \\ +\Delta y(t) = K\Delta u_1(t-\tau) \tag{3}$$

When the discharge through the upstream gates corresponds to the normal operation regime (nominal hydraulic conditions) of this canal pool the nominal model ($\hat{G}_0$) is obtained (nominal plant), whose parameters are represented as $K_0, T_{10}, T_{20}, \tau_0$. These will be estimated in Section 4.

The Ebro river discharge $Q_R(t)$ exhibits a random character and varies in a wide range. Therefore this magnitude cannot be regulated by any control system. Changes in $Q_R(t)$ originate variations in the upstream water level and, consequently, in the canal pool discharge in the range $(Q_{\min}, Q_{\max})$. Therefore all the dynamical parameters of mathematical model (3) will experience large variations in the following ranges:

$$K_{\min} \leq K(t) \leq K_{\max};\ T_{1\min} \leq T_1(t) \leq T_{1\max}; \\ T_{2\min} \leq T_2(t) \leq T_{2\max};\ \tau_{\min} \leq \tau(t) \leq \tau_{\max}. \tag{5}$$

Consequently it originates a set of models with real parametric uncertainties. As the parameters of our main canal pool exhibit large variations because of changes in the hydraulic conditions, the next incremental mathematical model obtained from (3) can be used:

$$T_1(t)T_2(t)\frac{d^2\Delta y_1(t)}{dt^2} + (T_1(t)+T_2(t))\frac{d\Delta y_1(t)}{dt} + \\ \Delta y(t) = K(t)\Delta u_1(t-\tau(t)). \tag{6}$$

Then any controller to be designed for this class of canal pool should a priori guarantee a certain minimum level of performance for a set of main irrigation canal pool dynamical parameters (set of models). This is the robust performance control system design problem. For the robust control system design it is necessary to know not only the nominal model but also the real main canal pool parameter variations (5) when the hydraulic conditions change (Litrico, Fromion and Baume, 2006).

3.2. Experiment with a binary signal command

In order to obtain data containing the most information about the Bocal dynamic behaviour, it should be excited with a persistent input signal. Pseudo random binary sequences (PRBS) are signals that fulfil this condition.This experiment was carried out by using a PRBS that acts on the upstream control gates. This command sequence was designed in such way that a significant, although not very large, downstream end water level variation was obtained. The results of the experiment with the step signal were used to determine the variation frequency of the PRBS. It was determined that the PRBS should change the gates opening magnitude in intervals multiples of 600 s. with a maximum variation interval of 3000 s.

The opening magnitudes of four upstream gates were simultaneously incremented in ± 25.0 cm. Then a total increment of ± 100 cm was carried out, which is a usual magnitude in the Bocal exploitation regime. The water level of the Ebro river during the whole experiment stayed in its habitual average value (3.50 m) with maximum variations of ± 5.0 cm. Therefore the discharge through the upstream gate corresponded to the Bocal normal operation regime (nominal hydraulic conditions). The experiment had duration of 25140 s. (7 hours). The registered data is shown in Fig. 3. An additional procedure was the splitting of the data register in data for estimation and data for validation (left and right of the vertical line respectively).

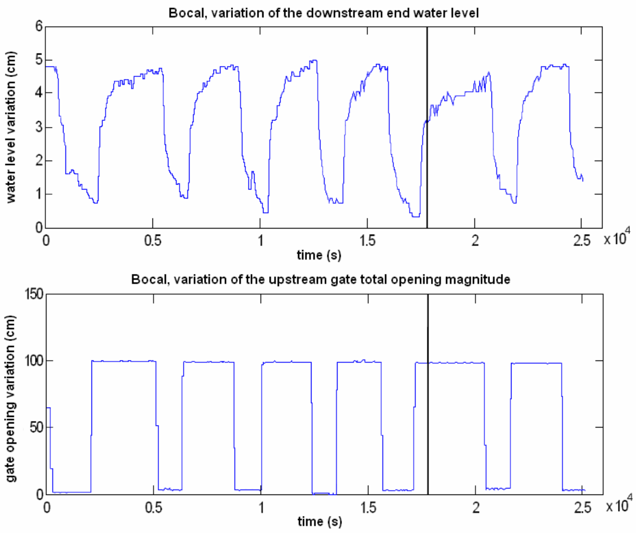

Fig. 3. Obtained data with binary signal.

4. MODEL STRUCTURE SELECTION AND PARAMETER ESTIMATION

4.1 Model structure selection

Different model structures like ARX, OE and ARMAX were tested to determine the one that best represents the Bocal dynamic behaviour. These structures are represented by means of the following expressions (Ljung, 1999):

$$A(q)\hat{y}_{1ARX}(t) = B(q)q^{-nk}u_1(t) + e_1(t); \tag{7}$$

$$\hat{y}_{1OE}(t) = \frac{B(q)}{F(q)}q^{-nk}u_1(t) + e_1(t); \tag{8}$$

$$A(q)\hat{y}_{1ARMAX}(t) = B(q)q^{-nk}u_1(t) + C(q)e_1(t), \tag{9}$$

where $\hat{y}_{1ARX}(t), \hat{y}_{1OE}(t), \hat{y}_{1ARMAX}(t)$ are the model output signals (the estimated downstream end water level) with structures ARX, OE and ARMAX respectively; the polynomials $A(q), B(q), C(q), F(q)$ are defined in terms of the delay operator q^{-1} and they are determined as:

$$A(q) = 1 + a_1 q^{-1} + \ldots + a_{na} q^{-na}; \tag{10}$$

$$B(q) = b_1 + b_2 q^{-1} + \ldots + b_{nb} q^{-nb+1}; \tag{11}$$

$$C(q) = 1 + c_1 q^{-1} + \ldots + c_{nc} q^{-nc}; \tag{12}$$

$$F(q) = 1 + f_1 q^{-1} + \ldots + f_{nf} q^{-nf}, \tag{13}$$

na, nb, nc, nf are the orders of the respective polynomials; a_i, b_i, c_i, f_i are the parameters of the respective model structures to be estimated, which constitute the nominal model estimated parameters vector $\hat{\theta}_{nom}(t)$; nk is the Bocal time delay; $e_1(t)$ is an uncorrelated random white noise sequence with zero mean. The final model structure will be determined during the procedure of model validation.

4.2. Parameters estimation

Parameters estimation involves the determination of the appropriate model order and the model structure parameters in order to obtain the model response that best fits the data recorded during the experiment with the binary signal (Ljung, 1999). The Bocal time delay was determined to be τ_1 = 360 s from the experiment with the step command. With the objective of considering the possible parametric uncertainties that can exist in this time delay, during the parameters estimation the time delay τ_1 was varied in a range between 180 and 720 s.

The nominal parameters vector $\hat{\theta}_{nom}(t)$ of a selected model structure was estimated with the prediction error method using a least mean square criterion to minimize the prediction error, which can be represented by means of the expression (Ljung, 1999):

$$\begin{aligned} \hat{\theta}_{nom}(t) &= \arg\min_{\theta} \frac{1}{N}\sum_{t=1}^{N} \varepsilon^2(t,\theta) = \\ &\arg\min_{\theta} \frac{1}{N}\sum_{t=1}^{N} (y_1(t) - \hat{y}_{1i}(t,\theta))^2, \end{aligned} \tag{14}$$

where $\varepsilon(t,\theta)$ is the prediction error; $\hat{y}_1(t,\theta)$ - the downstream end water level estimates by means of a model with a given structure; N - the total number of data used in the parameters estimation ($N=300$). The model that best reproduces the obtained experimental data was determined by carrying out the parameters estimation process for the three selected model structures (ARX, OE and ARMAX) with different orders and time delays.

5. MODEL VALIDATION

In this section we will evaluate the Bocal nominal model in each one of the selected model structures and we will determine the nominal model that best describes the Bocal dynamic behavior by means of the use of the crossed validation method. Then a portion of the Bocal experimental data, located at the right of the vertical line in Fig. 3, was used for this purpose. Several experiments were carried out for model validation. The results of the crossed validation of the estimated models that best describe the Bocal dynamic behavior in each of the three selected structures are shown in Fig. 4, Fig. 5 and Fig. 6.

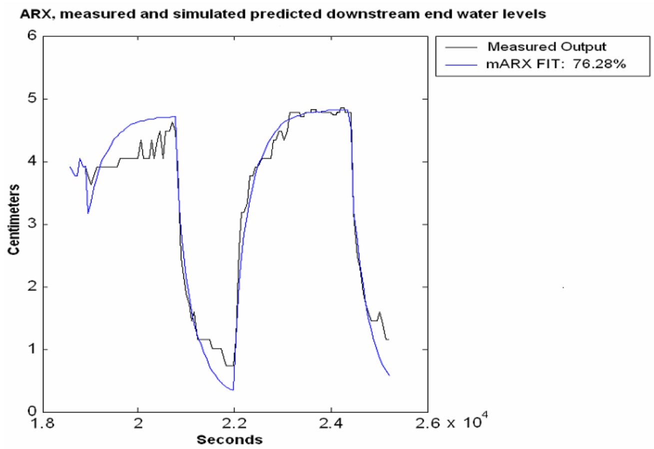

Fig. 4. Measured and simulated water levels on the validation data set with ARX model structure.

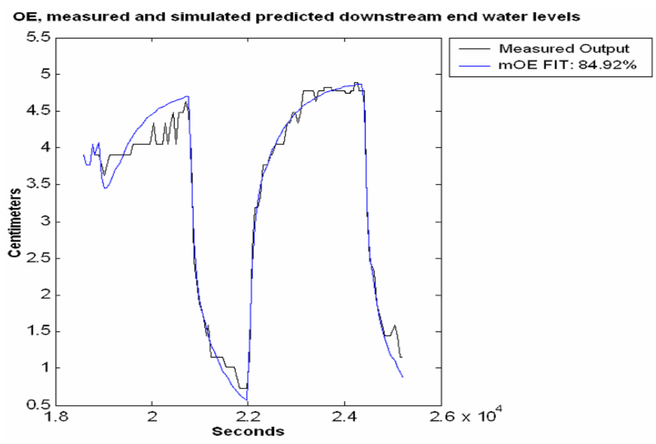

Fig. 5. Measured and simulated water levels on the validation data set with OE model structure.

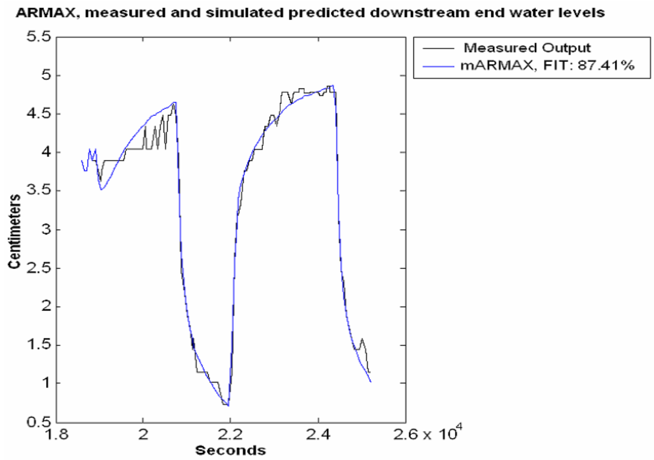

Fig. 6. Measured and simulated water levels on the validation data set with ARMAX model structure.

From these figures it is observed that the three models reproduce the experimental Bocal data adequately, even considering data that was not used in the parameters estimation. These models are of second order, they were adjusted with a time delay of 360 s and they can be represented respectively by means of the following equations:

$$y_{1ARX}(t)=0.8823\,y_{1ARX}(t-60)-0.02622\,y_{1ARX}(t-120)+0.01255\,u_1(t-360)-0.006938\,u_1(t-420); \tag{15}$$

$$y_{1OE}(t)=1.368\,y_{1OE}(t-60)-0.41565\,y_{1OE}(t-120)+0.01226\,u_1(t-360)-0.01038\,u_1(t-420); \tag{16}$$

$$y_{1ARMAX}(t)=1.412\,y_{1ARMAX}(t-60)-0.4464\,y_{1ARMAX}(t-120)+0.01232u_1(t-360)-0.01094\,u_1(t-420)+\xi_1(t)-0.9772\xi_1(t-60)+0.1741\xi_1(t-120). \tag{17}$$

The levels of accuracy of the three models that best describe the Bocal dynamics were quantified for the model selection. A performance index (FIT) was used, which constitutes a quantitative measure of the model quality, and it is obtained from the norm of the residual errors (Ljung, 1999).

Figs. 4, 5 and 6 show that the ARMAX structure model presents the best performance index (87.41 %) and therefore it is the nominal model that best reproduces the Bocal real dynamic behaviour. This nominal model can be represented in the continuous time domain by the expressions:

$$\hat{G}_{0,u_1}(s)=\frac{\Delta y_1(s)}{\Delta u_1(s)}=\frac{0.03375}{(880.79\,s+1)(81.27\,s+1)}e^{-360s}; \tag{18}$$

$$\hat{G}_{0,v_1}(s)=\frac{\Delta y_1(s)}{\Delta v_1(s)}=\frac{1.44\,s^2+0.03165\,s+0.000116}{s^2+0.01344\,s+0.00001397}, \tag{19}$$

From this model it is observed that the nominal values of the canal parameters are $K_0=0.03375$, $T_{10}=880.79$ s, $T_{20}=81.27$ s and $\tau_0=360$ s.

The water level in the Ebro river varies between 3.90 and 3.30 m. These variations originate changes in the discharge through the upstream gates and consequently changes in the Bocal model parameters. When the water level in the Ebro river presents its higher value it originates high flow hydraulic conditions in the Bocal. Otherwise when the water level in the Ebro river presents its lower value it originates low flow hydraulic conditions in the Bocal. For high flow hydraulic conditions the discharge is 30.0 m^3/s while for low flow conditions, it is equal to 12 m^3/s. Such a variety of hydraulic conditions enables us to determine the model parametric uncertainties. Then the identification procedure developed in Sections 3.2, 4 and 5 was repeated for the high flow and low flow hydraulic conditions, and the following ranges of Bocal model parameters variations were obtained:

$$\begin{aligned} &0.01 \leq K(t) \leq 0.1;\ 500 \leq T_1(t) \leq 15000\,; \\ &10 \leq T_2(t) \leq 300\,;\ 300 \leq \tau(t) \leq 360. \end{aligned} \qquad (20)$$

The parameters variations (20) originate a set of Bocal models with real parametric uncertainties. Therefore, any controller to be designed for the Bocal canal pool should consider not only the nominal model (18)-(19) but also the model parametric uncertainties (20) originated by the variations of the hydraulic conditions.

6. DISCUSSIONS AND CONCLUSIONS

This paper described the system identification for control procedure of the first pool (Bocal) of the Aragon's Imperial Irrigation Main Canal. The complete system identification for control procedure - from experiment design to model validation – has been presented, and prior information has been taken into account. The results of the parameter estimation and model validation processes showed that the best fitting to the canal pool nominal model was obtained with a second order linear ARMAX model structure and a time delay of 360 s.

The performance on the validation data set showed that the nominal model (18)-(19) is quite capable of describing the true canal nominal dynamic behaviour, even for data that was not used in the fitting process. Agreement between the measured and simulated canal pool water levels was excellent. Then the nominal model (18)-(19) is valid and can be used for accurate simulations of the Bocal downstream end water levels, and for prediction and control. This model differs from previous models obtained in (Euren and Weyer, 2007; Weyer, 2001), because these are non linear models of first and third order. However our linear second order model is much easier to use in prediction and control applications than those others.

The design of an effective controller for water distribution in this class of canal pools should consider not only the nominal model (18)-(19) but also the model parametric uncertainties (20) originated when the hydraulic conditions change.

The environmental benefits of this work are very large since by designing robust controllers based on our models, one can divert less water from the Ebro river for irrigation purposes while maintaining the same level of service to the farmers.

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