Robust Control Approach of SISO Coupled Tank System

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***Abstract*—This paper presents the design principles of sliding mode controller, which is implemented in the coupled tank system. The Sliding Mode Control (SMC) controller exhibited a robust stability which can overcome nonlinearities, reduce disturbances and noise that occur in the coupled tank system. The work start with mathematical modelling the coupled tank system using second order single input single output (SISO) technique. Then, the sliding mode controller design began by deriving the sliding surface according to the second order coupled tank system. The control variables in this system, which are C1 and C2 are manipulated to obtain the best performances of the SMC. From the simulations, the performances characteristic of the SMC is analysed and investigated. The output response is obtained by implementing the SMC on the plant and compared with the proportional, integral, and derivative (PID) controller as a benchmarked controller. The results show that the robust SMC has better output response compared to the PID controller.**

Keywords—Sliding Mode Control; PID controller; robustness; coupled tank system

I. Introduction

Coupled Tank System (CTS) playing important roles in the industrial sector due to the process in the coupled tank which stored, pumped, restored, and pumped the liquid continuously. The industries demand regarding the coupled tank is very high especially in food processing, pharmaceutical industries, mixing process, refilling devices, and the chemical processing. Modern utilization of coupled tanks system (CTS) is broadly utilized as a part of the chemical process. There are a few procedures of CTS, for example, single input single output (SISO) or multiple input multiple output (MIMO) that has been utilized generally as a part of the industrial area. Moreover, the control procedure for multiple input multiple output (MIMO) is more convoluted than SISO in light of the fact that there is a communication between other control circles of MIMO procedures. However, the control structure implemented in the SISO system is less complex as compared to the control of the MIMO system.

However, according to the previous study, it was stated that the problems always occur in controlling the level of the liquid and the flow between the tanks [1],[2], this is due to the industrial demand for the liquid to be pumped, stored, and to be pumped again to another tank. It is very important to monitor the level of the liquid, the flow between tanks and the interaction of the liquid levels. In [3] there are two configurations of CTS that are single input and single output (SISO) and multiple input multiple output (MIMO) which has different ways of controlling the liquid level.

The Sliding Mode Control (SMC) controller has been introduced and is known as a robust stability which will reduce the external disturbances and eliminates the chattering effect [4]. By referring to the Lyapunov's method, that approach using the lots of variable designs that create sliding mode on the intersection of a few switching surfaces. To ensure that the system trajectory always reaches the sliding surface, the control laws are designed. On top of that, the study shows that for SISO coupled tank system, the 2nd tank act as disturbance while the 1st tank act as a control variable. Meanwhile, a mathematical model for the coupled-tank system and the design of SMC for liquid control in the systems is presented. In this study, it's focussed on the nonlinear SISO mathematical model which is developed in order to use the SMC controller. It was stated that the tracking performances of the SMC controller [5] are tested using different input signals such as step, sinusoidal, and saw tooth. The controller showed that it has a strong robustness when some realistic situations are inserted in the plant. Moreover, the use of SMC can overcome nonlinearities, reduce disturbances and noise. The SMC need to use a suitable sliding surface for the system to slide to its desired final value.

Authors in [6] stated that the SMC controller was initially adopting the concept of variable structure control system which consists of two steps. The first step is to gain a sliding surface for desired stable dynamics and the second step is to get the control law to reach to the sliding surface. In this paper, the comparison between SMC and PID has been made, it shows that the external disturbances will affect the PID controller but not the SMC. The SMC is proven to be robust to parametric uncertainties and external disturbances [7].

Researchers [8] verified that the SMC nonlinear control have a capability to maintain the stability in the control of various different classes of model which are exposed to the disturbances and variations in the system parameters [9]. Thus it has been extensively used in various applications such as active suspension system [10], pneumatic systems [11] and active magnetic bearing systems [12]. Moreover, when a controller designed by the conventional approaches, The SMC controller can be easier to design, to tune and to implement [13] because in [14] it was stated that the Sliding Mode Control controller is the best method for a nonlinear system with uncertainties.

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Despite the advantages in various applications of the coupled tank system, it suffers from nonlinearities and parameter uncertainties which cause the performance deterioration. Recently, numerous control techniques have been reported for the coupled tank system in the literature. It can be divided to linear control, nonlinear control and intelligent control [15][16][17]. However, Sliding Mode Controller (SMC) has been proven to be outstanding over other controllers in providing robust performance for the nonlinear dynamic system [18], [19]. Therefore, SMC was chosen for the coupled tank system.The objective is to tune the best controller parameters in SMC in order to get the desired output performance of coupled tank system. According to [20], the tuning problem of controller gains can be considered as an optimization problem.

II. Mathematical Modelling

Based on the previous research [1][2], Fig. 1 shows the coupled tank system for the SISO system with the definition of parameters in the coupled tank system.

The area for the SISO coupled tank system can be expressed as,

$$A_1 \frac{dh_1}{dt} = Qi_1 - Qo_1 - Qo_3 \tag{1}$$

$$A_2 \frac{dh_2}{dt} = Qi_2 - Qo_2 - Qo_3 \tag{2}$$

where:

H_1, H_2 = Height of fluid in tank 1 and 2.

A_1, A_2 = Cross-sectional area of tank 1 and 2.

Q_{o3}= The rate flow of fluid between tanks.

Q_{i1}, Q_{i2} = Pump flow rate into tank 1 and 2.

Q_{o1}, Q_{o2} = Flow rate of fluid out of tank 1 and 2.

By using the Bernoulli's equation, the flow between the two tanks is proportional to the square root of the head differential.

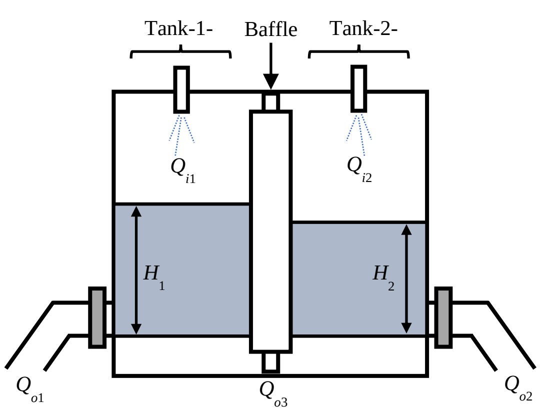

Fig. 1. Coupled Tank System with SISO Structure.

$$Qo_1 = \alpha_1 \sqrt{H_1} \tag{3}$$

$$Qo_2 = \alpha_2 \sqrt{H_2} \tag{4}$$

$$Qo_3 = \alpha_3 \sqrt{H_1 - H_2} \tag{5}$$

where α_1, α_2, α_3 are proportional constants that depends on the coefficients of discharge, cross sectional area of each tank and gravitational constant.

By substituting the equations (3), (4) and (5) into equation (1) and (2),

$$A_1 \frac{dH_1}{dt} = Q_{i1} - \alpha_1 \sqrt{H_1} - \alpha_3 \sqrt{H_1 - H_2} \tag{6}$$

$$A_2 \frac{dH_2}{dt} = Q_{i2} - \alpha_2 \sqrt{H_2} - \alpha_3 \sqrt{H_1 - H_2} \tag{7}$$

By linearized perturbation model, consider a small variation in each inflow q_1 in Q_{i1} and q_2 in Q_{i2}. And let the perturbation level be h_1 and h_2 respectively.

$$\begin{aligned} A_1 \frac{d(H_1 + h)}{dt} &= (Q_{i1} + q_1) - \alpha_1 \sqrt{H_1 + h_1} - \cdots \\ &\cdots - \alpha_3 \sqrt{(H_1 - H_2) + (h_1 - h_2)} \end{aligned} \tag{8}$$

$$\begin{aligned} A_1 \frac{d(H_2 + h_2)}{dt} &= (Q_{i2} + q_2) - \alpha_2 \sqrt{H_2 + h_2} - \cdots \\ &\cdots - \alpha_3 \sqrt{(H_1 - H_2) + (h_1 - h_2)} \end{aligned} \tag{9}$$

For small perturbations,

$$\sqrt{H_1 + h_1} = \sqrt{H_1 \left(1 + \frac{H_1}{2H_1}\right)} \tag{10}$$

$$\sqrt{H_1 + h_1} - \sqrt{H_1} \approx \frac{H_1}{2\sqrt{H_1}} \tag{11}$$

$$\sqrt{H_2 + h_2} - \sqrt{H_2} \approx \frac{H_2}{2\sqrt{H_2}} \tag{12}$$

$$\sqrt{(H_1 + h_1) + (h_1 - h_2)} - \sqrt{H_2 - H_1} \approx \frac{h_2 - h_1}{2\sqrt{H_2 - h_1}} \tag{13}$$

Then, assume that

$h_1 = h_2$ = Output

$q_1 = q_2$ = Input

$$A_1 \frac{dh_1}{dt} = q_1 - \frac{\alpha_1}{2\sqrt{H_1}} h_1 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \tag{14}$$

$$A_2 \frac{dh_2}{dt} = q_2 - \frac{\alpha_2}{2\sqrt{H_2}} h_2 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \tag{15}$$

From equation (14),

$$A_1 h'_1 = q_1 - \frac{\alpha_1}{2\sqrt{H_1}} h_1 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \tag{16}$$

And equation (15),

$$A_2 h'_2 = q_2 - \frac{\alpha_2}{2\sqrt{H_2}} h_2 - \frac{\alpha_3}{2\sqrt{H_1 - H_2}} (h_1 - h_2) \tag{17}$$

The manipulated variable is the perturbation to the inflow of tank 1. Assume that, mutually variables are at their steady state value.

$$A_1 h'_1 = q_1 - \left(\frac{\alpha_1}{2\sqrt{H_1}} h_1 + \frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right) \tag{18}$$

$$A_2 h'_2 = q_2 - \left(\frac{\alpha_2}{2\sqrt{H_2}} h_2 + \frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right) \tag{19}$$

where h_1 is the process variable and q_1 is the manipulated variable. The case will be considered when q_2 is zero. The equations (18) and (19) will be expressed between the manipulated variable, $q_1$and the process variable, h_2.

Rewrite the equation (18) and (19),

$$T_1 h'_1 + h_1 = K_1 q_1 + K_{12} h_2 \tag{20}$$

$$T_2 h'_2 + h_2 = K_2 q_2 + K_{21} h_1 \tag{21}$$

where,

$$T_1 = \frac{A_1}{\left[\frac{\alpha_1}{2\sqrt{H_1}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{22}$$

$$T_2 = \frac{A_2}{\left[\frac{\alpha_2}{2\sqrt{H_2}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{23}$$

$$K_1 = \frac{1}{\left[\frac{\alpha_1}{2\sqrt{H_1}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{24}$$

$$K_2 = \frac{1}{\left[\frac{\alpha_2}{2\sqrt{H_2}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{25}$$

$$K_{12} = \frac{\left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]}{\left[\frac{\alpha_1}{2\sqrt{H_1}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{26}$$

$$K_{21} = \frac{\left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]}{\left[\frac{\alpha_2}{2\sqrt{H_2}} \right] + \left[\frac{\alpha_3}{2\sqrt{H_1 - H_2}} \right]} \tag{27}$$

For SISO (Second order, Single Input), consider $q_2 = 0$. From equation (21),

$$h_1 = \frac{T_2 h'_2 + h_2}{K_{21}} \tag{28}$$

$$h'_1 = \frac{T_2 h''_2 + h'_2}{K_{21}} \tag{29}$$

Substitute equations (28) and (29) into (20),

$$T_1 h'_1 + h_1 = K_1 q_1 + K_{12} h_2$$

$$T_1 \left(\frac{T_2 h''_2 + h'_2}{K_{21}} \right) + \left(\frac{T_2 h'_2 + h_2}{K_{21}} \right) = K_1 q_1 + K_{12} h_2$$

$$T_1 T_2 h''_2 + T_1 h'_2 + T_2 h'_2 + h_2 = K_1 q_1 K_{21} + K_{12} K_{21} h_2$$

$$h''_2 = \frac{K_1 q_1 K_{21} + K_{12} K_{21} h_2 - T_1 h'_2 + T_2 h'_2 + h_2}{T_1 T_2}$$

$$h''_2 = \frac{1}{T_1 T_2} \left[K_1 q_1 K_{21} + K_{12} K_{21} h_2 - h'_2 (T_1 + T_2) - h_2 \right]$$

$$h''_2 = \frac{1}{T_1 T_2} \left[-h'_2 (T_1 + T_2) + h_2 (K_{12} K_{21} - 1) + K_{21} K_1 \right] \tag{30}$$

III. SLIDING MODE CONTROLLER DESIGN

In this paper, the SMC has been utilized to manipulate the operation of coupled tank system. The block diagram of coupled tank system integrated with SMC implemented in the Simulink environment is demonstrated in Fig. 2. The SMC controller brings a new solution to overcome nonlinearities, disturbances, and measurement noise. The most important characteristics of SMC is to deal with nonlinear and time varying systems.

The sliding surface is designed according to the second order coupled tank system which is expressed as below:

$$s = C_1 h_2 + C_2 h_2$$

$$s' = C_1 h''_2 + C_2 h'_2$$

When $s' = 0$, assume $C_1 = 1$.

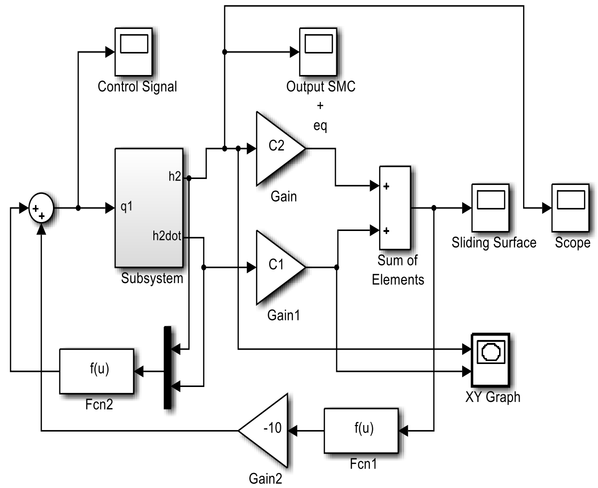

Fig. 2. Simulink Model for Coupled Tank System with the Assistant of SMC.

Generally, the control structure of SMC consists of switching and equivalent control as expressed,

$U_{smc} = U_{sw} + U_{eq}$

$$U_{sw} = -Ksign(s) = -K\left(\frac{s}{|s+\xi|}\right)$$

$U_{eq} = q_1$

Taking $\xi = 0$,

$$U_{q1} = \frac{h'_2}{K_{21}K_{12}}\left[(T_1+T_2) - \frac{C_2}{C_1}(T_1T_2) - \cdots \right.$$
$$\left. \cdots - \frac{h_2}{K_{21}K_1}(K_{21}K_{12})\right] \quad (31)$$

Table I and II composed of parameters that will be utilized in the model.

All the parameters in Table I and II will be substituted into the equation (22), (23), (24), (25), (26), (27). Then, the value of T_1, T_2, K_{12}, and K_{21} will be substituted into U_{q1} as follow,

TABLE I. THE VALUE OF SELECTED PARAMETERS

Parameters	**Value**
H_1 (cm)	17.00
H_2 (cm)	15.00
α_1 ($cm^{3/2}$/sec)	10.78
α_2 ($cm^{3/2}$/sec)	11.03
α_3 ($cm^{3/2}$/sec)	11.03
A_1 (cm)	32.00
A_2 (cm)	32.00

TABLE II. THE VALUE FOR THE EQUATIONS (22), (23), (24), (25), (26), (27)

Symbols	**Value**
T_1	6.15
T_2	6.011
K_1	0.1962
K_2	0.1878
K_{12}	0.749
K_{21}	0.7325

$$0 = -C_1h'_2(T_1+T_2) + C_1h_2(K_{21}K_{12}-1) + \cdots$$
$$\cdots + C_1K_{21}K_{12}q_1 + C_1K_{21}K_{12}q_1 \quad (32)$$

$$C_1K_{21}K_{12}q_1 = h'_2 - \big((C_2T_1T_2 + C_1(T_1+T_2) - \cdots$$
$$\cdots - C_1h_2(K_{21}K_{12}-1)\big) \quad (33)$$

$$q_1 = \frac{h'_2}{K_{21}K_{12}}\big(C_1(T_1+T_2) - C_2T_1T_2\big) - C_1h_2(K_{21}K_{12}-1) \quad (34)$$

$$q_1 = 86.469h'_2 - 262.85\frac{C_2}{C_1}h'_2 - 3.21h_2 \quad (35)$$

From the equation (30),

$$h''_2 = \frac{1}{(6.15)(6.011)}\big[-h'_2(6.15+6.011) + \cdots$$
$$\cdots + h_2(0.7325(0.749)-1) + (0.7325)(0.192)q_1\big]$$
$$= -0.329h'_2 - 0.0122h_2 + 3.8mq_1$$

IV. RESULTS AND DISCUSSION

The analysis of the performances of SMC in the coupled tank system toward disturbances is shown in Figures 3, 4, 5 and 6. The value of C_1 and C_2 are adjusted through two set up. First, the value of C_1 is constant and the value of C_2 is adjusted. Then for the next set up, the value of C_2 is constant and the value of C_1 is adjusted. Both performances are observed to get the best value of C_1 and C_2 which shows the sliding motion and the best performances in term of settling time and percentage of overshoot.

Sliding motion with the best performances. When $C_1 = 1$ cm^2 and $C_2 = 2$ cm^2. The sliding motion in Fig. 3 with the respected values of C_1 and C_2 show the performances of the sliding motion in the system. It's showing how the system slides across the section of the system until reaching to the zero.

Fig. 4 and Table III show the performances of SMC towards disturbances with a constant value of C_1 and the value of C_2 is adjusted. The settling time increase as the value of C_2 increase. This is due to the area of the orifice that allows the flow of liquid increase which simultaneously increase the disturbance.

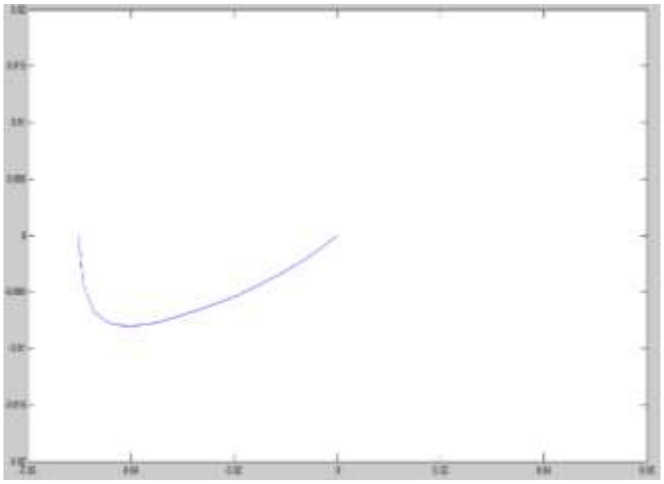

Fig. 3. The Sliding Motion of the System.

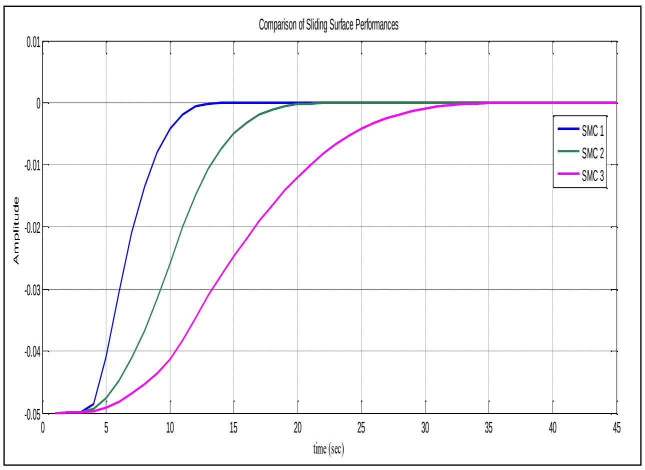

Fig. 4. Comparison of Sliding Surface Performances with a Constant Value of C1 and the Value of C2 is adjusted.

TABLE III. COMPARISON BETWEEN SMC WITH CONSTANT VALUE OF C_1

Sliding Surface	$C_1\,(cm^2)$	$C_2\,(cm^2)$	*OS* (%)	T_s(sec)
SMC 1	2	1	0	23
SMC 2	2	5	0	37
SMC 3	2	10	0	40

Referring to the Fig. 5 and Table IV, the settling time decreased when the area of $C_2 = 2\ cm^2$ and $C_1 = 5\ cm^2$. However, the settling time increase again when the area of $C_1 = 10\ cm^2$. Even though the settling time for $C_2 = 2\ cm^2$ and the area of $C_1 = 5\ cm^2$ shows better performances compared to settling time when $C_2 = 2\ cm^2$ and $C_1 = 1\ cm^2$ but the sliding motion for $C_2 = 2\ cm^2$ and $C_1 = 1\ cm^2$ show better performances when it is slide across the system's normal behaviour to zero.

Then the performances of the Sliding mode control using the best performances are compared with the PID controller using auto tuned method as shown in Fig. 6. The parameters of the PID controller including $K_p = 14.28289$, $K_i = 0.88983$, and $K_d = 38.21613$, while the best performance of SMC consist of the parameters of $C_2 = 2\ cm^2$ and $C_1 = 1\ cm^2$.

The SMC response in Fig. 6 shows that it is free from the overshoot unlike the PID controller. The desired level of error correction has been attained by the SMC within short time frame compared to the PID controller. The comparisons between SMC and PID controller are shown in Table V.

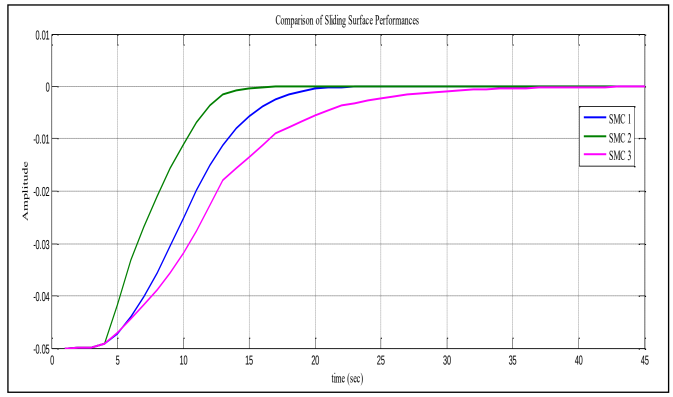

Fig. 5. Comparisons between Sliding Surface with different Value of c1 and c2.

TABLE IV. COMPARISON BETWEEN SMC WITH DIFFERENT VALUE OF C_1 AND C_2

Sliding Surface	$C_1\,(cm^2)$	$C_2\,(cm^2)$	*OS* (%)	T_s(sec)
SMC 1	1	2	0	23
SMC 2	5	2	0	16
SMC 3	10	2	0	43

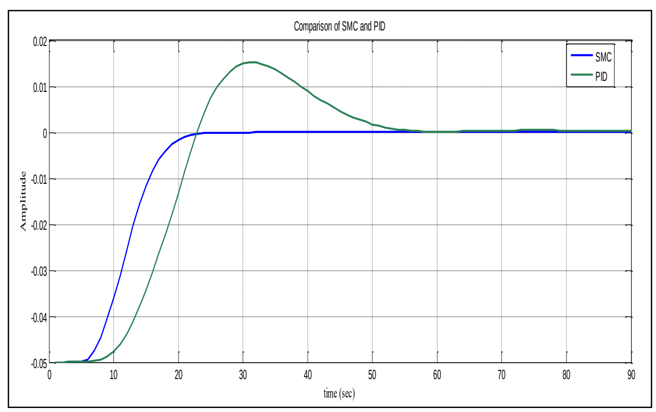

Fig. 6. Comparison between SMC and PID.

TABLE V. PERFORMANCES COMPARISON BETWEEN SMC AND PID CONTROLLERS

Character	**SMC**	**PID**
OS (%)	0	1.52
T_s (Sec)	23	105

V. Conclusions

We have succesfully demonstrated the sliding mode controller to the coupled tanks system. The mathematical modelling of the coupled tank system has been derived thoroughly. The sliding surface has been designed to suit the second order coupled tank system. The simulation results using MATLAB for the coupled tank system proves that the SMC work very well and is robust to change in the parameters of the system as well as to external disturbances acting on the system. SMC gives a better response than a standard PID controller when applied in the CTS system. This work provides a simple and effective optimization method for selecting the most optimal controller variable of the SMC specifically for the coupled tank system. This method is based on single input and single output coupled tank system. In future multiple input multiple output system could be considered to improve the accuracy. Besides, it could be applied to other industrial applications such as hydraulic, pneumatic and suspension system for future works.

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