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Design and Implementation of Robust PI Controller for Quadrapule Tank Process

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ABSTRACT: This paper proposes a simple approach to design a robust PI controller for an uncertain MIMO system that will guarantee closed loop stability. The Robust Controller design method used here is based on Small Gain theorem. The controller is designed for a Quadruple tank process which is a good example for an uncertain system. The variable to be controlled is the liquid level in tank2. Inflow into tank1 is considered as the manipulated variable. The performance of the controller is evaluated using Settling time, Rise time and ISE. Simulation is carried out using MATLAB SIMULINK software.

KEYWORDS: Controller, Quadruple Tank, Small Gain Theorem, Closed Loop Stability.

I.INTRODUCTION

Despite the enormous interest that modern control techniques have sparked during the last few decades, PID controllers are still preferred in industrial process control. The reason is that controllers designed with the aid of modern control techniques are usually of high order difficult to implement, and virtually impossible to re-tune on line.

Controllers are always designed based on the information about the dynamic behaviour of the process regardless of the design technique. This information may have a system of coupled partial differential equations or simply the process gain and the settling time experienced by the plant operator. The accuracy of this information varies but is never perfect. Moreover, the behaviour of the plant itself changes with time and these changes are rarely captured in the models. It is most desirable that the controller be insensitive to this kind of model uncertainty that is the controller should be robust.Robust controller design is one way of dealing with uncertainty upon the parameters of the plant model in order to guarantee the stability of the closed loop system and a certain level of performance for the given domain of parameter variations. However for large variations of the plant model characteristics it may become difficult to assure a satisfactory level of performance and even to guarantee the stability.Robust controllers can be designed using various approaches. Robust controller design using Small Gain Theorem is presented in [1]. The optimal control approach is used to design robust controllers in [3]. Dubravska M. and Harsanyi L. [4, 5] have proposed robust controller design procedure for uncertain system. In [6] the author presented robust controller design for uncertain plant with bounded parameters using Kharitonov theorem.

II. DESCRIPTION OF THE PROCESS

The quadruple tank system is a benchmark system used to analyse the nonlinear effects in a multivariable process. This helps in realizing the multi loop systems in industries. The multivariable dynamic property in a quadruple tank system is the way in which each pump affects both the outputs of the system. The quadruple tank system is widely used in visualizing the dynamic interactions and non-linearity exhibited in the operation of power plants, chemical industries and biotechnological fields.

Multivariable system involves a number of control loops which interact with each other where one input not only affects its own output but also influences other outputs of the system.

A schematic diagram of Quadruple tank process is shown in Fig. The target is to control the level in the lower two tanks using two pumps. The process inputs are V_1 and V_2 (input voltages to the pumps) and the outputs are y_1 and y_2 (voltages from level measurement devices).

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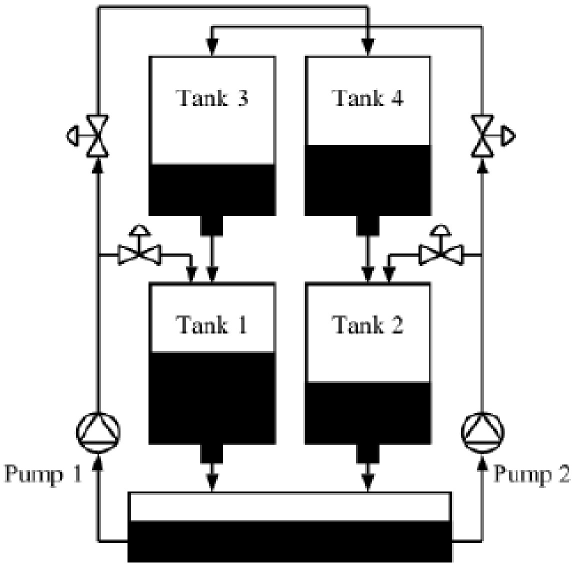

Mass balance and Bernoulli's law yield,

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}v_1$$
$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}v_2$$
$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}v_2$$
$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}v_1$$

Where

A_i cross-section of Tank ;
a_i cross-section of the outlet hole;
h_i water level.
γ_1 , γ_2 are valve flow co-efficient.

TABLE 1
PARAMETER VALUES OF LABORATORY QUADRUPLE TANK PROCESS

A_1, A_3 $[cm^2]$	28
A_2, A_4 $[cm^2]$	32
a_1, a_3 $[cm^2]$	0.071
a_2, a_4 $[cm^2]$	0.057
k_c [v/cm]	0.50
g [cm/s^2]	9.81

A. ***Minimum Phase System***

When the fraction of liquid entering the lower tanks is less than that of upper tanks then the system is said to be minimum phase system.

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TABLE 2
OPERATING POINTS OF MINIMUM PHASE SYSTEM

Parameters	Minimum phase system
(h_1, h_2) [cm]	(8.516,8.877)
(h_3, h_4) [cm]	(1.135,0.97)
(v_1, v_2) [V]	(2.5,2.5)
(k_1, k_2) $[cm^3/Vs]$	(3.33,3.35)
(γ_1, γ_2)	(0.70,0.60)

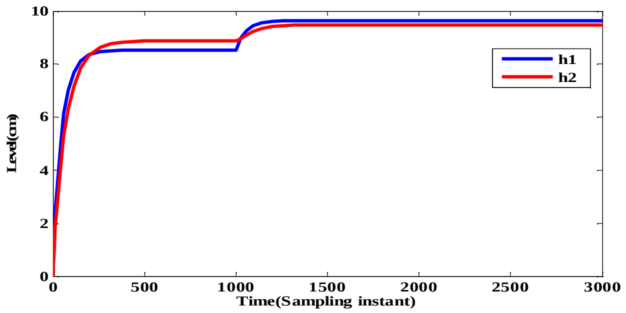

Fig.2 Open loop response of the process with 5% change in 1st input

Corresponding transfer functions are,

$$G_{11} = \frac{4.464}{47.04S+1} e^{-9.86s}$$

$$G_{21} = \frac{2.396}{89.7S+1} e^{-20.1s}$$

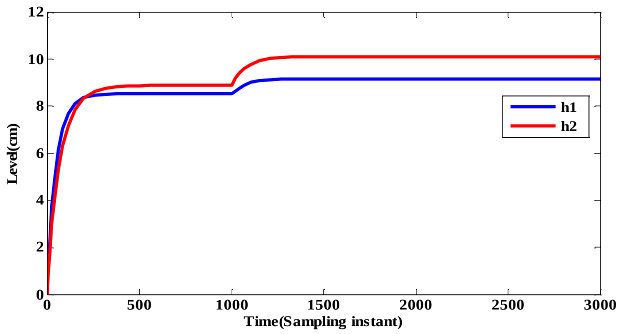

Fig.3 Open loop response of the process with 5% change in 2nd input

Corresponding transfer functions are,

$$G_{12} = \frac{2.532}{62.715S+1} e^{-14.72s}$$

$$G_{22} = \frac{4.892}{80.13S+1} e^{-0.5s}$$

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For minimum phase,

$$G_+(S) = \begin{bmatrix} \frac{4.464}{463.8s^2+56.9s+1} & \frac{2.532}{923.16s^2+77.43s+1} \\ \frac{2.936}{1802.9s^2+109.8s+1} & \frac{4.892}{40.06s^2+80.3s+1} \end{bmatrix}$$

B. ***Relative Gain Array analysis for Minimum Phase system***

$$\overline{y_1} = \frac{4.464}{463.8s^2+56.9s+1}\overline{m_1} + \frac{2.532}{923.16s^2+77.43s+1}\overline{m_2}$$

$$\overline{y_1} = \frac{2.396}{180.2s^2+109.8s+1}\overline{m_1} + \frac{4.892}{40.06s^2+80.63s+1}\overline{m_2}$$

$$\Lambda = \begin{bmatrix} 1.495 & -0.495 \\ -0.495 & 1.495 \end{bmatrix}$$

Recommended Paring is $y_1$with m_1 and y_2 withm_2.

C. ***Non-Minimum Phase System***

When the fraction of liquid entering the upper tanks is less than that of lower tanks then the system is said to be non minimum phase system.

TABLE 3
OPERATING POINTS OF NON-MINIMUM PHASE SYSTEM

Parameters	Non-minimum phase system
$(h_1,)$ [cm]	(7.837,8.294)
(h_3, h_4) [cm]	(2.98,3.141)
(v_1, v_2) [V]	(2.5,2.5)
(k_1, k_2) [cm^3/Vs]	(3.14,3.29)
(γ_1, γ_2)	(0.43,0.34)

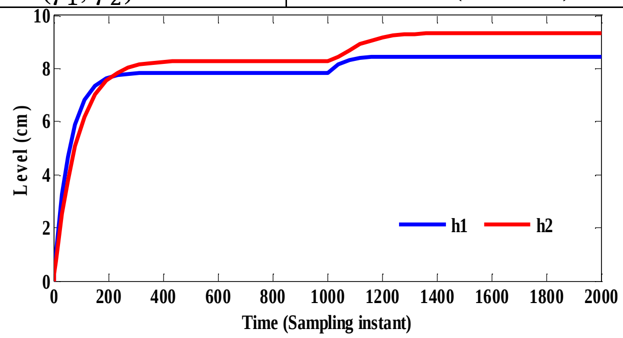

Fig.4 Open loop response of the process with 5% change in 1st input

Corresponding transfer functions are,

$$G_{11} = \frac{2.448}{48.9S+1}e^{-4.5s}$$

$$G_{21} = \frac{4.208}{101.71S+1}e^{-29.15s}$$

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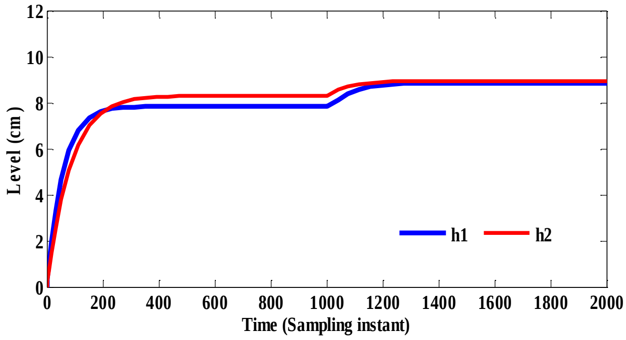

Fig.5 Open loop response of the process with 5% change in 2nd input

Corresponding transfer functions are,

$$G_{12}=\frac{3.984}{72.31S+1}e^{-18.84s}$$

$$G_{22}=\frac{2.6}{69.7S+1}e^{-4s}$$

For non-minimum phase,

$$G\_(S)=\begin{bmatrix}\frac{2.448}{220.05s^2+53.4s+1} & \frac{3.984}{1362.3s^2+91.15s+1}\\ \frac{4.208}{2964.8s^2+130.86s+1} & \frac{2.6}{278.8s^2+73.7s+1}\end{bmatrix}$$

D. ***Relative Gain Array analysis for Non-Minimum Phase system***

$$\overline{y_1}=\frac{2.448}{220.05s^2+53.4s+1}\overline{m_1}+\frac{3.984}{1362.3s^2+91.15s+1}\overline{m_2}$$

$$\overline{y_1}=\frac{4.208}{2964.8s^2+130.86s+1}\overline{m_1}+\frac{2.6}{278.8s^2+73.7s+1}\overline{m_2}$$

$$\Lambda=\begin{bmatrix}-0.612 & 1.612\\ 1.612 & -0.612\end{bmatrix}$$

Recommended Paring is $y_1$with m_2 and y_2 with m_1.

III. DESIGN OF ROBUST CONTROLLER

The robust PI controller is designed using Small Gain Theorem for Quadruple-Tank process. The parameters of the controller for minimum and non-minimum phase system are given below.

1. ROBUST- PI USING SMALL GAIN THEOREM

A. Minimum Phase System

For G_{11}, n_p=47.03, n_i=1 and K is selected as 70 so that the stability condition is satisfied. For G_{22}, n_p=80.12, n_i=1 and K=30. The closed loop servo and regulatory responses of the process under nominal operating condition as well as for another operating condition are obtained and presented in Figures **1** and **2** respectively for a set point change of 1cm from the nominal level and a load change of 10%.

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B. Non-Minimum Phase System

For G_{11}, n_p=48.9, n_i=1 and K is selected as 50 so that the stability condition is satisfied. For G_{22}, n_p=69.7, n_i=1 and K=70. The closed loop servo and regulatory responses of the process under nominal operating condition as well as for another operating condition are obtained and presented in Figures **3** and **4** respectively for a set point change of 1cm from the nominal level and a load change of 10%.

2. ZN-PI CONTROLLER

For G_{11}, K_c=9.78, T_i=14.98. For G_{22}, K_c=15.68, T_i=13.32 are obtained using Ziegler Nichol's method. The closed loop servo and regulatory response of the process is presented in Figures **5**. The closed loop servo response of the process with ZN-PI controller for non-minimum phase behaviour is unstable.

IV. SIMULATION RESULTS

The performance of the process with the robust PI controller is evaluated using Settling time, Overshoot, ISE through MATLAB Simulink software.

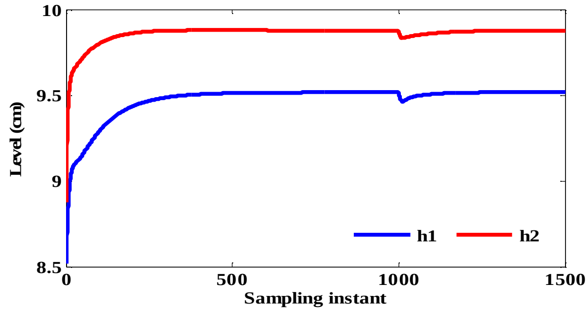

Fig.6 Servo and Regulatory response of the process with Robust PI controller using SGT (Minimum phase system- under nominal operating condition).

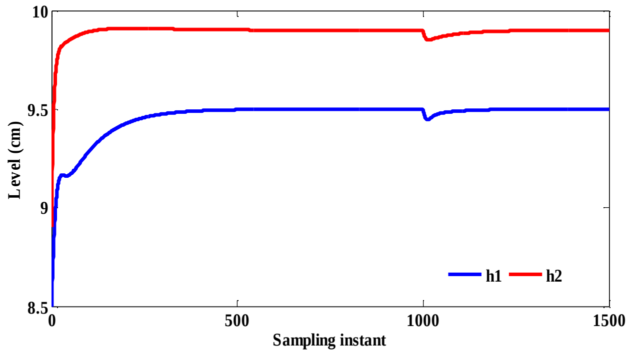

Fig.7 Servo and Regulatory response of the process with Robust PI controller using SGT (Minimum phase system- under operating condition a_1, a_3=0.05 &a_2, a_4=0.03).

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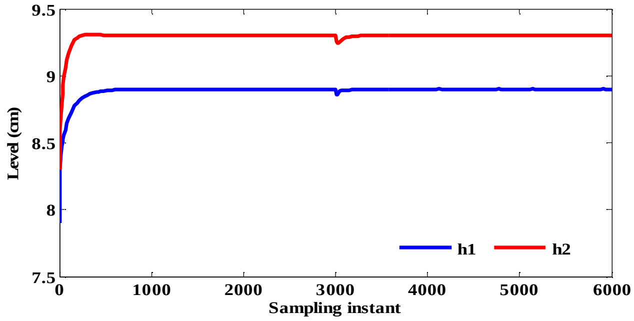

Fig.8 Servo and Regulatory response of the process with Robust PI controller using SGT (Non-minimum phase system - under nominal operating condition).

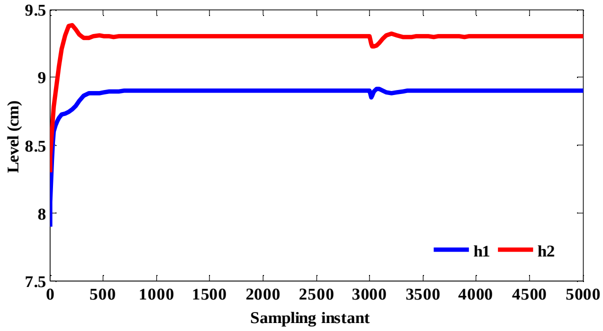

Fig.9 Servo and Regulatory response of the process with Robust PI controller using SGT (Non-minimum phase system-under Operating condition a_1, a_3=0.05 & a_2, a_4=0.03).

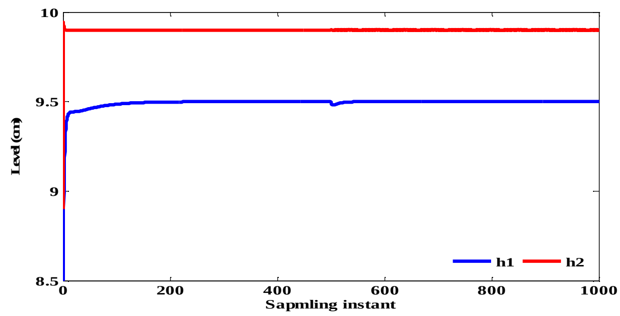

Fig.10 Servo and Regulatory response of the process with ZN based PI controller (Under nominal operating condition).

TABLE 4

PERFORMANCE EVALUATION OF THE PROCESS (MINIMUM PHASE) WITH DESIGNED CONTROLLERS (NOMINAL OPERATING CONDITION)

Controller	Settling time		Overshoot (%)		ISE	
	h_1	h_2	h_1	h_2	h_1	h_2
SGT	900	800	-	-	19.73	6.407
ZN-PI	400	-	-	4.68	1.757	0.04

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Vol. 7, Issue 9, September 2018

TABLE 5

PERFORMANCE EVALUATION OF THE PROCESS (MINIMUM PHASE) WITH DESIGNED CONTROLLERS

(Operating condition a_1, a_3=0.05 & a_2,a_4= 0.03)

Controller	Settling time		Overshoot (%)		ISE	
	h_1	h_2	h_1	h_2	h_1	h_2
SGT	1000	1050	-	0.10	17.05	3.625
ZN-PI	400	-	-	0.47	1.399	0.047

V. CONCLUSION

The Robust PI controller using Small Gain Theorem is designed and implemented over Quadruple tank process. The design method based on the Small Gain Theorem guarantee the required closed-loop stability degree. The Robust PI controller performance is compared with Z-N based PI controller. The simulation is carried out using MATLAB SIMULINK software. The simulation results are presented along with performance evaluation Table. It is observed from the results that the performance of the process with robust PI controller is better than ZN based PI controller in view of Settling time, Rise time and ISE.

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