Jurnal
Teknologi

Full Paper

CONTROL OF A COUPLED TANK SYSTEM USING PI CONTROLLER WITH ADVANCED CONTROL METHODS

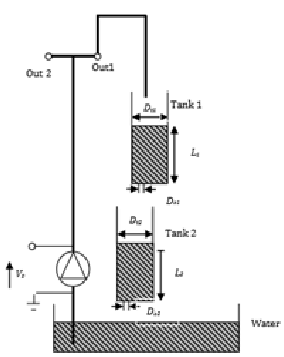
Ling Nai Ho, Norhaliza Abdul Wahab*, Ibrahim A. Shehu, A. Alhassan, I. Albool, N. Ibnihajar, B. M. Othman, M. S. Zainal, M. J. Ibrahim, M. S. Rasol

Control and Mechatronics Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Received
15 December 2015
Received in revised form
30 March 2016
Accepted
30 May 2016

*Corresponding author
aliza@fke.utm.my

Graphical abstract



Abstract

The liquid level control in tanks and flow control between cascaded or coupled tanks are the basic control problems exist in process industries nowadays. Liquids are to be pumped, stored or mixed in tanks for various types of chemical processes and all these require essential control and regulation of flow and liquid level. In this paper, different types of tuning methods are proposed for Proportional-Integral (PI) controller and are further improved with integration of Advanced Process Control (APC) method such as feedforward and gain scheduling to essentially control the liquid level in Tank 2 of a coupled tank system. The MATLAB/Simulink tools are used to design PI controller using pole-placement, Ciancone, Cohen Coon and modified Ziegler-Nichols tuning method with Cohen Coon tuning method found to have a better performance. Advanced process control such as feedforward-plus-PI, Gain Scheduling (GS) based PI, Internal Model Control (IMC) based PI, feedforward-plus-GS-based PI and feedforward-plus-IMC-based PI controllers are further tested as improvement version to further compare the significance of the advanced process control outcomes hence GS-PI, improved GI-base PI-plus FF found to have better performance. The GS method is built over five operating points to approximate the system's nonlinearity and is eventually combined with feedforward control to yield a much better performance.

Keywords: Level control, PI controller, Control Tuning,Feedforward,Internal Model Control, Gain Scheduling

1.0 INTRODUCTION

In the process of industrial production, liquid-level is an important parameter, and widely applied in various field such as liquid storage tank, feeding tank, product tank, intermediate buffer containers and water tanks as well as other equipment [1]. The liquid-level control of coupled tank system is a typical representative of the process control and is also one of the hot researches in control field. Usually, liquid-level control of coupled tanks is always associated with lumping lag, nonlinear and complex characteristics where the control accuracy is directly affected by system status, system parameters and the control algorithm [2]. The primary objective of process control is to maintain a process at the desired operating conditions safely and efficiently, while satisfying environmental and product quality requirements [3, 4].

In typical control application, it's almost impossible to achieve all the control goals such as zero steady state, stable closed loop system with no disturbances, good tracking, and high robustness simultaneously since they involve inherent conflicts and tradeoffs [5, 6]. The tradeoffs must balance between performance and robustness which can be achieved by applying the right tuning method to the system but, sometimes the best turning methods seems to be something of a puzzle because the turning method that is best for a particular process or system may not necessary be the best in another process/or system of entirely different configuration [7, 8]. That is why, one may not generalized and conclude the best turning among all the tuning method because every turning method has its own pros and cons but can conclude that some turning method have excellent performance in disturbance rejection and /or robustness than others . Thus, different types of tuning method have been proposed to achieve the satisfactory tradeoffs between performance and robustness as suggested by Astrom and Hagglund [5]. In this paper the same notion is being adopted in the study of coupled tank system whereby different turning method have been investigated to achieved the best tradeoff and couple it with the advanced control strategy have been proposed in order to improve the transient response of the system.

The coupled-tank system as shown in Figure 1, consists of one water basin, two tanks and a water pump where the closed-loop system is designed to control the water level in tank 2 with a feedback loop between tank 1 and tank 2. Input to the system is voltage applied to the pump where tank 1 is assumed to be in steady state. The pump thrusts water vertically to the orifice "Out1" before entering the upper tank. Tank 1 then feeds tank 2 as shown in Figure 1 and water levels are measured in unit of centimeters. The other elements of the work include modeling and analysis of the control system using Proportional Integral (PI) controller as well as various tuning methods in obtaining the desirable performances of the system. Implementation of advanced process control methods are also being done to show the distinguish improvement of the transient response of the system over the conventional single loop feedback system.

This paper is organized in five sections where Section 1 gives the introduction of process control problems and detailed description of the coupled tank system. This is followed by the mathematical derivation of tank 2 model using both analytical and empirical method in Section 2. In Section 3, various tuning methods are used in PI control design whereas APC method such as feedforward, IMC and gain scheduling are adopted for further improvement. The simulations results are presented and analyzed in Section 4 and ended with conclusion in Section 5.

2.0 MATHEMATICAL MODELING

Two approaches have been used to obtain the model of the system. The first method is via analytical approach with derivation of fundamental laws and followed by the use of Process Reaction Curves (PRC) in empirical approach.

2.1 Analytical Approach

The parameters for the coupled-tank system and the design specifications of the controller are presented in Table 1 and 2 respectively.

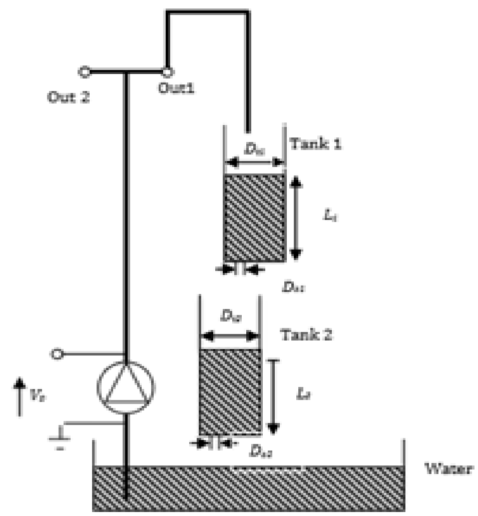


Figure 1 Coupled tank system

Table 1 Tank 2 model parameters

Parameters	Value
Inside Diameter of Tank 1, D_{t1}	4.445 cm
Inside Diameter of Tank 2, D_{t2}	4.445 cm
Pump flow constant, K_p	3.3 cm^3/s/V
Cross sectional area of tank 1 outlet hole, A_{o1}	0.1781 cm^2
Cross sectional area of tank 2 outlet hole, A_{o2}	0.1781 cm^2
Cross sectional area of tank 1, A_{t1}	15.5179 cm^2
Cross sectional area of tank 2, A_{t2}	15.5179 cm^2
Gravitational constant, g	981 cm/s^2

Table 2 Controller design specifications

Performance Specifications	Value
The operating point, $L_{10} = L_{20}$	15 cm
Percent overshoot, PO_2	$PO_2 \leq 10\%$
Settling time, T_s	$T_{s2} \leq 20$ s
Steady state error, ε_{ss}	0

By using the law of conservation of mass and Bernoulli's theorem:

$$Q_{in} = A_{o1}\sqrt{2gL_1} \quad \text{and} \quad Q_o = A_{o2}\sqrt{2gL_2}$$

$$\frac{dL_2}{dt} = -\frac{A_{o2}}{A_{t2}}\sqrt{2gL_2} + \frac{A_{o1}}{A_{t2}}\sqrt{2gL_1}$$

$$\frac{dL_2}{dt} = -\frac{A_{o2}}{A_{t2}}\sqrt{2g}(\sqrt{L_2}) + \frac{A_{o1}}{A_{t2}}\sqrt{2g}(\sqrt{L_1})(1)$$

Since equation 1 is nonlinear, linearize using Taylor Series Expansion:

$$f(h) = f(h_0) + f^{'}(h_0)(h - h_0) \qquad (2)$$

Where the non linear terms are $\sqrt{h_1}$ and $\sqrt{h_2}$

$$f(h) = \sqrt{L_1}$$

$$= \sqrt{L_{1o}} + \frac{df}{dh}|_{h_0}(h - h_0)$$

$$= \sqrt{L_{1o}} + \frac{1}{2}L_{1o}^{-\frac{1}{2}}(L_1 - L_{1o}) \qquad (3)$$

and

$$f(h) = \sqrt{L_2}$$

$$= \sqrt{L_{2o}} + \frac{df}{dh}|_{h_0}(h - h_0)$$

$$= \sqrt{L_{2o}} + \frac{1}{2}L_{2o}^{-\frac{1}{2}}(L_2 - L_{2o})(4)$$

Substitute the linearized equation (3) and (4) into equation (1),

$$A_{t2}\frac{dL_2}{dt} = -A_{o2}\sqrt{2g}\left[\sqrt{L_{2o}} + \frac{1}{2}L_{2o}^{-\frac{1}{2}}(L_2 - L_{2o})\right] + A_{o1}\sqrt{2g}\left[\sqrt{L_{1o}} + \frac{1}{2}L_{1o}^{-\frac{1}{2}}(L_1 - L_{1o})\right](5)$$

In steady-state, equation (5) becomes

$$A_{t2}\frac{dL_{2,0}}{dt} = -A_{o2}\sqrt{2g}\left[\sqrt{L_{2o}} + \frac{1}{2}L_{2o}^{-\frac{1}{2}}(L_{2o} - L_{2o})\right] + A_{o1}\sqrt{2g}\left[\sqrt{L_{1o}} + \frac{1}{2}L_{1o}^{-\frac{1}{2}}(L_{1o} - L_{1o})\right] \quad (6)$$

Expressing in deviation terms, equation (5)-(6):

$$A_{t2}\frac{dL_2^{'}}{dt} = -A_{o2}\sqrt{2g}\left[\frac{1}{2}L_{2o}^{-\frac{1}{2}}(L_2 - L_{2o})\right] + A_{o1}\sqrt{2g}\left[\frac{1}{2}L_{1o}^{-\frac{1}{2}}(L_1 - L_{1o})\right] \quad (7)$$

Let $L_1^{'} = L_1 - L_{1o}$ and $L_2^{'} = L_2 - L_{2o}$,

Equation (7) becomes

$$A_{t2}\frac{dL_2^{'}}{dt} = -A_{o2}\sqrt{2g}\left[\frac{1}{2}L_{2o}^{-\frac{1}{2}}L_2^{'}\right] + A_{o1}\sqrt{2g}\left[\frac{1}{2}L_{1o}^{-\frac{1}{2}}L_1^{'}\right]$$

Therefore the linearized equation become;-

$$\frac{dL_2^{'}}{dt} = \frac{1}{2}\left(-\frac{A_{o2}\sqrt{2g}L_2^{'}}{A_{t2}\sqrt{L_{2o}}} + \frac{A_{o1}\sqrt{2g}L_1^{'}}{A_{t2}\sqrt{L_{1o}}}\right) \qquad (8)$$

Applying Laplace transform on equation (8),

$$sL_2^{'}(s) = -\frac{1}{2}\frac{A_{o2}\sqrt{2g}}{A_{t2}\sqrt{L_{2o}}}L_2^{'}(s) + \frac{1}{2}\frac{A_{o1}\sqrt{2g}}{A_{t2}\sqrt{L_{1o}}}L_1^{'}(s)$$

$$\frac{L_2^{'}(s)}{L_1^{'}(s)} = \frac{\frac{A_{o1}\sqrt{L_{2o}}}{A_{o2}\sqrt{L_{1o}}}}{\frac{\sqrt{2}A_{t2}\sqrt{L_{2o}}}{A_{o2}\sqrt{g}}s+1}$$

Rearranging the equations,

$$G_2^{'}(s) = \frac{K_p}{\tau s+1} \qquad (9)$$

Where

$$\frac{L_2^{'}(s)}{L_1^{'}(s)} = G_2^{'}(s), \qquad \tau = \frac{\sqrt{2}A_{t2}\sqrt{L_{2o}}}{A_{o2}\sqrt{g}} \text{and } K_p = \frac{A_{o1}\sqrt{L_{2o}}}{A_{o2}\sqrt{L_{1o}}}$$

Therefore,

$$G_2\ (s) = \frac{1}{15.2368s+1} \qquad (10)$$

Hence, $G_2(s)$ is the 1st order transfer function with process gain, K_p = 1, and time constant, τ_2 = 15.2438 s. Tank 2 is a 1st order system with no time delay.

2.2 Empirical Model

Process Reaction Curve (PRC) method is used in this section to obtain the model of Tank 2. Cohen and coon reported that process reaction curve for most controlled process can be reasonably approximated by the step response of a first order system with time delay requiring only some parameters k_p, τ_i and θ to determine the process without which the turning parameters for the corresponding controllers will not be possible. Figure 2 shows the nonlinear output response of Tank 2.

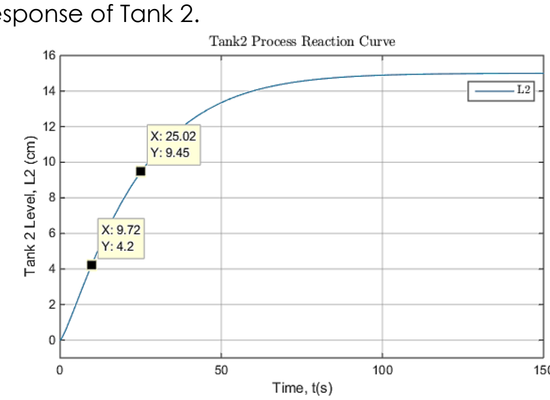


Figure 2 Process reaction curve for Tank 2

From Figure 2, the parameters needed to obtained the models are as follows

$$t_{63\%} = 25.02\ s\ ,\ \ t_{28\%} = 9.72\ s$$

We obtain,

$$K_p = \frac{\Delta y}{\Delta x} = 1\ ,\ \ \tau = 1.5(t_{63\%} - t_{28\%}), \qquad \theta = t_{63\%} - \tau$$

$$= 1.5(25.02 - 9.72) \qquad = 25.02 - 22.95$$

$$= 22.95\ s \qquad\qquad = 2.07\ s$$

Hence,

$$G(s) = \frac{1}{22.95s+1}e^{-2.07\ s} \tag{11}$$

Basically both the analytical and empirical methods obtain the same 1st order model but with slightly different time constant, and dead time as shown below:

$$\left.\begin{matrix}\tau_{analytical} = 15.23\ s \\ \tau_{empirical} = 22.95\ s\end{matrix}\right\} differenceof\ 7.72\ s$$

And

$$\left.\begin{matrix}\theta_{analytical} = 0\ s \\ \theta_{empirical} = 2.07\ s\end{matrix}\right\} differenceof\ 2.07\ s$$

This shows that the transfer function obtained from empirical method has a much slower response compared to analytical method and there is also a small dead time of 2.07 seconds in the empirical method.

In conjunction with that, referring to the linearized model obtained in equation (8), the nonlinear term, ($\sqrt{h_1}$ and $\sqrt{h_2}$) has been removed through the linearization process and the whole system is multiplied by a gain of 0.5. This makes the time constant for linearized model equation (10) become much smaller compare to one obtained from empirical modeling equation (11). Thus, linearized model of equation (10) has faster response as clearly shown in Figure 3.

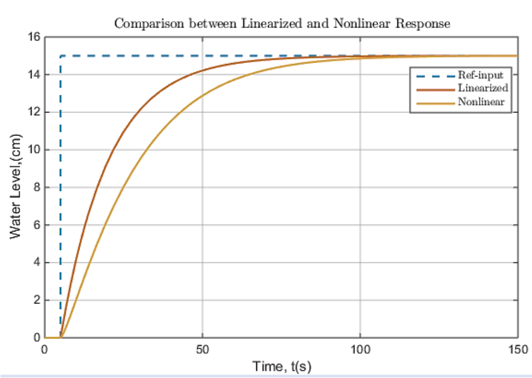


Figure 3 Comparisons between linear and nonlinear response

3.0 CONTROLLER DESIGN

The design of PI controller and integration of advanced control methods are discussed in this section.

3.1 Proportional-Integral (PI) Control Design

In this paper, we focus only on the design of Proportional-Integral (PI) controller where the controller gains K_c and K_I are obtained and compare via four different tuning methods to get the best performance, namely pole placement, Ciancone, Modified Ziegler-Nichols and Cohen-Coon methods.

3.1.1 Pole Placement Method

Proportional-plus-Integral (PI) controller gains are designed using pole placement method which yields $K_c = 5.1$ and $K_I = 1.7$.

The characteristic equation of the system is obtained as

$$1 + G_2(s)Gc_2(s) = 0$$

Hence,

$$1 + \frac{K_{dc2}}{\tau_2 s + 1}\left[\frac{K_{p2}s + K_{i2}}{s}\right] = 0$$
$$\tau_2 s^2 + s + (K_{dc2})(K_{p2})s + K_{i2}K_{dc2} = 0$$
$$\tau_2 s^2 + (1 + K_{dc2}K_{p2})s + K_{i2}K_{dc2} = 0$$

Therefore,

$$s^2 + \frac{(1 + K_{dc2}K_{p2})}{\tau_2}s + \frac{K_{i2}K_{dc2}}{\tau_2} = 0$$

Comparing with

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$$

$$2\zeta\omega_n = \frac{(1+K_{dc2}K_{p2})}{\tau_2} \text{and} \qquad \omega_n^2 = \frac{K_{i2}K_{dc2}}{\tau_2}$$
$$K_{p2} = \frac{2\zeta\omega_n\tau_2 - 1}{K_{dc2}} \qquad K_{i2} = \frac{\omega_n^2\tau_2}{K_{dc2}}$$

Where,

$$\tau_2 = \frac{4}{\zeta_2\omega_{n2}}$$

Therefore,

$$\omega_{n2} = \frac{4}{\zeta_2(20)} = 0.3383\ rad/s$$

After we obtained the value of ζ_2 and ω_{n2}, the gain value of K_{p2} and K_{i2} can be obtained as follows:

$$K_{p2} = \frac{2(0.5912)(0.3383)(15.2368) - 1}{1} = 5.0948 \approx 5.1$$

$$K_{i2} = \frac{\omega_n^2\tau_2}{K_{dc2}} = \frac{(0.3383)^2(15.2368)}{1} = 1.7438 \approx 1.7$$

Therefore, the transfer function of the controller is obtained as

$$G_c(s) = K_c + \frac{K_i}{s} = 5.1 + \frac{1.7}{s} \qquad (12)$$

3.1.2 Ciancone Method

By referring to the empirical model obtained in equation (11) and the Ciancone Correlation Curve for set point change, fraction dead time is obtained as

$$\left(\frac{\theta}{\theta+\tau}\right) = 0.083 \text{ s}$$

and

$$K_c K_p = 1.3$$
$$K_c = 1.35$$

and

$$\frac{\tau_i}{\theta+\tau} = 0.73$$
$$\tau_i = 0.73(2.07 + 22.95)$$
$$= 18.2646\, s$$

Hence,

$$K_i = \frac{K_c}{\tau_i} = \frac{1.35}{18.2646} = 0.0739$$

Therefore, the transfer function of the controller is obtained as

$$G_c(s) = K_c + \frac{K_i}{s} = 1.35 + \frac{0.0739}{s} \qquad (13)$$

3.1.3 Modified Ziegler-Nichols Method

By referring to the empirical model obtained in equation (11) and the modified Ziegler-Nichols method by Seborg [6],

$$K_c = 0.9\frac{\tau}{K_p\theta} = \frac{0.9(22.95)}{1(2.07)} = 9.9783$$

and

$$\tau_i = 3.33(\theta) = 3.33(2.07) = 6.8931$$

Thus,

$$K_i = \frac{K_c}{\tau_i} = \frac{9.9783}{6.8931} = 1.4476$$

Therefore, the transfer function of the controller is obtained as

$$G_c(s) = K_c + \frac{K_i}{s} = 9.9783 + \frac{1.4476}{s} \qquad (14)$$

3.1.4 Cohen Coon Method

By referring to the empirical model obtained in equation (11) and the Cohen-Coon Method,

$$K_c = \left[0.9 + \frac{\theta}{12\tau}\right]\left(\frac{\tau}{K_p\theta}\right) = \left[0.9 + \frac{2.07}{12(22.95)}\right]\left(\frac{22.95}{1(2.07)}\right)$$

Thus,

$$K_c = 10.0616$$

and

$$\tau_i = \frac{\theta\left[30 + 3\left(\frac{\theta}{\tau}\right)\right]}{9 + 20\left(\frac{\theta}{\tau}\right)} = \frac{2.07\left[30 + 3\left(\frac{2.07}{22.95}\right)\right]}{9 + 20\left(\frac{2.07}{22.95}\right)} = 5.7998$$

Hence,

$$K_i = \frac{K_c}{\tau_i} = \frac{10.0616}{5.7998} = 1.7348$$

Therefore,

$$G_c(s) = K_c + \frac{K_i}{s} = 10.06 + \frac{1.73}{s} \qquad (15)$$

3.2 Advanced Process Control Method

In order to further improve the transient response of the system, feed forward control and gain scheduling method have been introduced in this paper for liquid level control. Advanced process control methods are said to be have much higher efficiency than the conventional single loop feedback response.

3.2.1 PI-plus-Feedforward Control Design

Combination of feedforward and PI feedback controller can improve the feedback response of the system significantly as compared to single feedback control alone. This is due to the fact that, feedforward controller is able to anticipate the disturbances effect by taking earlier compensate actions before it affects the output of the system. The block diagram of feedforward-plus-PI controller is as shown in Figure 4.

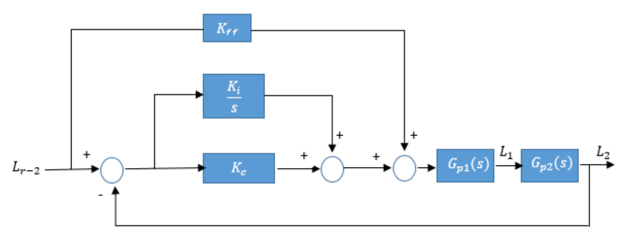


Figure 4 Tank 2 control system block diagram

In this system we assume that the dynamics in Tank 1 is neglected for simplicity of analysis since we only focus on controlling the water level for Tank 2, in which $G_{p1}(s) = 1$.

By definition, at static equilibrium point (L_{1o}, L_{2o});

$$L_1 = L_{r-1} = L_{1o} \quad , \quad L_2 = L_{r-2} = L_{2o}$$

At steady-state:

$$0 = -A_{o2}\sqrt{2g}\sqrt{L_{2o}} + A_{o1}\sqrt{2g}\sqrt{L_{1o}}$$

$$A_{o2}\sqrt{2g}\sqrt{L_{2o}} = A_{o1}\sqrt{2g}\sqrt{L_{1o}}$$

Rearranging,

$$\sqrt{\frac{L_{1o}}{L_{2o}}} = \frac{A_{o2}}{A_{o1}}$$

Thus,

$$\frac{L_{1o}}{L_{2o}} = \frac{A_{o2}^2}{A_{01}^2}$$

Therefore,

$$K_{ff} = 1.0 \tag{16}$$

Thus, the feedforward controller is used to compensate the water withdrawal through Tank 2's bottom outlet orifice.

3.2.2 IMC-based-PI Control Design

In designing the IMC-based-PI controllerfor Tank 2, the control block diagram is as shown in Figure 5.

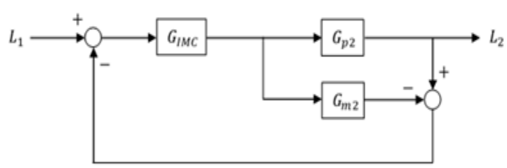


Figure 5 Tank 2 control system block diagram

The IMC controller is defined as

$$G_{IMC}(s) = (G_{m2}(s)^{-})^{-1}$$

$$= \frac{\tau_2 s+1}{K_{p2}}$$

and must be augmented with a proper filter

$$f(s) = \frac{1}{(\lambda s+1)^n}$$

Thus, the final control equation is obtained as

$$G_{IMC,final}(s) = G_{IMC}(s) \times f(s)$$

$$= \left(\frac{\tau_2 s+1}{(\lambda s+1)^n}\right) \tag{17}$$

where

λ is a parameter which determines speed of response.

n is the filter order.

According to [4], the value of λ must be greater than 0.1τ, thus, by setting λas 4 and $n$as 1, the final equation of controller becomes

$$G_{IMC,final}(s) = \frac{15.2368s+1}{4s+1} \tag{18}$$

The PI control parameters can be found by equating the standard transfer function of IMC controller with the transfer function of a PI controller where:

$$G_{IMC}(s) = \frac{G_{IMC,final}(s)}{1-G_{p2}(s)G_{IMC,final}(s)}$$

$$G_{IMC}(s) = \frac{\tau_2 s+1}{K_{p2}\lambda s} \tag{19}$$

$$G_{PI}(s) = K_C\left(\frac{T_i s+1}{T_i s}\right) \tag{20}$$

Comparing equation (19) and (20), the PI parameters are obtained as below:

$$K_C = \frac{\tau_2}{K_{p2}\lambda} = \frac{15.2368}{4} = 3.81$$

$$T_i = \tau_2 = 15.236$$

$$K_i = \frac{K_C}{T_i} = 0.25$$

Therefore, the transfer function of the controller is obtained as

$$G_c(s) = K_c + \frac{K_i}{s} = 3.81 + \frac{0.25}{s} \tag{21}$$

3.2.3 Gain Scheduling-based-PI Control Design

Gain Scheduling is a simple effective technique that is used widely in industry. It is good when the system is non-linear or when the system dynamics vary with time [9, 10]. Engineers prefer it as it is relatively easy to implement and needs small execution time comparing to other controlling techniques.

A steady state input output relationship is measured for tank 2 system to study the non-linearity of the system and decide the where to setup the operation points for the gain scheduling.

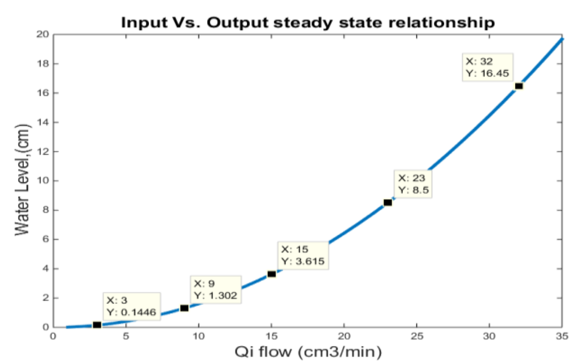


Figure 6 Operating points for Tank 2 linearized model

Five different operating points are selected from the nonlinear output response of tank 2 to be applied in gain scheduling. The system is then linearized based on the five points and five 1st order linear models are obtained. PI controller is designed based on each model. The models are tuned and PI parameters are obtained. Table 3 shows the models with their tuned parameters.

Table 3 Controller Design Specifications

Operation Points	Model	Kc	Ki
(3.0, 0.144)	$\frac{0.04821}{1.496\,s\,+\,1}$	106.55	71.22
(9.0, 1.30)	$\frac{0.1446}{4.488\,s\,+\,1}$	56.29	12.54
(15.0, 3.62)	$\frac{0.241}{7.48\,s\,+\,1}$	40.61	5.42
(23.0, 8.5)	$\frac{0.3696}{11.47\,s\,+\,1}$	21.77	1.91
(32.0, 16.45)	$\frac{0.5142}{15.96\,s\,+\,1}$	21.77	1.91

The input to the model is used for the selection of parameters. Parameters are inserted into a lookup table, linear interpolation is used to approximate values in the intervals between the operation points. The interpolated parameters are injected into a dynamic PI controller.

4.0 RESULTS AND DISCUSSION

The simulation results of each of the controllers designed in section III are showed and discussed in this section. The Simulink blocks for controller tuning is as shown in Figure 7.

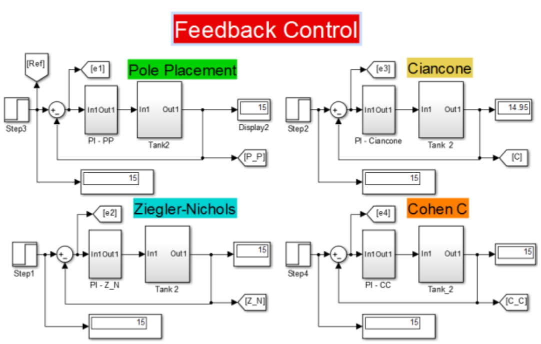


Figure 7 PI Control tuning simulink blocks

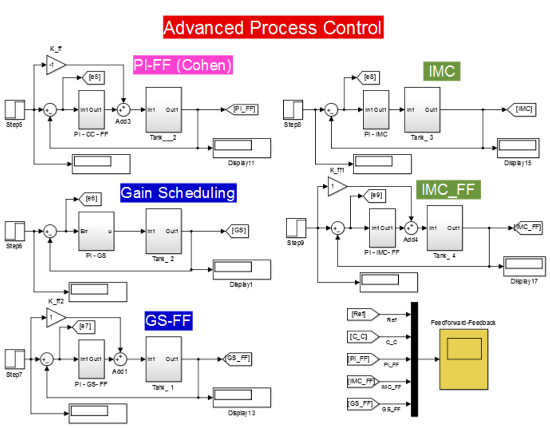


Figure 8 APC Control design simulink blocks

4.1 Performance of Feedback Control using different Methods

The output responses of pole placement, Ciancone, Cohen Coon and modified Ziegler Nichols are simulated using the Simulink block as shown in Figure 8. The responses of the controllers are compared and shown in Figure 9.

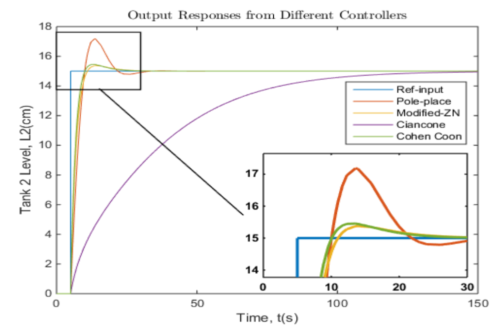


Figure 9 Comparison of different controller tuning performances

From Figure 9, four types of tuning methods namely pole placement method, Ciancone method, Modified Ziegler-Nichols method and lastly Cohen-Coon method have been used to tune the controller parameters of PI controller. Figure 9 shows that the Cohen Coon method tends to outperform the other method with the fastest response and lowest overshoot. This is then closely followed by the Z-N method with slightly higher overshoot. On the other hand, Ciancone method shows a sluggish response whereas pole placement method yields a very high overshoot.

ITAE performance is chosen to validate the performance since it gives the balance trade-off between response speed and percentage of overshoot. The transient performances and ITAE values of each of the controllers are shown in Table 4:

Table 4 Transient Performance and ITAE Value of PI Control

Controller	Percent OS (%)	Rise Time (s)	Settling Time (s)	ITAE Value
Pole Placement	14.4528	3.8184	20.2591	457.7
Modified Z-N	2.5146	3.5665	16.9936	220.2
Ciancone	104.8263	62.1505	104.8263	$1.316e^{+4}$
Cohen Coon	3.0465	3.0178	16.7844	198.1

From Table 4, Cohen Coon method gives the best transient response with fastest rise time and settling time as well as lowest overshoot percentage. As expected, it gives the lowest ITAE value of 198.1 followed by Z-N method of 220.2.

4.2 Performance of PI-plus-Feedforward Control

The performance of PI-plus-Feedforward Controller is shown in Figure 10 where it can be seen that the feedforward-feedback control shows improved speed response and lower ITAE value of 188.2 as compared to feedback controlwith ITAE value of 198.1.

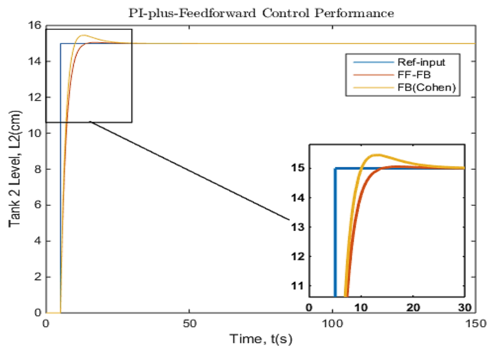


Figure 10 PI-plus-feedforward control performances (cohen coon)

This shows that addition of feedforward control loop is able to compensate for the disturbance (outflow of water through Tank 2's bottom outlet orifice).

4.3 Performance of Advanced Process Controllers

PI-plus-Feedforward control has shown an improved performance in water level control which is as expected. Nevertheless, other advanced control methods such as IMC-based-PI, gain scheduling-based-PI are also being simulated and compared to investigate the most suitable controller for the coupled tank system. The comparison results are shown in Figure 11.

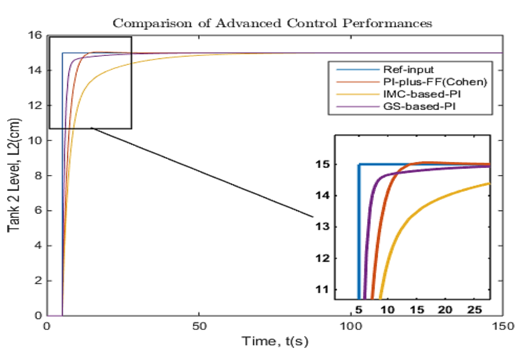


Figure 11 Comparisons of advanced control performances

From Figure 11, it can be seen that among all the advanced control methods, GS-based-PI control tends to outperform all the other controllers with zero overshoot and fast settling time. It gives an ITAE value of 151.2 which is much better than what we obtained using PI-plus-FF previously.

Table 5 Transient performance and ITAE value of advanced control methods

Controller	Percent OS (%)	Rise Time (s)	Settling Time (s)	ITAE Value
PI-plus-FF (Cohen)	0.3770	3.9889	11.5734	188.2
IMC-based-PI	0	9.9631	38.5144	1019
GS-based-PI	0	1.8015	10.9540	151.2

On the other hand, IMC-based-PI does not perform as expected which is probably due to the influence of disturbance that affects the overall transient response. Although it shows zero overshoot but overall a sluggish response as compared to PI-plus-FF (Cohen). The detailed transient performance and ITAE value of the advanced controllers are tabulated in Table 5.

4.4 Comparisons of different Feedforward-Feedback Control

From previous simulation results, the advanced control methods are most likely to outperform the conventional feedback control. This is definitely the case for feedforward-feedback control.

In order to further investigate the best controllers for the system, different types of feedforward-feedback PI controllers with the integration of advanced control methods have been simulated and compared with the best result achieved so far using Gain scheduling-based-PI. The results are as shown in Figure 12.

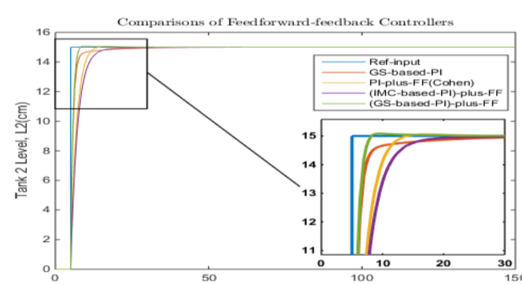


Figure 12 Comparisons of feedforward-feedback controllers

As expected, GS-based-PI-plus-FF control has shown the best transient performance as well as ITAE valuewith the addition of feedforward control in the control loop.Thus, we can conclude that feedforward-feedback control is able to improve the closed loop response of the system significantly especially an advanced control method is being incorporated. The detailed transient performance and ITAE value of each of the controllers are tabulated in Table 6.

Table 6 Transient performance and ITAE value of feedforward-feedback controllers & GS-based-PI

Controller	Percent OS (%)	Rise Time (s)	Settling Time (s)	ITAE Value
GS-based-PI	0	1.8015	10.9540	151.2
PI-plus-FF (Cohen)	0.3770	3.9889	11.5734	188.2
(IMC-based-PI)-FF	0	4.9327	14.3540	273.2
(GS-based-PI)-FF	0.1557	1.5512	7.4916	68.46

From Table 6, GS-based-PI-plus-feedforward control gives the best transient response with slight overshoot but the fastest rise time and settling time as compared to other controllers. It also shows the best ITAE value achieved so far of 68.46 only.

5.0 CONCLUSION

This paper studies about the best controller to control the water level of tank 2 in a coupled tank system. The coupled tank system is a nonlinear system that requires an advanced controller to achieve both robust and good transient performance. The system is linearized and PI controller is applied to yield closed loop performance. Pole placement, modified Z-N, Ciancone and Cohen Coon method were used to tune the PI parameters. The best tuning performance was obtained with Cohen method. However, the controller can still be further improved with the integration of advanced control method where the Gain Scheduling-based-PI control was implemented in the system, tuned and finally further improved with the addition of feedforward control loop to give the best transient performance and ITAE value.

Acknowledgement

The authors would like to thank the Fundamental Research Grant Scheme Vote 4F425 and the Universiti Teknologi Malaysia for its financial support.

References

[1] JE. P. Gatzke, E. S. Meadows, C. Wang, and F. Doyle. 2000. Model Based Control Of A Four-Tank System. *Computers & Chemical Engineering*. 24: 1503-1509.
[2] T. Marlin. 2000. *Process Control, Designing Processes and Control Systems for Dynamic Performance*. 2nd ed. New York: McGraw Hill.
[3] K. J. Astrom and T. Hagglund. 1995. *PID Controllers: Theory, Design and Tuning*. 2nd ed: Instrument Society of America.
[4] D. E. Rivera, M. Morari, and S. Skogestad. 1986. Internal Model Control: PID Controller Design. *Industrial & Engineering Chemistry Process Design and Development*. 25: 252-265.
[5] F. Wu, X. H. Yang, A. Packard, G. Becker. 1996. Induced L2-Norm Control for LPV Systems with Bounded Parameter Variation Rates. *International Journal of Robust and Nonlinear Control*. 6: 2379-2383.
[6] D. E. Seborg, T. F. Edgar, and D. A. Mellichamp. 1989 *Process Control Dynamics*. 1st ed. John Wiley and Sons Inc.
[7] J. Barroud, Y. Creff and N. Petit. 2004. PI Controllers Performance for A Process Model with Varying Delay. *Control Conference, University of Bath, United Kingdom.*
[8] A. Hassaan. 2014. Tuning of a PD-PI Controller used with First-OrderDelayed Processes. *International Journal of Engineering Research and Technology*. 3(4).
[9] F. Wang, V. Balakrishnan. 2002. Improved Stability Analysis And Gain-Scheduled Controller Synthesis For Parameter-Dependent Systems. *IEEE Transactions on Automatic Control*. 47(5): 720-734.
[10] W. J. Rugh, J. S. Shamma. 2000. A Survey Of Research On Gain-Scheduling. *Automatica*. 36: 1401-1425.