

Design and Simulation of IMC based PI Controller for a MIMO Process

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ABSTRACT

The objective of this paper is to develop the Internal Model Control (IMC) based PI Controller for a MIMO (SISO) Process. The controller thus developed is implemented on Laboratory interacting coupled tank process through simulation. This can be regarded as the relevant process control in petrol and chemical industries. These industries involve controlling the liquid level and the flow rate in the presence of nonlinearity and disturbance which justifies the use of IMC based PI Controller scheme. For this purpose, mathematical models are obtained for each of the input-output combinations using white box approach and the respective controllers are developed. A detailed analysis on the performance of the chosen process with these controllers is carried out. Simulation studies reveal the effectiveness of proposed controller for MIMO process that exhibits nonlinear behaviour.

Keywords : Interacting coupled tank system, IMC, PI controller, MIMO.

I. INTRODUCTION

The controls of liquid level in multiple tanks and flow between the tanks are basic problems in the process industries. The process industries require liquid to be pumped and stored in the tanks and then pump it to another tank. Often the tanks are so coupled together that the levels interact and these must also be controlled.

Classical Proportional Integral (PI) controller remains the most popular approach for industrial process control. According to a survey conducted by Japan electric Measuring Instruments Manufacturers Association in 1989, 90 percent of the control loops in industries are of PID type [1] and only small portion of the control loop works well. Also survey by ender [10-11] indicates 30 percent of the controller are

operated in manual mode and 20 percent of the loops use factory tuning. It means that PID controller is widely used but poorly tuned. Poor tuning can lead to mechanical wear associated with excessive control activity, poor control performance and even poor quality products. However, tuning of PID controller parameters is a challenging task.

Many authors have suggested different algorithms for tuning PID controller parameters. These include methods based on conventional Ziegler-Nichols (ZN) tuning method [3-6], Genetic Algorithm (GA) [7], Internal Model Control (IMC) [8-9], Neural Network and Fuzzy Logic Control (FLC) [2] etc. The conventional ZN parameter tuning method has a fixed structure of PID controller design and ZN tuning is applicable to only stable systems.

Hence, these parameters may not provide satisfactory performance under transient conditions. Neural network based methods are especially useful for classification and function approximation problems which are tolerant of some imprecision having lots of training data available. Consequently, these tuning methods are less robust under momentary disturbances.

An alternative to this controller is the usage of Internal Model controller (IMC) which gives satisfactory performance for Interacting coupled tank system Level systems [1]. In this paper an Internal Model Controller is designed and implemented to Interacting coupled tank system [2]. This controller uses the model of the process to run in parallel with the actual process [3]. The IMC design procedure is exactly same as the open loop control design procedure. Unlike the open loop control the IMC structure compensates for disturbances and model uncertainty.

The paper is organized as follows: The laboratory interacting coupled tank process setup chosen for the study is detailed first. The procedure involved in developing Internal Model Control (IMC) based PI Controller is presented. In the third section simulation results on interacting coupled tank will be given with comparison study of closed loop PID controller response using Ziegler-Nichols and IMC tuning methods. The final section concludes our approach of IMC based PID controller for MIMO process.

II. PROCESS DESCRIPTION

The schematic diagram of the chosen Interacting coupled tank system is illustrated in Fig. 1.

The mass balance equations of tank1 and tank2 are given in Equations 1 and 2. The rate of change of liquid volume in each tank is equal to the net flow of

liquid into the tank. The volumetric inflow rate into the tank1 and tank2 are q_{in1} and q_{in2} . The volumetric flow rate from the tank1 and tank2 are q_{o1} and q_{o2} . Flow rate between tank1 and tank2 is q_{12} . The height of the liquid level is h_1 in tank1 and h_2 in tank2.

$$A_1 \frac{dh_1}{dt} = q_{in1} - q_{o1} - q_{12} \tag{1}$$

$$A_2 \frac{dh_2}{dt} = q_{in2} - q_{o2} + q_{12} \tag{2}$$

The system model can be formulated by ordinary differential equation using Bernoulli's law as shown in Equations 3 and 4.

$$\frac{dh_1}{dt} = \frac{q_{in1}}{A_1} - \frac{a_1}{A_1} \sqrt{2gh_1} - \frac{a_{12}}{A_1} \sqrt{2g(h_1 - h_2)} \tag{3}$$

$$\frac{dh_2}{dt} = \frac{q_{in2}}{A_2} - \frac{a_2}{A_2} \sqrt{2gh_2} + \frac{a_{12}}{A_1} \sqrt{2g(h_1 - h_2)} \tag{4}$$

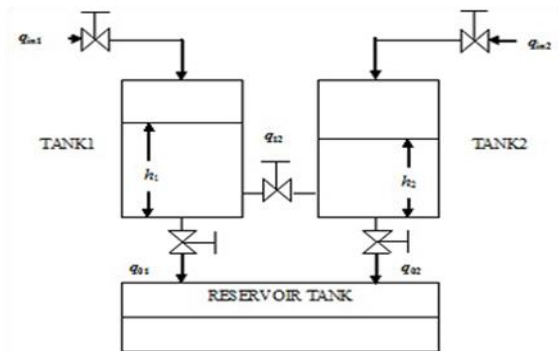


Figure 1. Schematic diagram of coupled tank process

The cross sectional area of tank1 and tank2 are $A_1=A_2=1130.4\text{cm}^2$, restriction areas in the outlet pipes of tank1 and tank2 are $a_1=a_2= 3.9\text{cm}^2$. Restriction area of interconnecting pipe is $a_{12}=1.27\text{cm}^2$ and g is the specific gravity. The maximum capacity of two tanks is 25cm. Equations 3 and 4 describe the coupled tank system dynamics. To design the control systems for this process the equations are linearized by considering small variations in q_{n1} , q_{n2} , h_1 and h_2 [3].

The variations are measured with respect to nominal operating conditions. The hand valves are adjusted so that the levels in both the tanks are brought to nominal condition initially. Nominal values of q_{n1} , q_{n2} are 26 and 20.75 l/hr and for h_1 and h_2 are 12.5 and 12.1cm respectively.

Rearranging the equations (3) & (4) and then taking laplace transform on both sides, we get

$$h_1(s) = \frac{R_1}{\tau_1 s + 1} [q_{in1}(s) - q_{12}(s)] \tag{5}$$

$$h_2(s) = \frac{R_2}{\tau_2 s + 1} [q_{in2}(s) + q_{12}(s)]$$

1. Multiloop Process

The four models relating the two controlled outputs h_1 and h_2 with two manipulated inputs q_{in1} and q_{in2} are essential to design the multiloop controllers [5]. The model transfer functions with the flow rates as manipulated inputs and the levels as controlled outputs can be written as follows:

$$G_{11}(s) = \left(\frac{h_1}{q_{in1}} \right)_{q_{in2}} ; G_{21}(s) = \left(\frac{h_2}{q_{in1}} \right)_{q_{in2}} ; \tag{6}$$

$$G_{12}(s) = \left(\frac{h_1}{q_{in2}} \right)_{q_{in1}} ; G_{22}(s) = \left(\frac{h_2}{q_{in2}} \right)_{q_{in1}}$$

The Transfer functions are computed and represented in matrix form as follows:

$$G = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} = \begin{bmatrix} \frac{0.737}{61s+1} & \frac{0.583}{111s+1} \\ \frac{0.443}{106s+1} & \frac{0.633}{81s+1} \end{bmatrix} \tag{7}$$

The block diagram of Multiloop control system of a coupled tank process employed with G_{c1} and G_{c2} as PI controllers for tank1 and tank2 is shown in Fig. 2.

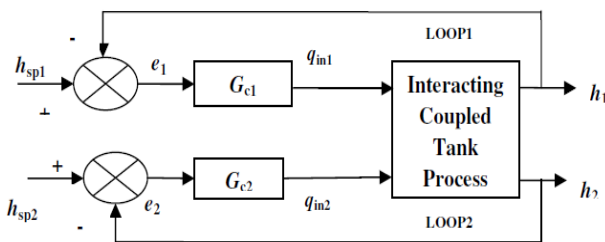


Figure 2. Multiloop PI control system

Synthesis Method of Tuning

The PI controller parameters are tuned using synthesis method for the two first order processes G_{11} and G_{22} obtained from modelling. K_c is proportional gain. T_i is integral time. K_i is integral gain. τ_c is closed loop time constant of the process. Controller parameters are determined and tabulated in Table I.

Table I. Controller Parameters for PI Controller

Parameters	Controller	
	G_{c1}	G_{c2}
$K_c = \frac{\tau_p}{k_p \tau_c}$	2.357	2.579
$K_i = \frac{K_c}{T_i}$	0.038	0.032

2. IMC based PI Controller

A more comprehensive model based design method; Internal Model Control was developed by Morari and co-workers. The IMC method is based on the simplified block diagram as shown in Fig. 3.

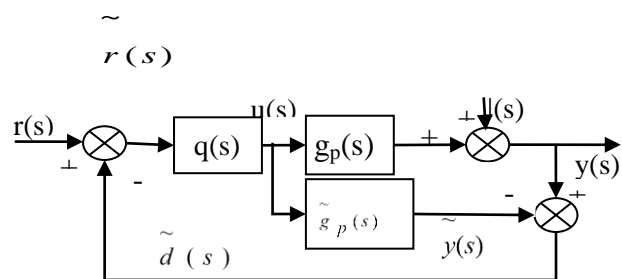


Figure 3. Internal Model Control (IMC)

We have found that the IMC structure can be rearranged to the feedback control (FBC) structure, as shown in Figure 4. This reformulation is advantageous because we will find that a PID controller often results when the IMC design procedure is used. Also, the standard IMC block diagram cannot be used for unstable systems, so this feedback form must be used for those Cases.

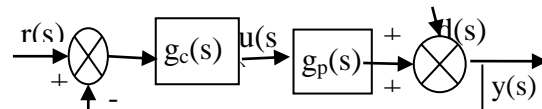


Figure 4. Standard Feedback Diagram Illustrating the Equivalence with Internal Model Control.

Step 1. Find the PI-equivalent to IMC for a First-order process,

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Parameters	Controller	
	Gc1	Gc2
$K_c = \frac{\tau_p}{K_p \lambda}$	82.76	239.27
$T_I = \tau_p$	61	106

$$\tilde{g}_p(s) = \frac{k_p}{(\tau_p s + 1)} \tag{8}$$

Step 2. Find the IMC controller transfer function, q(s) - here we allow q(s) to be improper, because we wish to end up with a PID controller when we are

$$q(s) = \tilde{q}(s) f(s) = \tilde{g}_p^{-1}(s) f(s) \tag{9}$$

$$q(s) = \frac{(\tau_p s + 1)}{k_p} \frac{1}{(\lambda s + 1)} \tag{10}$$

where λ is the tuning parameter for PI controller (and also the IMC filter factor).

Step 3. Find the equivalent standard feedback controller using the transformation

$$g_c(s) = \frac{q(s)}{1 - \tilde{g}_p(s)q(s)} \tag{11}$$

$$g_c(s) = \frac{\tau_p s + 1}{K_p \lambda s} \tag{12}$$

Step 4. Rearrange equation (12). Multiplying equation (12) by $\frac{\tau_p}{\tau_p}$, we find

$$g_c(s) = \frac{\tau_p}{K_p \lambda} \frac{\tau_p s + 1}{\tau_p s} \tag{13}$$

Step 5. Sometimes this procedure results in a PI controller cascaded with a lag term (τ_f). The general PI form is given by

$$g_c(s) = K_c \left[\frac{\tau_I s + 1}{\tau_I s} \right] \left[\frac{1}{\tau_F s + 1} \right] \tag{14}$$

Step 6. Comparing Equation (13) with Equation (14), we find K_c, T_I .

$$K_c = \frac{\tau_p}{K_p \lambda}, T_I = \tau_p \tag{15}$$

Step 7. For MIMO Process, we will consider two models from equation (7),

$$\tilde{g}_{p11}(s) = \frac{0.737}{(61s + 1)} \quad \tilde{g}_{p21}(s) = \frac{0.443}{106s + 1} \tag{16}$$

Step 8. We find K_p, τ_p values by comparing equation (16) with equation (8) and then substituting these values in equation 15) we get two set of controller parameters are shown in Table II.

Table II. Controller parameters for IMCPI

III. SIMULATION RESULTS

The simulation is carried out using MATLAB software for coupled Tank systems. Both servo and regulatory responses are obtained for the MIMO process. The servo and regulatory responses of PI Controller is shown in Fig 5(a), 5(b), 5(c).

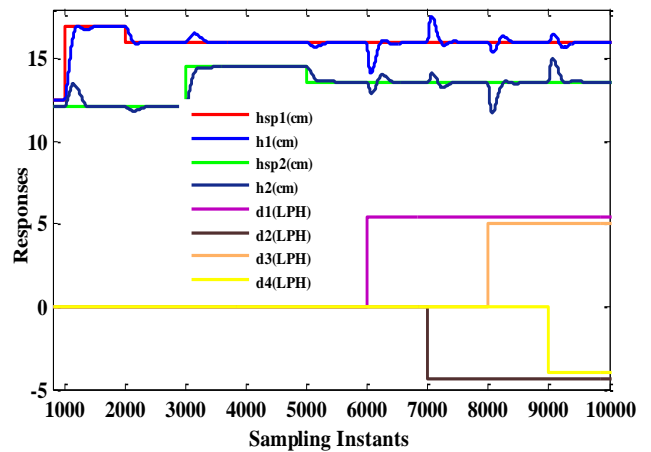


Figure 5(a). Servo and Regulatory Responses of PI Controller

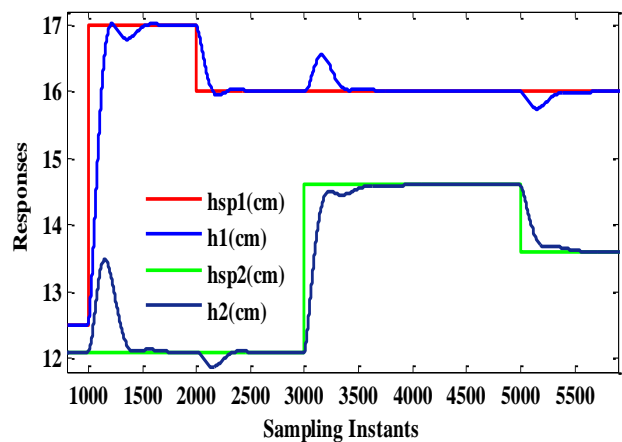


Figure 5(b). Servo Response of PI Controller

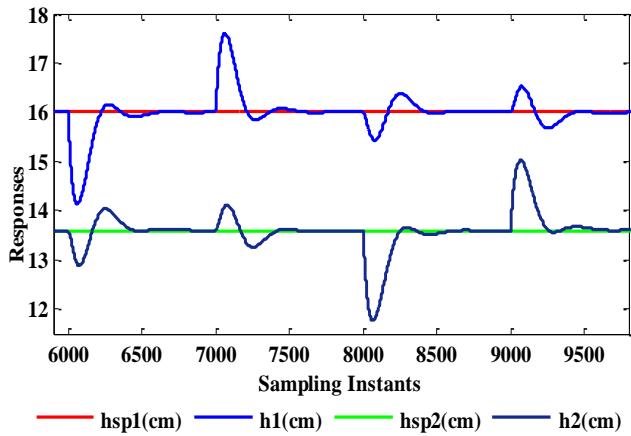


Figure 5(c) Regulatory Response of PI Controller

The servo and regulatory responses of IMC based PI Controller is shown in Fig 6(a), 6(b), 6(c).

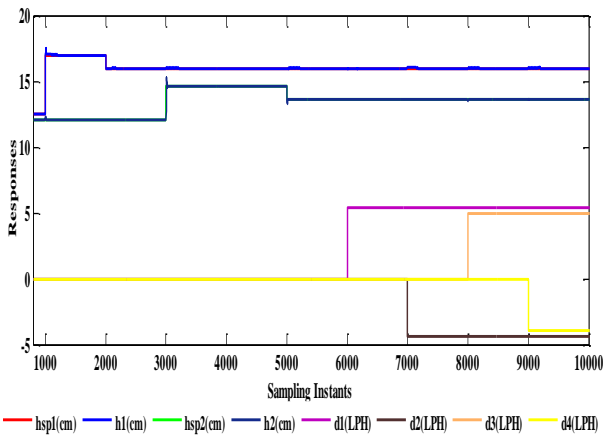


Figure 6(a) Servo Response and Regulatory of IMC PI controller

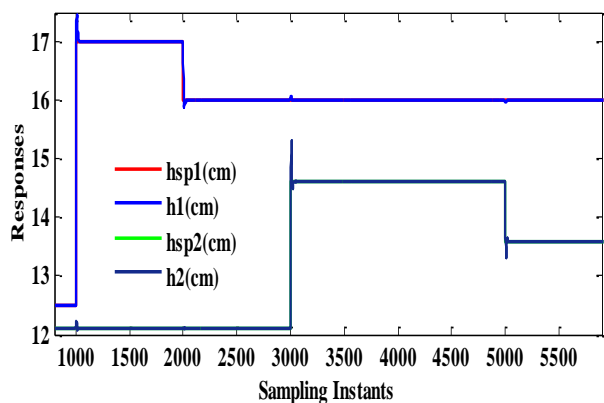


Figure 6(b) Servo Response of IMC PI Controller

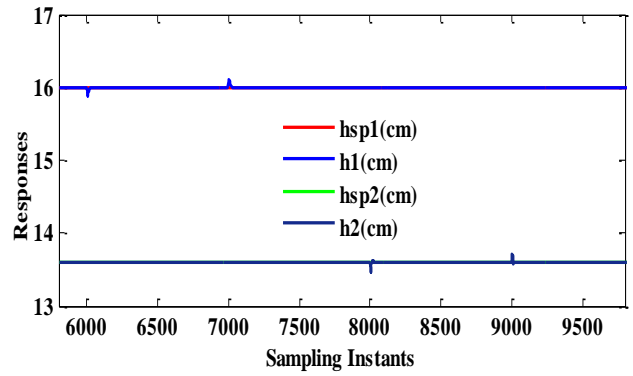


Figure 6(c) Regulatory Response of IMC PI Controller

The regulatory responses of IMCPI controller is shown in figure 7. The figure 7(a), 7(b) shows the interaction of h2 when positive and negative disturbance is applied in h1.

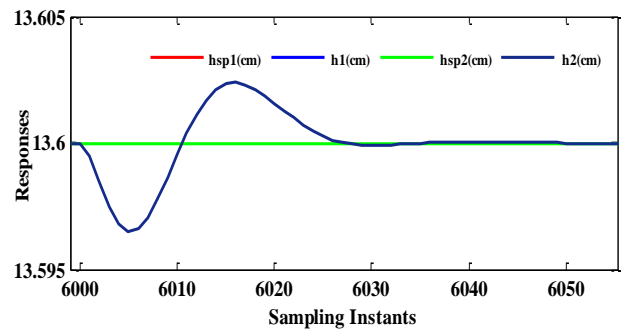


Figure 7(a) Regulatory Response of h2 for IMC PI Controller

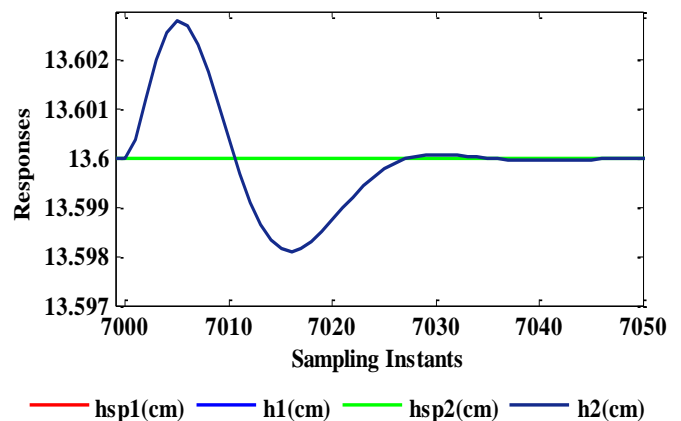


Figure 7(b) Regulatory Response of tank2 for IMC PI Controller

The figure 7(c), 7(d) shows the interaction of h1 when positive and negative disturbance is applied in h2.

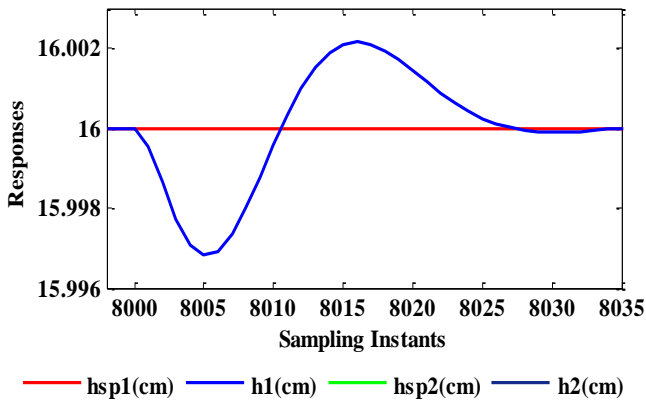


Figure 7(c) Regulatory Response of h1 for IMC PI Controller

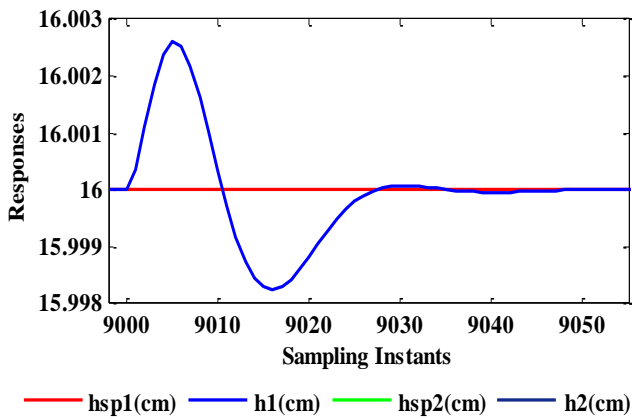


Figure 7(d) Regulatory Response of h1 for IMC PI Controller

Performance Measures of PI and IMCPI controller for h1 and h2 in shown in Table III and Table IV respectively.

Table III. Performance Measures of PI and IMCPI for h1

Controller	Settling Time				ISE			
	Servo1	Servo2	d1	d2	Servo1	Servo2	d1	d2
PI	850	300	664	724	53.6	58.34	35.11	32
IMCPI	33	34	35	37	45.4	50	27.2	24.1

Table IV. Performance Measures of PI and IMCPI for h2

Controller	Settling Time				ISE			
	Servo3	Servo4	d3	d4	Servo3	Servo4	d3	d4
PI	612	724	564	876	43.5	40.8	70.7	68
IMCPI	41	44	52	46	34.5	31.2	61.3	59.7

IV. CONCLUSION

The performance of coupled tank MIMO process has been investigated using IMC based PI controller design. Interaction effects are projected for both servo tracking and load disturbance rejection. From the plots, it is clear that the overall system performance with IMCPI is observed to have better tracking and disturbance rejection than that of the system with PI controller. From the Table it is observed that IMCPI have better settling time and ISE values when compared to PI controller. The resulting performance could be improved by a better choice of the gain. This concludes that the Internal Model Control based PI controller is applicable for nonlinear coupled tank systems.

V. REFERENCES

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