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Mathematical model for robust control of an irrigation main canal pool

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ABSTRACT

This paper describes the formulation and development of a mathematical model for high-performance robust controller design techniques, based on a complete *identification for control* procedure, of an irrigation main canal pool (true plant), which is characterized by the exhibition of large variations in its dynamic parameters when the discharge regime changes in the operating range [Q_{min}, Q_{max}]. Real-time field data has been used. Four basic steps of the proposed procedure have been defined in which all the stages, from the design of the experiments to the model validation, are considered. This procedure not only delivers a nominal model of the true plant, but also a reliable estimate of its model uncertainty region bounded by the true plant models under minimum and maximum operating discharge regimes (limit operating models). The model uncertainty set, defined by the nominal model and its uncertainty region, is characterized by its being as tight as possible to the true irrigation main canal pool. The obtained results are very promising since this kind of models facilitates the design of robust controllers, which allow improving the operability of irrigation main canal pools and also substantially reduce water losses.

1. Introduction

A significant part of the control system design of irrigation main canals is devoted to obtaining their mathematical models. These mathematical models should provide an accurate description of the relevant irrigation main canal pool dynamics. The physical dynamics of an irrigation main canal pool (plant) are usually modeled and simulated by using the Saint–Venant equations, owing to their capacity to represent the nonlinear hydraulic characteristics of real interest (Chaudhry, 1993). These equations are not easy to use directly as a model for control system design (Kovalenko, 1983; Litrico and Fromion, 2009; Rivas-Perez et al., 2007). Linearization or simplifications of the Saint–Venant equations are therefore recurrently used by the irrigation canal control research community. Linear and rational models open up the possibility to apply well-known control system design techniques, which are relatively easy to implement.

Water demand for irrigation varies with time as a result of the users' variable water needs. In order to satisfy water demand, the irrigation main canals need to be operated under different discharge regimes in the range [Q_{min}, Q_{max}], in order to maintain water levels and supply the desired discharge rates at specific locations. Experiments developed by certain authors (Deltour and Sanfilippo, 1998; Litrico et al., 2006; Rivas-Perez et al., 2008a; Schuurmans et al., 1999) confirm that when the discharge regimes change in the operating range [Q_{min}, Q_{max}] and/or other hydraulic parameters change, the irrigation main canal pools may exhibit large variations in their dynamic parameters. The mathematical models to be obtained must therefore consider these parameter variations. Indeed, control system design methods are usually based on a nominal model, whereas the dynamics of irrigation main canal pools vary with the alteration in operating hydraulic conditions, thus causing uncertainties in the nominal model (Feliu-Batlle et al., 2011; Litrico et al., 2006; Rivas-Perez et al., 2011).

Identification for control is an area in which a renewed interest has been shown since the beginning of the 1990s and which still attracts a growing number of researchers (Gevers, 2005). One of its main objectives is to estimate mathematical models that are suitable for high performance robust control design techniques

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(*control-oriented models*), i.e. estimate the plant nominal models and its uncertainties regions (Chen and Gu, 2000).

Various works concerning the design of robust controllers to control water distribution in irrigation main canal pools, which are characterized by large time-varying dynamic parameters, have been reported (Calderon-Valdez et al., 2009; Feliu-Batlle et al., 2005, 2011; Litrico and Fromion, 2009; Rivas-Perez et al., 2002). These controllers should guarantee a specified minimum level of performance for the whole range of variation of canal pool dynamical parameters (model uncertainty set). One of the main problems in the design of robust controllers is that of systematically obtaining the model uncertainty set when the irrigation canal is operating under different discharge regimes (Litrico and Fromion, 2009; Kovalenko et al., 1993; Rivas-Perez, 1984). In this paper, an identification for control procedure is used to obtain a reliable model uncertainty set of a main irrigation canal pool when the design of a robust controller is demanded.

The paper makes an intensive use of standard model structures and algorithms found in the literature, for example in Data-Based Mechanistic (DBM) modeling of hydrological and other environmental systems (see, e.g. Andrews et al., 2011; Camacho and Lees, 1999; Jakeman et al., 2006; Lekkas et al., 2001; McIntyre et al., 2011; Ochieng and Otieno, 2009; Ooi and Weyer, 2008; Price et al., 1999; Romanowicz et al., 2006; Young, 1998, 2011; Young and Garnier, 2006).

The main contributions of this paper are: 1) to the best of our knowledge it is the first time that a complete algorithmic procedure has been formulated and developed (using real-time field data) for the identification for robust control of an irrigation main canal pool, which is characterized by the exhibition of large variations in its dynamic parameters when the discharge regime changes in the operating range; 2) the estimation, through the use of real-time field data and the Prediction Error Framework, of a nominal model of the true plant and its explicit uncertainty region, bounded by the true plant models under minimum (lower) and maximum (upper) operating discharge regimes (limit operating models); 3) the derivation of a true plant model uncertainty set, defined by the nominal model and its uncertainty region, which is characterized by its being as tight as possible to the true plant; 4) the design of a robust controller for an irrigation main canal pool based in this model uncertainties set. The approaches used in this paper for obtaining the mathematical model are within the indirect techniques based directly on the experimental data (Garnier and Wang, 2008). The obtained plant mathematical model has been developed using the software platform of the System Identification Toolbox of Matlab.

The paper is organized as follows. In Section 2 the algorithmic procedure is presented in four steps. The main results are given in Section 3. Section 4 provides some comments and conclusions.

2. Methodology

We propose the following four basic steps algorithm for the *identification for control* procedure of a true irrigation main canal pool from N field sampled measurements of the input and output $Z^N = \{u(t_k);\ y(t_k)\}_{k=1}^{N}$.

Step 1: Design of the experiments;

Step 2: Data collection, parameter estimation and validation of the linear nominal model of the true plant under nominal operating discharge regime ($Q(t) = Q_{nom}$);

Step 3: Data collection, parameter estimation and validation of the linear models of the true plant under limit operating discharge regimes (model uncertainty region);

Step 4: Delivery of the true plant model uncertainty set, comprised by the nominal model and its uncertainty region.

Remarks: a) the model parameters of an irrigation main canal pool change with variations in its operating discharge regime ($Q(t)$). The identification experiments should therefore be developed so that they represent the typical discharge regimes in which the true plant is operated; b) according to robust control theory it is desirable to reduce the model uncertainty region as little as possible, i.e., to make the nominal model represent the true plant dynamics as well as possible, or to make the model uncertainty set as tight as possible; and c) in irrigation main canal pool practice the limit operating discharge regimes are obtained when $Q(t) = Q_{min}$ (minimum (lower) limit of $Q(t)$) and $Q(t) = Q_{max}$ (maximum (upper) limit of $Q(t)$) with $Q(t) \in [Q_{min}, Q_{max}]$. The subscripts *min*, *nom*, *max* represent respectively the minimum, nominal and maximum discharge regimes.

This paper focuses on the application of this four basic steps algorithm in order to obtain a mathematical model for high-performance robust control of an irrigation main canal pool.

3. Results

In this Section we develop the four basic steps algorithm in the *identification for control* procedure proposed in Section 2 for the first pool of the Aragon Imperial Main Canal (AIMC).

3.1. Irrigation main canal description

The irrigation main canal considered in this paper is the Aragon Imperial Main Canal, which pertains to the Ebro Hydrographical Confederation in Zaragoza, Spain. It obtains its water from the Ebro River thanks to the elevation of the Pignatelli dam. The water passes through the Gate House, which controls the designed discharge at its origin, although this value may sometimes be superior as a result of a high flow in the *Ebro River*. The *Ebro River* represents the Spanish most important catchment of the Iberian Peninsula (Pedregal et al., 2009). The AIMC is a 108 km long cross-structure canal. It has a trapezoidal cross-section and ten pools of different lengths which are separated by undershoot flow gates.

Several of the pools in the AIMC are characterized by time-varying dynamics when the discharge regimes change in the operating range [Q_{min}, Q_{max}] and/or other hydraulic parameters change (Rivas-Perez et al., 2011). The controllers which are currently installed do not, therefore, guarantee an effective water distribution control. In order to improve the control and management of the whole AIMC, the implementation of decentralized robust control systems of water distribution has been considered for canal pools that are characterized by time-varying dynamics. These systems will be based on independently tuned robust controllers to which additional control elements will be added in order to minimize pool interactions. The first step in this study is, therefore, to obtain the control-oriented models of the canal pools.

3.2. Design of the experiments (step 1 of the procedure)

The field data and results reported in this paper were obtained from the first pool in the AIMC, which is known as the *Bocal*. It is a lined trapezoidal canal pool of 8 km in length, with a variable depth of between 3.5 and 4.15 m, a variable width of between 21 and 26.9 m, and a design maximum discharge of 30 m^3/s, in its entire extension. Fig. 1 shows an upper view of the *Bocal* in which it is possible to observe the *Ebro River*, the Pignatelli dam, and the Gate House.

This canal pool is operated in a downstream end regulation mode (Kovalenko, 1983). The downstream end water level is controlled by means of 10 upstream undershoot gates located in the *Gate House* on the side of the canal. The measurements available