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Nonlinear PID Controller of MIMO Hammerstein model

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***Abstract*—This paper focuses on the identification and control of multi-input multi-output (MIMO) Hammerstein model. Decoupled and coupled structures are based on the Recursive Least Square algorithm (RLS). A nonlinear discrete-time PID is proposed. A quadruple-tank process is used to illustrate the effectiveness of the coupled structure.**

***Index Terms*—Parametric identification, Decoupled and Coupled MIMO Hammerstein model Quadruple-tank process.**

I. Introduction

System modeling, identification and control conception of nonlinear systems have been the subject of many research activities in the literature [1], [2].

Indeed, for most of the dynamic systems, the use of nonlinear models is often of great interest since it generally characterizes suitable physical processes over their entire range of operation [3].

Thus, performances and accuracy of the control law improve significantly. Among the nonlinear realization frequently studied is the Hammerstein model, which is composed of a static nonlinearity in series with a linear dynamic system [4], [5].

Many system identification methods have been used to identify the single-input single-output (SISO) model [6]–[11]. On the other hand, a few methods are used to modeling and identify the MIMO Hammerstein. Among the approaches, neuronal networks and fuzzy logic have been proposed in [12] to deal with more general nonlinearities. The Least Squares Support Vector Machines (LS-SVMs) have been used in [13], [14]. A most generalized Hammerstein model is developed in [15]. Hammerstein models have a special structure that facilitates the analysis and the control of MIMO nonlinear process [16], [17].

In most of these algorithms, their performance functions are minimized based on nonlinear programming techniques to estimate the future variables in on-line optimization. This complicates the development of algorithms for real-time control.

The advantages of the present block-structured models is the use of standard linear controller design methods. This advantage is due to the possibility of canceling the static nonlinearity in the process by inserting the inverse of the nonlinearity at the appropriate place in the loop [18]–[21].

The remainder of this paper is organized as follows: first, a parametric identification of the MIMO Hammerstein model is defined used a decoupled and coupled structures. Second, a method to control this model is presented. Third, a simulation results of a quadruple-tank process is given and finally, some concluding remarks are provided.

II. Parametric identification of MIMO Hammerstein model

In order to obtained the multivariable plant model convenient for employing nonlinear PID controller, nonlinear Hammerstein system identification approach has been considered [22]. In this work, we use a decoupled and coupled structures to describe the MIMO Hammerstein model and we presented the corresponding identification algorithms. They are presented in figures 2 and 4 where $u_j,\ v_{i,j},\ y_i,\ F_{i,j}(.)$ for $i = 1,\ 2, \ldots, p$ and $j = 1,\ 2, \ldots, m$ are the system input, internal signal, system output and nonlinear function.

A. A decoupled structure identification of MIMO Hammerstein model

The decoupled structure of MIMO Hammerstein model is given in Fig. 1. Each output $y_{i,k},\ i = 1,\ 2,\ \ldots p$, of the multivariable system corresponds to a linear model, which at its input are introduced a nonlinear functions, Fig. 2.

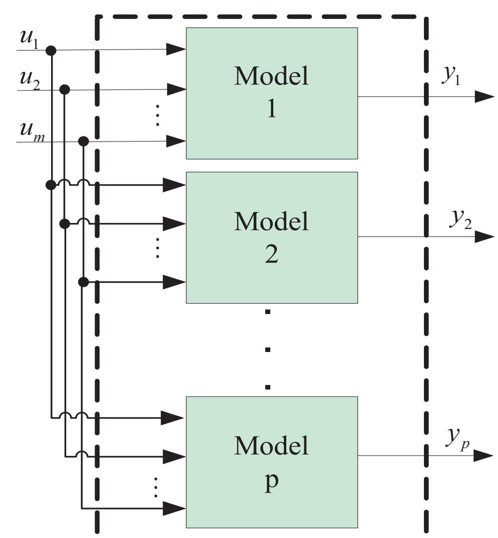

Fig. 1. Decoupled structure of MIMO Hammerstein model

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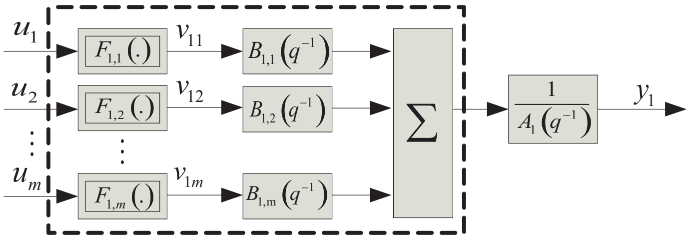

Fig. 2. Structure of decoupled submodel

Each output $y_{i,k},\ \ i=1,\ 2,\ \ldots p$, of the MIMO Hammerstein model is proposed by:

$$\left\{\begin{array}{l} A_i\left(q^{-1}\right)y_{i,k}=\sum\limits_{j=1}^{m}B_{i,j}\left(q^{-1}\right)v_{j,k} \\ v_{i,j,k}=F_{i,j}\left(u_{j,k}\right)=u_{j,k}+\sum\limits_{\rho=2}^{N}\lambda_{i,j,\rho}\,u_{j,k}^{\rho} \end{array}\right. \tag{1}$$

with:

$$A_i\left(q^{-1}\right)=1+a_{i,1}q^{-1}+a_{i,2}q^{-2}+\ldots+a_{i,n_{A_i}}q^{-n_{A_i}}$$

$$B_{i,j}\left(q^{-1}\right)=b_{i,j,1}q^{-1}+b_{i,j,2}q^{-2}+\ldots+b_{i,j,n_{B_{i,j}}}q^{-n_{B_{i,j}}}$$

System (1) can be rewritten as:

$$\begin{aligned} y_{i,k}=&-\sum_{\tau=1}^{n_{A_i}}a_{i,\tau}\,y_{i,k-\tau}+\sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}b_{i,j,\tau}\,u_{j,k-\tau} \\ &+\sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}\sum_{\rho=2}^{N}b_{i,j,\tau}\,\lambda_{i,j,\rho}\,u_{j,k-\tau}^{\rho} \end{aligned} \tag{2}$$

then:

$$\begin{aligned} y_{i,k}=&-\sum_{\tau=1}^{n_{A_i}}a_{i,\tau}\,y_{i,k-\tau}+\sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}b_{i,j,\tau}\,u_{j,k-\tau} \\ &+\sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}\sum_{\rho=2}^{N}s_{i,j,\tau,\rho}\,u_{j,k-\tau}^{\rho} \end{aligned} \tag{3}$$

Equation (3) can be written in the following form:

$$y_{i,k}={\Phi_{i,k}}^{T}\ \theta_i \tag{4}$$

with:

$$\Phi_{i,k}=\left(\begin{array}{c} Y_{i,k} \\ U_k \\ \varphi_k \end{array}\right),\ \theta_i=\left(\begin{array}{c} A_i \\ B_i \\ S_i \end{array}\right)$$

$\Phi_{i,k}$ and $\theta_i\in\ R^{n_R}$; $n_R=n_{A_i}+\sum\limits_{j=1}^{m}Nn_{B_{i,j}}$

$$Y_{i,k}=\left(-y_{i,k-1},\ -y_{i,k-2},\ \ldots,\ -y_{i,k-n_{A_i}}\right)\in R^{n_{A_i}}$$

$$U_k=\left(U_{1,k},\ U_{2,k},\ \ldots,\ U_{m,k}\right)\in R^{m\times n_{B_{i,j}}}$$

$$U_{j,k}=\left(u_{j,k-1},\ u_{j,k-2},\ \ldots,\ u_{j,k-n_{B_{i,j}}}\right)\in R^{n_{B_{i,j}}}$$

$$\varphi_k=\left(\varphi_{1,k},\ \varphi_{2,k},\ \ldots,\ \varphi_{m,k}\right)\in R^{(N-1)\times m\times n_{B_{i,j}}}$$

$$\varphi_{j,k}=\left(\varphi_{j,1,k},\ \varphi_{j,2,k},\ \ldots,\ \varphi_{j,n_{B_{i,j}},k}\right)\in R^{(N-1)\times n_{B_{i,j}}}$$

$$\varphi_{j,\tau,k}=\left(u_{j,k-\tau}^{2},\ u_{j,k-\tau}^{3},\ \ldots,\ u_{j,k-\tau}^{N}\right)\in R^{(N-1)}$$

$$A_i=\left(a_{i,1},\ a_{i,2},\ \ldots,\ a_{i,n_{A_i}}\right)\in R^{n_{A_i}}$$

$$B_i=\left(B_{i,1},\ B_{i,2},\ \ldots,\ B_{i,m}\right)\in R^{m\times n_{B_{i,j}}}$$

$$B_{i,j}=\left(b_{i,j,1},\ b_{i,j,2},\ \ldots,\ b_{i,j,n_{B_{i,j}}}\right)\in R^{n_{B_{i,j}}}$$

$$S_i=\left(S_{i,1},\ S_{i,2},\ \ldots,\ S_{i,m}\right)\in R^{(N-1)\times m\times n_{B_{i,j}}}$$

$$S_{i,j}=\left(S_{i,j,1},\ S_{i,j,2},\ \ldots,\ S_{i,j,n_{B_{i,j}}}\right)\in R^{(N-1)\times n_{B_{i,j}}}$$

$$S_{i,j,\tau}=\left(s_{i,j,\tau,2},\ s_{i,j,\tau,3},\ \ldots,\ s_{i,j,\tau,N}\right)\in R^{(N-1)}$$

$$s_{i,j,\tau,\rho}=b_{i,j,\tau}\,\lambda_{j,\rho}$$

for $i=1,2,\ldots,p$, $j=1,2,\ldots,m$, and $\tau=1,2,\ldots,n_{B_{i,j}}$

The steps of the identification scheme are summarized as follows:

1) choosing an initial values for the adaptation matrix,
2) acquiring the input and output of the system and form the vector data as shown in (4) using the present and past values of the input u, output y, and u power,
3) solving the estimate parameter $A_i,\ B_i$ and S_i using the algorithm RLS.
   It is described by the following equations:

$$\left\{\begin{array}{l} \hat{\theta}_k=\hat{\theta}_{k-1}+P_k\,\Phi_k\,\varepsilon_k \\ P_k=P_{k-1}-\frac{P_{k-1}\,\Phi_k\,\Phi_k^T\,P_{k-1}}{1+\Phi_k^T P_{k-1}\Phi_k} \\ \varepsilon_k=y_k-\ \hat{\theta}_{k-1}^{T}\,\Phi_k \end{array}\right. \tag{5}$$

   where P_k is the adaptation gain matrix, Φ_k is the observation vector and θ_k is the parameters vector,
4) solving $\lambda_{i,j,\rho}$ using the estimated values $b_{i,j,\tau}$ and $s_{i,j,\tau,\rho}$ as:

$$\lambda_{i,j,\rho}=\left(\sum_{\tau=1}^{n_{B_{i,j}}}b_{i,j,\tau}^{2}\right)^{-1}\left(\sum_{\tau=1}^{n_{B_{i,j}}}b_{i,j,\tau}\,s_{i,j,\tau,\rho}\right) \tag{6}$$

B. A new coupled structure identification of MIMO Hammerstein system

The schematic diagram of the new coupled structure to be identified is proposed in Fig. 3. Each output of the system is depended on inputs and all other system outputs, Fig. 4.

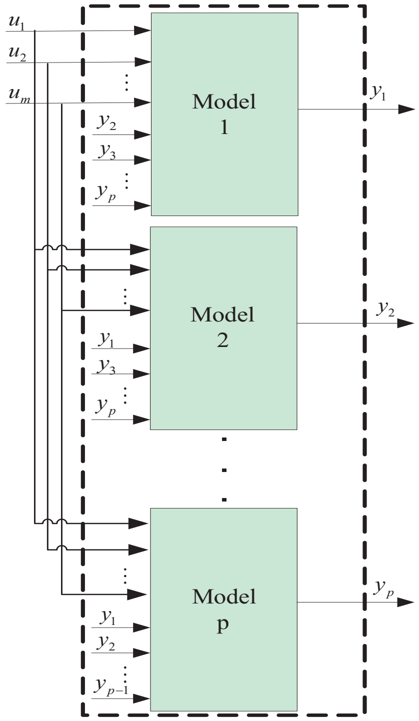

Fig. 3. A proposed structure of MIMO Hammerstein model

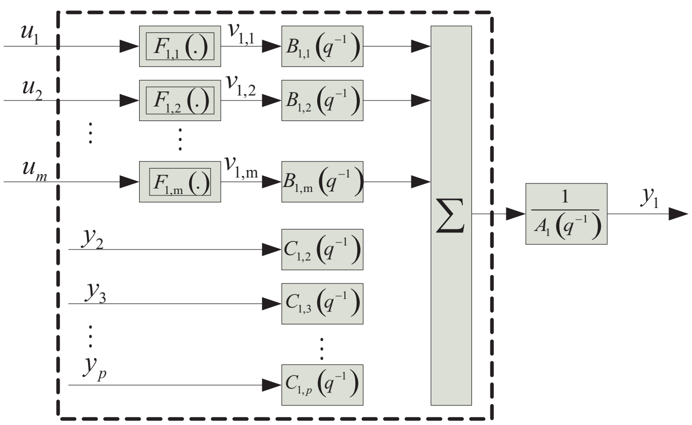

Fig. 4. Structure of coupled submodel

Each output $y_{i,k},\ i = 1,\ 2,\ \ldots p$, of the MIMO Hammerstein model is described by:

$$\begin{cases} A_i\left(q^{-1}\right) y_{i,k} = \sum\limits_{j=1}^{m} B_{i,j}\left(q^{-1}\right) v_{j,k} + \sum\limits_{\substack{l=1\\ l\neq i}}^{p} C_{i,l}\left(q^{-1}\right) y_{l,k} \\ v_{i,j,k} = F_{i,j}\left(u_{j,k}\right) = u_{j,k} + \sum\limits_{\rho=2}^{N} \lambda_{i,j,\rho}\, u_{j,k}^{\rho} \end{cases} \tag{7}$$

with:

$$A_i\left(q^{-1}\right) = 1 + a_{i,1}q^{-1} + a_{i,2}q^{-2} + \ldots + a_{i,n_{A_i}}q^{-n_{A_i}}$$

$$B_{i,j}\left(q^{-1}\right) = b_{i,j,1}q^{-1} + b_{i,j,2}q^{-2} + \ldots + b_{i,j,n_{B_{i,j}}}q^{-n_{B_{i,j}}}$$

$$C_{i,l}\left(q^{-1}\right) = c_{i,l,1}q^{-1} + c_{i,l,2}q^{-2} + \ldots + c_{i,l,n_{C_{i,l}}}q^{-n_{C_{i,l}}}$$

System (7) can be rewritten as:

$$\begin{aligned} y_{i,k} = &-\sum_{\tau=1}^{n_{A_i}} a_{i,\tau}\, y_{i,k-\tau} + \sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}} b_{i,j,\tau}\, u_{j,k-\tau} \\ &+ \sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}\sum_{\rho=2}^{N} b_{i,j,\tau}\,\lambda_{i,j,\rho}\, u_{j,k-\tau}^{\rho} + \sum_{\substack{l=1\\ l\neq i}}^{p}\sum_{\tau=1}^{n_{C_{i,l}}} c_{i,l,\tau}\, y_{l,k-\tau} \end{aligned} \tag{8}$$

then:

$$\begin{aligned} y_{i,k} = &-\sum_{\tau=1}^{n_{A_i}} a_{i,\tau}\, y_{i,k-\tau} + \sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}} b_{i,j,\tau}\, u_{j,k-\tau} \\ &+ \sum_{j=1}^{m}\sum_{\tau=1}^{n_{B_{i,j}}}\sum_{\rho=2}^{N} s_{i,j,\tau,\rho}\, u_{j,k-\tau}^{n} + \sum_{\substack{l=1\\ l\neq i}}^{p}\sum_{\tau=1}^{n_{C_{i,l}}} c_{i,l,\tau}\, y_{l,k-\tau} \end{aligned} \tag{9}$$

Equation (9) can be written in the following form:

$$y_{i,k} = \Psi_{i,k}^{T}\theta_i^{new} \tag{10}$$

with:

$$\Psi_{i,k} = \begin{pmatrix} Y_{i,k} \\ U_k \\ \varphi_k \\ Y_{L,k} \end{pmatrix},\ \theta_i^{new} = \begin{pmatrix} A_i \\ B_i \\ S_i \\ C_i \end{pmatrix}$$

$$\Phi_{i,k} \text{ and } \theta_i \in R^{n_R}\ ;\ n_R = n_{A_i} + \sum_{j=1}^{m} N n_{B_{i,j}} + n_{C_{i,l}} \times (p-1)$$

$$\underset{L\neq i}{Y_{L,k}} = \left(Y_{1,k},\ Y_{2,k},\ \ldots, Y_{p,k}\right) \in R^{(p-1)\times n_{C_{i,l}}}$$

$$Y_{l,k} = \left(-y_{l,k-1},\ -y_{l,k-2},\ \ldots,\ -y_{l,k-n_{C_{i,l}}}\right) \in R^{n_{C_{i,l}}}$$

$$C_i = \left(C_{i,1},\ C_{i,2},\ \ldots,\ C_{i,p}\right) \in R^{(p-1)\times n_{C_{i,l}}}$$

$$C_{i,j} = \left(c_{i,j,1},\ c_{i,j,2},\ \ldots,\ c_{i,j,n_{C_{i,l}}}\right) \in R^{n_{C_{i,l}}}$$

for $i = 1, 2, \ldots, p$, $j = 1, 2, \ldots, m$, and $\tau = 1, 2, \ldots, n_{B_{i,j}}$, and $l = 1, 2, \ldots, p$, such as $l \neq i$.

Parametric identification consists to determine the parameters of the system based on vectors of inputs and outputs, using the recursive least squares algorithm.

III. Nonlinear PID controller of coupled structure of MIMO Hammerstein model

In this section, the control of the new coupled MIMO Hammerstein model with a nonlinear PID will be discussed.

The design strategy discrete-time control for MIMO Hammerstein model is implemented by applying an inverse function of the static nonlinearity model, $f^{-1}(.)$ precedent to the Hammerstein model [19]. Fig. 5. illustrate the schematic block diagram control of SISO Hammerstein model. It is based PID regulator as [27]:

$$u_k = K_p\,\varepsilon_k + K_i\,T_e \sum_{j=0}^{k} \varepsilon_j \,+\, K_d \frac{\varepsilon_k - \varepsilon_{k-1}}{T_e} \tag{11}$$

where $\varepsilon_k = y_k^c - y_k^m$ is the error, y_k^c is the set point, y_k^m is the response of the model, T_e is the sampling period and K_p, K_i and K_d are the proportional, integral and derivative controller gains, respectively.

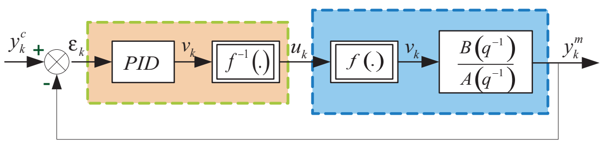

Fig. 5. Nonlinear PID controller of a Hammerstein model [20].

In this work, we proposed to use the nonlinear PID to control the coupled MIMO Hammerstein model.

IV. Application: quadruple-tank process

A quadruple-tank process is used to illustrate the performance of the proposed structures of the MIMO Hammerstein model.

A. System description

The system setup is a model of a chemical plant fragment. Very often tanks are coupled through pipes and the reactant level and flow has to be controlled. The type of the experiments was performed on the 33-041 Coupled Tanks System of Feedback Instruments [24]. This plant, a variant of the quadruple tank process originally proposed in [25], is a model of a fragment of a chemical plant, Fig. 6.

Fig. 6. Plant of four coupled tanks [26]

The line diagram of the reservoir system is shown in Fig. 7. The coupled tanks unit consists of four tanks placed on a rig. Another reservoir tank is placed at the bottom. In the reservoir two submersible pumps are placed, which pump the water on command to the tanks. The water flows freely to the bottom tanks through the configurable orifice. The way the water flows through the setup can be configured in many ways with manual valves label led (MVA, MVB, MVC, MVD, MVE, MVF, MVG, MV1, MV2, MV3 and MV4).

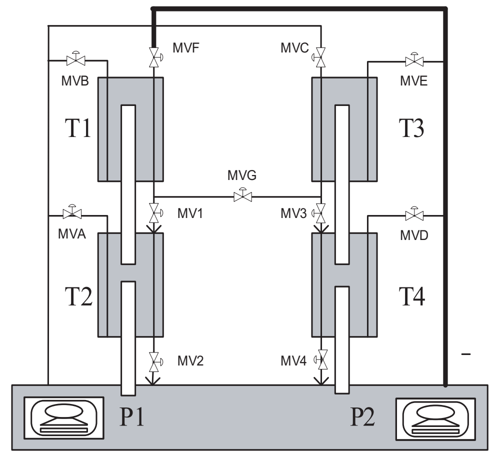

Fig. 7. Line diagram for quadruple-tank process

B. Mathematical modelling

The quadruple-tank process admits the following nonlinear model [25] which has been assembled in simulink:

$$\begin{cases} \frac{dh_1(t)}{dt} = \eta v_1(t) - \frac{a_1}{A}\sqrt{2\,g\,h_1(t)} - \frac{a_{13}}{A}\sqrt{2\,g\,(h_1(t) - h_3(t))} \\ \frac{dh_2(t)}{dt} = \frac{a_1}{A}\sqrt{2\,g\,h_1(t)} - \frac{a_2}{A}\sqrt{2\,g\,h_2(t)} \\ \frac{dh_3(t)}{dt} = \eta v_2(t) - \frac{a_3}{A}\sqrt{2\,g\,h_3(t)} - \frac{a_{13}}{A}\sqrt{2\,g\,(h_1(t) - h_3(t))} \\ \frac{dh_4(t)}{dt} = \frac{a_3}{A}\sqrt{2\,g\,h_3(t)} - \frac{a_4}{A}\sqrt{2\,g\,h_4(t)} \end{cases} \tag{12}$$

where h_i, for $i = 1, 2, 3, 4$, denote the water level in the corresponding tank and v_i, for $i = 1, 2$, are voltages applied to the pumps. a_i, for $i = 1, 2, 3, 4$, are the outlet area of the tanks, a_{13} is the outlet area betwixt tanks 1 and 3; η constant relating the control voltage with the water flow from the pump, A is the cross-sectional area of the tanks and g is the gravitational constant.

C. Simulation and results

The proposed structures has been tested with the model parameters presented in table 1.

TABLE I
PARAMETERS OF THE PLANT

	Value	Unit	Description
h_i	$0-25$	cm	Water level of tank i
v_i	$0-5$	V	Voltage level of pump i
S	0.014	m^2	Cross-sectional area
a_i	$5e-5$	m^2	Outlet area of tank i
a_{13}	$5e-5$	m^2	Outlet area betwixt $T1$ and $T3$
η	$2e-3$	$\frac{m^3}{V.s_2}$	Water level of tank i
g	9.81	m^{-2}	Gravitational constant

The choice of the excitation signal is very important issue of concern before finding the suitable model of the multivariable nonlinear process under observation . The system should be excited in such a way that all interesting areas of the input space and all relevant frequencies are covered. The pseudo-random binary sequence (SBPA) has been considered in designing the experiments for system identification. The inputs u_1 and u_2 are show in Fig. 8. They are set to $[0 \dots +5V]$. The sample time used for all simulations is $T_e = 1s$.

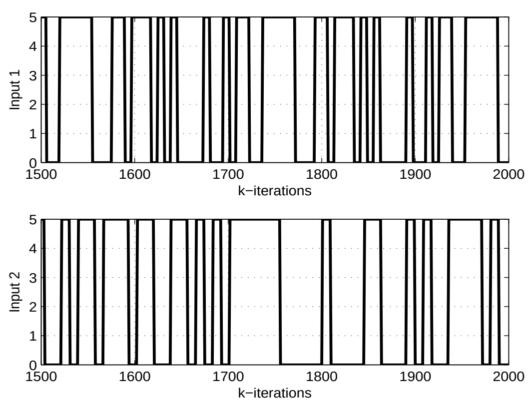

Fig. 8. Inputs u_1 and u_2

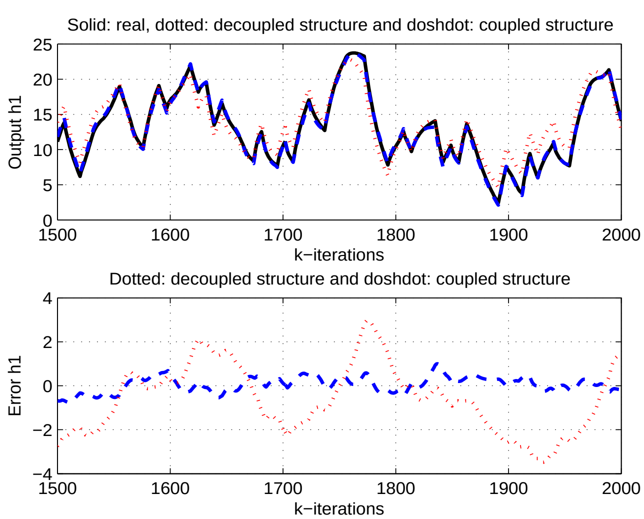

Fig. 9. Response of the real and estimated h_1

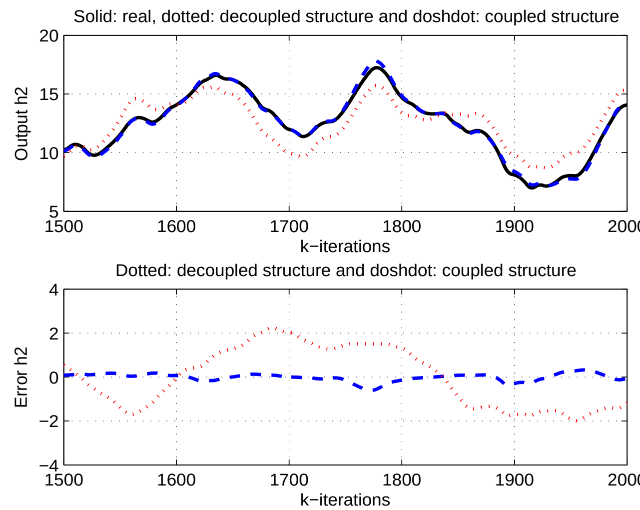

Fig. 10. Response of the real and estimated h_2

Figures 9 to 10 show the results of the experiments with two method from a comparative point of view. Each of them shows a superposition of the actual output and the two outputs estimated as their two error curves. Solid line represents the real output, dotted line represents the estimated systems output signals with the decoupled structure and the dash dot lines represent the estimated systems output signals with the coupled structure in all four graphs. The responses of the original system and the results of the proposed method are very similar. It is clear that the error corresponds to the proposed structure is smaller than that corresponding to the decoupled structure. On inspection, the proposed structure is seen to work better than the decoupled structure. Thus, the feasibility and superiority of this proposed identification method are validated.

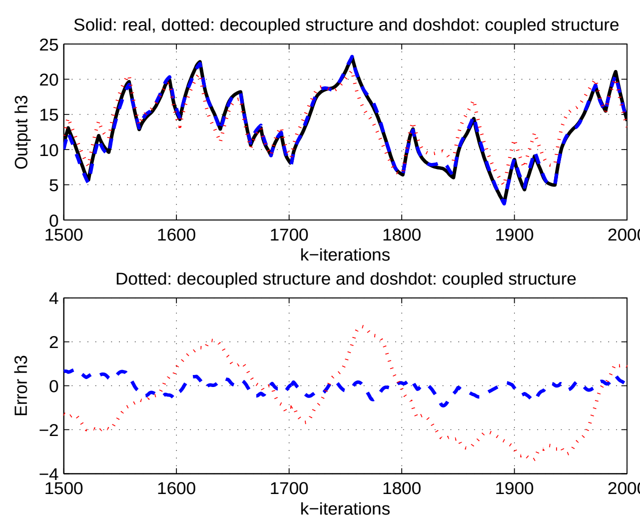

Fig. 11. Response of the real and estimated h_3

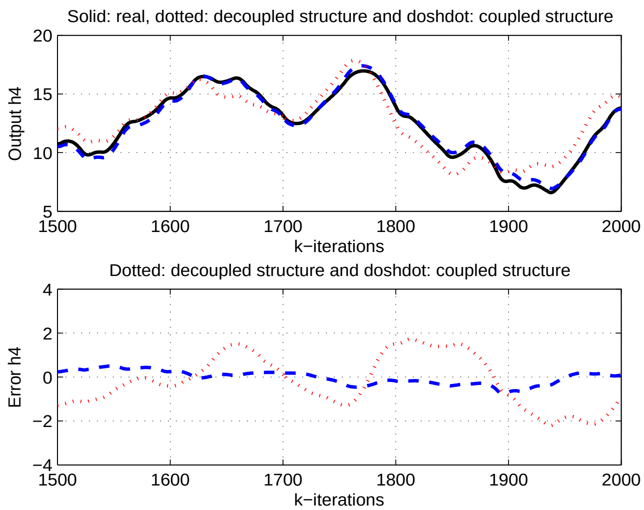

Fig. 12. Response of the real and estimated h_4

Fig. 13 illustrate the proposed strategies to control the MIMO Hammerstein model. In this part, we will present a comparison between the results of this control strategies using the models identified in the previous part in order to prove the efficiency of the coupled structure.

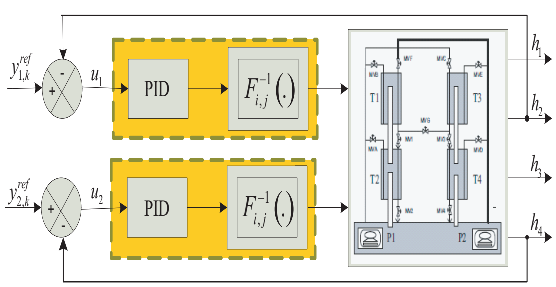

Fig. 13. Nonlinear PID structure for MIMO Hammerstein model

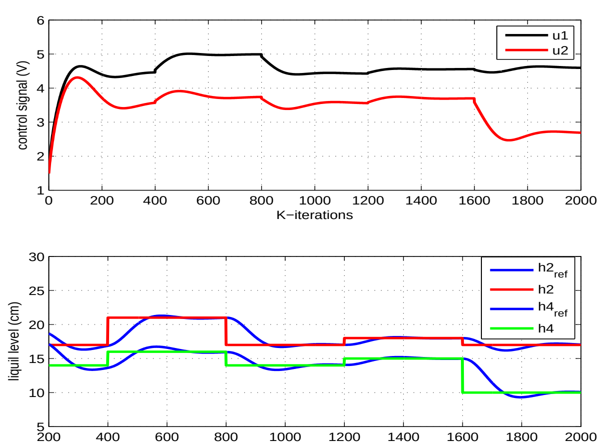

Fig. 14. Response of the identified model used the decoupled structure

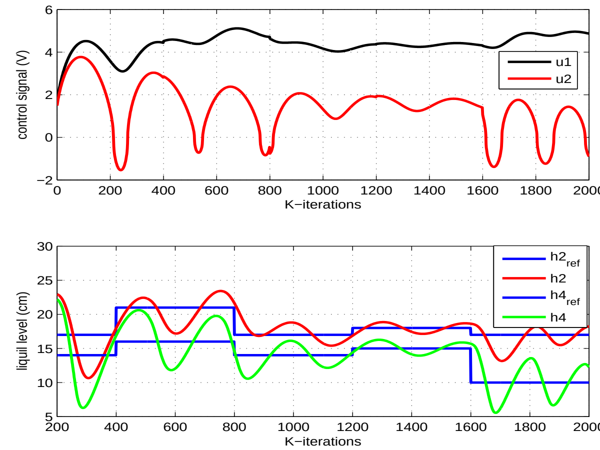

Fig. 15. Response of the system based on the decoupled structure

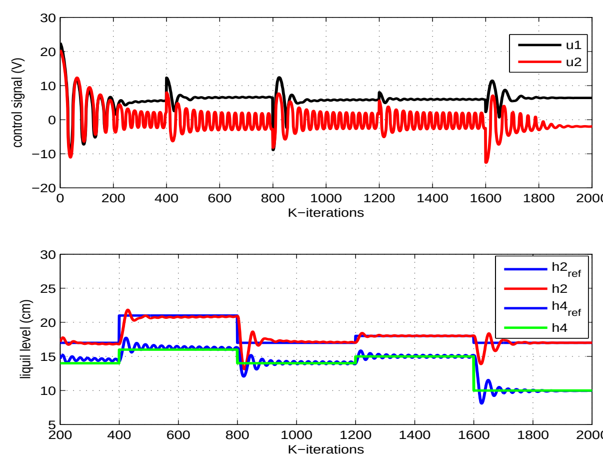

Fig. 16. Response of the identified model used the coupled structure

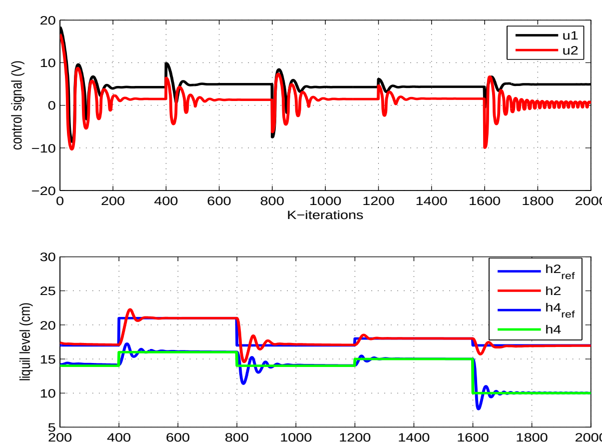

Fig. 17. Response of the system based on the coupled structure

Figures 14 and 15 show the response, respectively, of the identified model based on the decoupled structure and the real system. We used the same values of the PID regulator for the two, associate to the inverse of the nonlinearities. Figures 16 and 17 presents the responses of identified model based on the coupled structure and the real system. The proved that the used of the coupled structure has achieved a satisfactory performance in tracking the reference signal.

V. Conclusion

In this study, a nonlinear PID controller techniques has been strategically applied for the quadruple-tank process. The present paper shows a scheme for improving the nonlinear control performances strategies, form the input output data collected, and thereafter, identification of the MIMO system parameters using the RLS algorithm. In the work, two different Hammerstein design structures have been studied, and they have been compared. The effectiveness of the study is that it shows a scheme for proper design and implementation of nonlinear PID control with close loop experimental data of the process, to specify the water level in two tanks. Simulation results reveal the performance and effectiveness of the proposed method.

As a perspective, we will discusses the stability of MIMO Hammerstein model in the presence of perturbations.

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