# Adaptive Sliding Mode Control Based on Fuzzy Logic and Low Pass Filter for Two-Tank Interacting System

Original Scientific Paper

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***Abstract*** *– An adaptive sliding mode control (SMC) based on fuzzy logic and low pass filter is designed in this research. The SMC is one of the most widely accepted robust control techniques. However, the main disadvantage of the SMC is chattering phenomena, which inhibits its usage in many practical applications. Fuzzy logic control has supplanted conventional techniques in many applications. A major feature of fuzzy logic is the ability to express the amount of ambiguity in individual perception and human thinking. In this study, a fuzzy inference system is applied to approximate the function in the SMC law. A low pass filter is used to reduce chattering phenomena around the sliding surface. The stability of the control system is proved by the Lyapunov theory. The proposed controller is tested to position tracking control for two-tank interacting system. This system has been applied in process industries like petroleum refineries, chemical, paper industries, water treatment industries. Simulation results in MATLAB/Simulink show that the proposed algorithm is more effective than the sliding mode control, sliding mode control using conditional integrators and fuzzy control without steady-state error, the overshoot is 0 (%), the rising time achieves 2.187 (s) and the settling time is about 3.9133(s).*

***Keywords****: sliding mode control, adaptive, fuzzy logic, low pass filter, two-tank interacting*

## 1. INTRODUCTION

A sliding mode control (SMC) methodologies emerged as an effective tool to tackle uncertainty and disturbances, which are inevitable in most of the practical systems [1]. The most significant advantage of the SMC method is the ability to eliminate the effects of uncertainties caused by model errors and unwanted disturbances that affect the system response. Therefore, different and hybrid structures of the SMC method, which is known as robust control technique [2]. It is evident that real-time implementation of SMC is comparatively easier in contrast to other types of nonlinear controllers [3-5] and is applied to both linear and nonlinear systems [6, 7]. However, for the amplitude of the sliding mode control law, if not selected properly, it will cause chattering phenomenon [8, 9]. Chattering can be described as the phenomenon of finite-frequency, finite-amplitude oscillations appearing in systems with sliding mode control [8]. Chattering phenomenon due to imperfections and time delays in switching, due to small time constant actuators, power circuits are prone to overheating leading to damage [10, 11]. Many research have provided solutions to overcome chattering phenomenon in the SMC, such as a signum function of the SMC is replaced by saturation function and a Recurrent Elman Neural Network was developed for optimal determination of the switching gain of the Smoothed Sliding Mode Control was given in [8], the feed forward neural network was used [12], an adaptive terminal sliding mode control was given [13], a Smooth Hyperbolic Tangent Function was utilized to replace the discontinuous signum function [14, 15] was used a nearly optimal sliding mode controller, a robust multi-channel control system based on SMC was given [16], and an adaptive finite time robust control methods were employed [17] based on SMC method.

Liquid level control of the two-tank interacting system is widely used in the chemical industry [18, 19], paper chemical, mixing treatment industries, pharmaceutical and food processing industries [19], nuclear power plants, and automatic liquid dispensing and replenishment devices [20]. Several researchers have investigated the problem of liquid level control for this system, such as the Fuzzy-PID Controller [18, 20, 21] was used the SMC using conditional integrators, [22] was used an intelligent self-tuning fuzzy-PID controller, the PID controller was given [23], the PID Controller and SMC were given [24] and [25] was used the Fuzzy-Optimized model reference adaptive control based on MIT and Lyapunov rules.

This study proposes to use fuzzy logic combined with a low pass filter to reduce chattering phenomenon of the control signal around the sliding surface. The aim of reducing chattering is not to lead to problems such as saturation, high energy consumption and heat for mechanical parts and also, high wear and tear of moving mechanical parts and high heat losses in electrical power circuits. The proposed controller is test to control the liquid level of the two-tank interacting system with the effects of external disturbance and changes the time constant of the filter.

The paper contribution is 1 - the SMC controller is designed to ensure that the actual liquid level position follows the desired position; 2 - the fuzzy system is used to approximate the function *f*(**x**) in the SMC law; 3 - the low pass filter is used to reduce chattering phenomenon around the sliding surface. Simulation results in MATLAB of the proposed controller are compared with the SMC, the SMC using conditional integrators and the fuzzy controller.

This paper is organized in 5 sections: section 2 presents the mathematical model of the two-tank interacting system, the adaptive sliding mode control based on fuzzy logic and low pass filter is presented in section 3, the results and discussion are presented in the section 4 and section 5 is the conclusion.

## 2. MATHEMATICAL MODEL OF THE TWO-TANK INTERACTING SYSTEM

The model of the two-tank interacting system [25] shows in Fig. 1. Where the height of the liquid level is $h_1$ (cm) in tank 1 and $h_2$ (cm) is tank 2. Volumetric flow into tank 1 is $q_{in}$ ($cm^3$ /min), the volumetric flow rate from $q_1$ ($cm^3$ /min), and the volumetric flow rate from tank 2 is $q_2$ ($cm^3$ /min). Cross sectional area of tank 1 is $A_1$ ($cm^2$) and area of tank 2 is $A_2$ ($cm^2$).

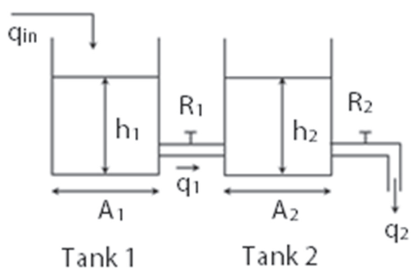


**Fig. 1.** The model of the two-tank interacting system

The state space representation of the system [25] as (1):

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(\boldsymbol{x}) + \frac{a}{b}q_{in} + d(t) \end{aligned} \tag{1}$$

where:

$$f(\boldsymbol{x}) = -\frac{1}{b}x_1 - \frac{c}{b}x_2 \tag{2}$$

$a = R_2; b = T_1T_2; c = T_1 + T_2 + A_1R_2$; $T_2 = A_2R_2$ and $T_1 = A_1R_1$ are the time constant of tank 1 and 2, respectively. $x_1 = h_2$ is the actual liquid level, $x_2 = \dot{x}_1 = \dot{h}_2$ is the velocity of the liquid level and $\boldsymbol{x} = [x_1 \quad x_2]^T$ is the state vector of the system; $d(t)$ is the unknown disturbance, $|d(t)| \le D$

The control reality shows that the *f*(***x***) component in (2) is not easily measured. Therefore, this study is aimed at approximating *f*(***x***) by a fuzzy system.

## 3. DESIGN OF ADAPTIVE SLIDING MODE CONTROLLER BASED ON FUZZY LOGIC AND LOW PASS FILTER

### 3.1. DESIGN OF SLIDING MODE CONTROLLER

The structure of the SMC controller is presented in Fig. 2.

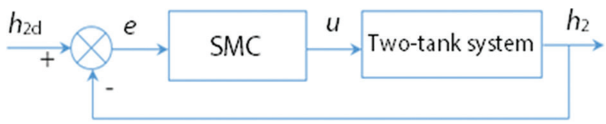


**Fig. 2.** The structure of the SMC controller

The sliding surface [10, 11] is described as (3):

$$s = ce + \dot{e} \tag{3}$$

Where *c* must satisfy Hurwitz condition,

The tracking error and its derivative value as (4) and (5):

$$e = h_{2d} - h_2 \tag{4}$$

$$\dot{e} = \dot{h}_{2d} - \dot{h}_2 \tag{5}$$

Where $h_{2d}$ is the reference liquid level, $h_2$ is the reality position.

Taking the derivative of (3), we have (6):

$$\dot{s} = c\dot{e} + \ddot{e} = c\dot{e} + \ddot{h}_{2d} - \ddot{h}_2 \tag{6}$$

Substituting (1) into (6), we get (7):

$$\dot{s} = c\dot{e} + \ddot{h}_{2d} - \ddot{h}_2 = c\dot{e} + \ddot{h}_{2d} - f(\boldsymbol{x}) - \frac{a}{b}q_{in} - d(t) \tag{7}$$

The reaching law with constant rate [10] as (8):

$$\dot{s} = -\eta sign(s) \tag{8}$$

We get the SMC law for the two-tank interacting system as (9):

$$u_{SMC}=q_{in}=\frac{b}{a}\left[c\dot{e}+\ddot{h}_{2d}-f(\boldsymbol{x})+\eta sign(s)\right] \tag{9}$$

Now, (7) becomes (10):

$$\begin{aligned}\dot{s}&=c\dot{e}+\ddot{h}_{2d}-\ddot{h}_2=c\dot{e}+\ddot{h}_{2d}-f(\boldsymbol{x})-\frac{a}{b}q_{in}-d(t)\\&=-\eta sign(s)-d(t)\end{aligned} \tag{10}$$

If $\eta \geq D$, we have (11):

$$s\dot{s}=-\eta|s|-sd(t)\leq 0 \tag{11}$$

In this paper, the fuzzy system will be use to approximate the function *f(**x**)* in (9).

## 3.2 APPROXIMATION USING A FUZZY SYSTEM

Using the universal approximation theorem, we will replace *f(**x**)* with the fuzzy system $\hat{f}(\boldsymbol{x})$ to realize feedback control. Three steps [10] are designed as follows:

Step 1. For $x_1$ and $x_2$, define five fuzzy sets for $A_1^{l_i}$ and $A_2^{l_i}$ respectively, $l_i=1,2,\ldots,5$;

Step 2. Design $\prod_{i=1}^{n}p_i=p_1\times p_2=25$ fuzzy rules to construct fuzzy system $\hat{f}(\boldsymbol{x}|\theta)$ as (12):

$$\begin{aligned}&R^{(1)}:\text{if } x_1 \text{ is } A_1^1 \text{ and} \ldots \text{and } x_2 \text{ is } A_2^1 \text{ then } \hat{f} \text{ is } B^1\\&\vdots\\&R^{(25)}:\text{if } x_1 \text{ is } A_1^5 \text{ and} \ldots \text{and } x_2 \text{ is } A_2^5 \text{ then } \hat{f} \text{ is } B^{25}\end{aligned} \tag{12}$$

Where $l_i=1,2,3,4,5; i=1,2; p_1=p_2=5$

Step 3. Using fuzzy inference, the output of fuzzy system as (13)

$$\hat{f}(\boldsymbol{x}|\boldsymbol{\theta})=\frac{\sum_{l_1=1}^{5}\sum_{l_2=1}^{5}\bar{y}_f^{l_1l_2}\left(\prod_{i=1}^{2}\mu_{A_i^{l_i}}(x_i)\right)}{\sum_{l_1=1}^{5}\sum_{l_2=1}^{5}\left(\prod_{i=1}^{2}\mu_{A_i^{l_i}}(x_i)\right)} \tag{13}$$

Where $\mu_{A_i^j}(x_i)$ is membership function of $x_i$

Let $\bar{y}_f^{l_1l_2}$ to be freedom parameter and be put in the set $\hat{\boldsymbol{\theta}}\in\boldsymbol{R}^{(25)}$. Column vector $\xi(\boldsymbol{x})$ is introduced and (13) can be written as (14):

$$\hat{f}(\boldsymbol{x}|\boldsymbol{\theta})=\hat{\boldsymbol{\theta}}^T\xi(\boldsymbol{x}) \tag{14}$$

Where

$$\boldsymbol{x}=\begin{bmatrix}x_1 & x_2\end{bmatrix}^T \tag{15}$$

$\xi(\boldsymbol{x})$ is $\prod_{i=1}^{n}p_i=p_1\times p_2=25$ dimensional column vector, and $l_1,l_2$ elements are, respectively,

$$\xi_{l_1l_2}(\boldsymbol{x})=\frac{\prod_{i=1}^{2}\mu_{A_i^{l_i}}(x_i)}{\sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\left(\prod_{i=1}^{2}\mu_{A_i^{l_i}}(x_i)\right)} \tag{16}$$

The membership functions are needed to be selected according to experiences. Moreover, all the states must be known.

## 3.3 ANALYSIS AND DESIGN OF ADAPTIVE SLIDING MODE CONTROLLER BASED ON FUZZY LOGIC

Suppose the optimal parameter [10] as (17):

$$\boldsymbol{\theta}^*=\arg\min_{\theta\in\boldsymbol{\Omega}}\left[\sup_{x\in\boldsymbol{R}^n}\left|\hat{f}\left(\boldsymbol{x}|\boldsymbol{\theta}\right)\right|-f(\boldsymbol{x})\right] \tag{17}$$

Where $\Omega$ is the set of $\theta$, i.e., $\theta\in\Omega$.

The term *f(**x**)* [10] can be expressed as (18):

$$f(\boldsymbol{x})=\boldsymbol{\theta}^{*T}\xi(\boldsymbol{x})+\varepsilon, \tag{18}$$

where ***x*** is the input signal of the fuzzy system, where is the fuzzy vector, $\xi(\boldsymbol{x})$ is approximation error of fuzzy system, and $\varepsilon\leq\varepsilon_N$.

The fuzzy system is used to approximate *f(**x**)*. The fuzzy system input is selected as $\boldsymbol{x}=\begin{bmatrix}x_1 & x_2\end{bmatrix}^T$, and the output [10] of the fuzzy system as (19):

$$\hat{f}(\boldsymbol{x}|\boldsymbol{\theta})=\hat{\boldsymbol{\theta}}^T\xi(\boldsymbol{x}) \tag{19}$$

We get the adaptive fuzzy SMC (AFSMC) law for the two-tank interacting system as (20):

$$u_{AFSMC}=\frac{b}{a}\left[c\dot{e}+\ddot{h}_{2d}-\hat{f}(\boldsymbol{x})+\eta sign(s)\right] \tag{20}$$

Substituting (20) into (10), we get (21):

$$\begin{aligned}\dot{s}&=c\dot{e}+\ddot{h}_{2d}-f(\boldsymbol{x})-\frac{a}{b}q_{in}-d(t)\\&=-f(\boldsymbol{x})+\hat{f}(\boldsymbol{x})-\eta sign(s)-d(t)\\&=-\tilde{f}(\boldsymbol{x})-\eta sign(s)-d(t)\end{aligned} \tag{21}$$

Since

$$\begin{aligned}\tilde{f}(\boldsymbol{x})&=f(\boldsymbol{x})-\hat{f}(\boldsymbol{x})\\&=\boldsymbol{\theta}^{*T}\xi(\boldsymbol{x})+\varepsilon-\hat{\boldsymbol{\theta}}^T\xi(\boldsymbol{x})=\tilde{\boldsymbol{\theta}}^T\xi(\boldsymbol{x})+\varepsilon\end{aligned} \tag{22}$$

where $$\tilde{\boldsymbol{\theta}}=\boldsymbol{\theta}^*-\hat{\boldsymbol{\theta}} \tag{23}$$

Lyapunov function [10] is defined as (24):

$$V=\frac{1}{2}s^2+\frac{1}{2}\gamma\tilde{\boldsymbol{\theta}}^T\tilde{\boldsymbol{\theta}},\ \gamma>0 \tag{24}$$

With a derivative *V*, and from (21), we have (25):

$$\begin{aligned}\dot{V}&=s\dot{s}+\gamma\tilde{\boldsymbol{\theta}}^T\dot{\tilde{\boldsymbol{\theta}}}\\&=s\left(-\tilde{f}(\boldsymbol{x})-d(t)-\eta sign(s)\right)-\gamma\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}}\\&=s\left(-\tilde{\boldsymbol{\theta}}^T\xi(\boldsymbol{x})-\varepsilon-d(t)-\eta sign(s)\right)-\gamma\tilde{\boldsymbol{\theta}}^T\dot{\hat{\boldsymbol{\theta}}}\\&=-\tilde{\boldsymbol{\theta}}^T\left(s\xi(\boldsymbol{x})+\gamma\dot{\hat{\boldsymbol{\theta}}}\right)-s\left(\varepsilon+d(t)+\eta sign(s)\right)\end{aligned} \tag{25}$$

Let the adaptive law [10] as (26):

$$\dot{\hat{\theta}} = -\frac{1}{\gamma} s\xi(\boldsymbol{x}) \tag{26}$$

Then,

$$\dot{V} = -s\left(\varepsilon + d(t) + \eta sign(s)\right) = -s\left(\varepsilon + d(t)\right) - \eta|s| \tag{27}$$

Due to the approximation error $\varepsilon$ is sufficiently small, if we design $\eta \geq \varepsilon_N$, we can obtain approximately $\dot{V} \leq 0$.

Using LaSalle's invariance principle, if $t\rightarrow\infty$, then $s\rightarrow 0$, i.e., $e\rightarrow 0$ and $\dot{e}\rightarrow 0$.

### 3.4 ADAPTIVE SLIDING MODE CONTROL BASED ON FUZZY LOGIC AND LOW PASS FILTER

The adaptive fuzzy sliding mode control (AFSMC) in (19) still exhibits the chattering phenomenon around the sliding surface because of high level switching frequency in control input signal. To overcome this phenomenon, the study proposes to combine the adaptive fuzzy sliding mode control with the low pass filter (LPF). The proposed controller is aimed to drive the sliding variable 's' to zero in the presence of system uncertainties. The structure of the AFSMC system with LPF (AFSMC_LPF) is shown in Fig. 3.


**Fig. 3.** Structure of the AFSMC_LPF

Where $\tau$ is the AFSMC output and $u$ is the actual control input. The LPF transfer function [11] is given as (28):

$$Q(s) = \frac{\lambda}{s+\lambda} \tag{28}$$

Where $\lambda$ is the time constant of the filter.

We get the AFSMC_LPF for two-tank interacting as (29):

$$u_{ASMCF\_LPF} = \left(\frac{b}{a}\left[-c\dot{e} + \ddot{h}_{2d} - \hat{f}(\boldsymbol{x}) - \eta sign(s)\right]\right)Q(s) \tag{29}$$

Equation (29) provides the necessary control input for a system with filter function Q(s) along with the AFSMC.

## 4. RESULTS AND DISCUSSION

The structure of the AFSMC _ LPF in MATLAB/Simulink is presented as Fig. 4 with $d(t)=5sin(t)$.

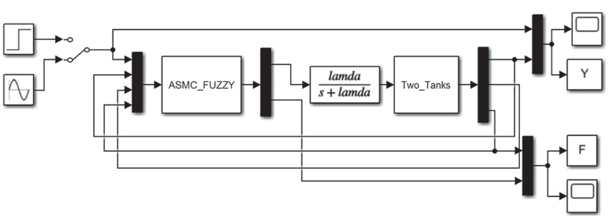


**Fig. 4.** Structure of the AFSMC _ LPF for two-tank interacting in MATLAB/Simulink

The parameters of the two-tank interacting system are presented in Table 1. The fuzzy logic rules are shown in Table 2 with NM - Negative Medium, NS - Negative Small, Z - zero, PS - Positive Small and PM - Positive Medium.

**Table 1.** The parameters of the two-tank interacting system

| Parameters | A1 | A2 | R1 | R2 |
|---|---|---|---|---|
| Value | 0.0145 | 0.0145 | 1478.57 | 642.86 |
| Unit | m2 | m2 | sec/m2 | sec/m2 |

**Table 2.** Fuzzy rule based table

| $\hat{f}(\boldsymbol{x})$ | | x1 | | | | |
|---|---|---|---|---|---|---|
| | | NM | NS | Z | PS | PM |
| x2 | NM | NM | NM | NM | NS | Z |
| | NS | NM | NM | NS | Z | PS |
| | Z | NM | NS | Z | PS | PM |
| | PS | NS | Z | PS | PM | PM |
| | PM | Z | PS | PM | PM | PM |

The membership functions are given as Fig. 5. The approximation result of the function *f(**x**)* with the fuzzy system is shown as Fig. 6. The response in Fig. 6 shows that the fuzzy system has effectively approximated the function *f(**x**)* with the approximation error approaches 0.

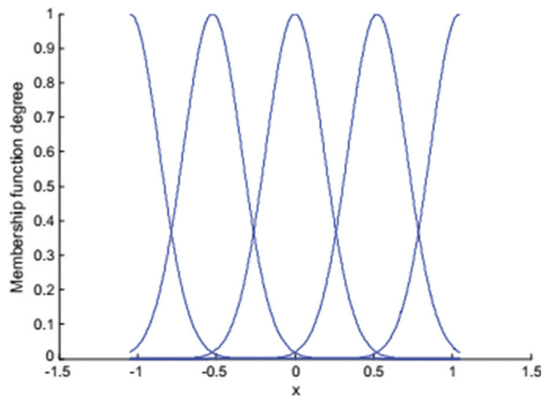


**Fig. 5.** Membership functions of *xi*

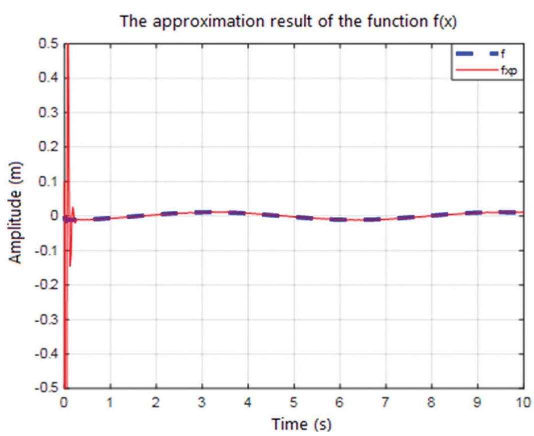


**Fig. 6.** Approximation result of the function *f(**x**)* with fuzzy system

The step response (0.055m) and error of the system with the AFSMC _ LPF are shown as Fig. 7.

**Table 3.** The achieved quality criteria of the AFSMC _ LPF controller

| **Quality criteria** | **Rising time (s)** | **Settling time (s)** | **Overshoot (%)** | **Steady state error (m)** |
|---|---|---|---|---|
| AFSMC _LPF | 2.187 | 3.9133 | 0 | 0 |
| Fuzzy control [19] | 33 | 47.2 | 1.45 | 0 |
| Sliding mode control using conditional integrators [21] | 87.18 | 330 | - | 1.6 |
| Sliding mode control [24] | - | 7.6 | 0 | - |

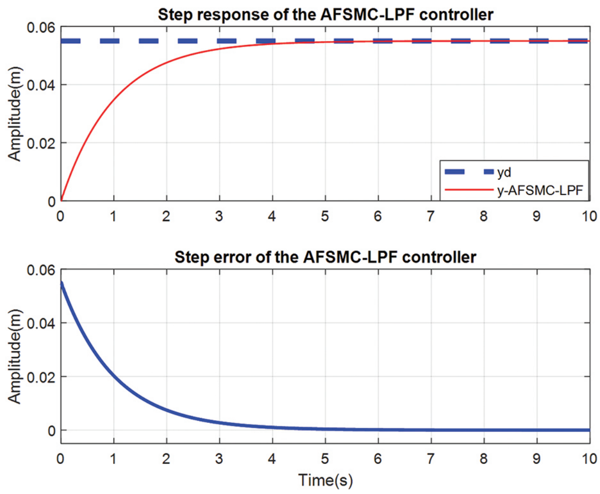


**Fig. 7.** Step response and error of the system with the AFSMC_LPF

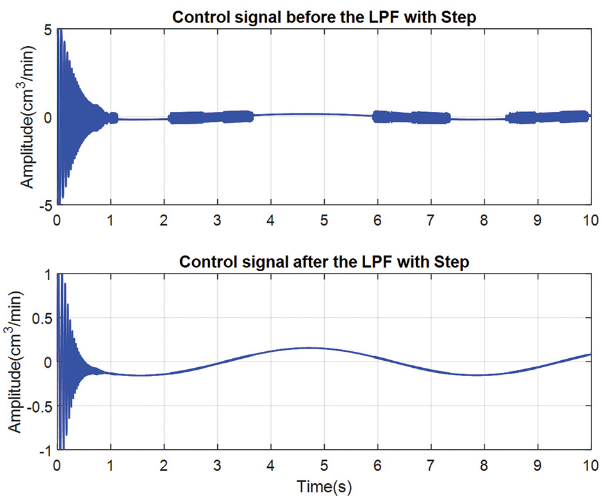


**Fig. 8.** Control signal of the AFSMC _ LPF before and after the LPF with Step

The actual liquid level (denoted as y-AFSMC-LPF) of the system tracks to the reference input (denoted as yd) in a finite time without the overshoot, the rising time achieves 2.187(s), the settling time is about 3.9133(s) and the steady state error converges to 0. These criteria are presented in Table 3 and compared with fuzzy control [19], SMC using conditional integrators [21] and SMC controller [24]. The amplitude of the control signal after passing the low pass filter is reduced about 5 times and significantly reduces the oscillation compared to before the low pass filter when the system response is at steady state. This signal is presented as Fig. 8.

The sine response and error of the AFSMC _ LPF with initial state is [0.1, 0], are shown as Fig. 9. The actual position of the system still tracks the desired input in a finite time with the steady state error converges to 0 and to reduces the chattering phenomenon in control signal as Fig. 10.

The step and sine response of the AFSMC _ LPF with Band Limited White Noise (0.0001w) is used to simulate sensor noise acting at the output of the system are shown in Fig. 11 and 12, respectively. The actual responses of the system still converge to the reference signal in the finite time. This proves that the AFSMC _ LPF controller is suitable to control the system.

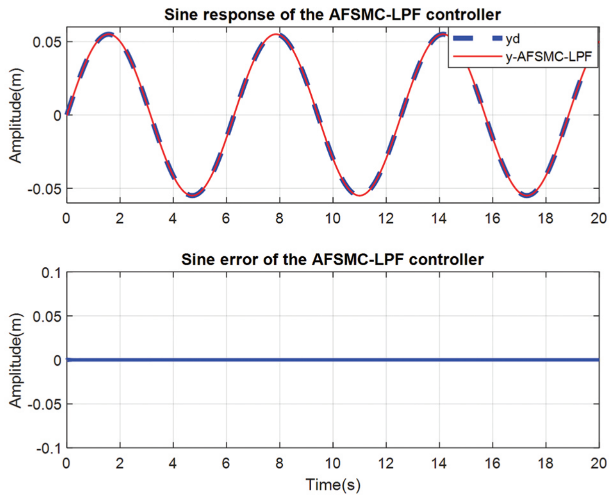


**Fig. 9.** Sine response and error of the AFSMC_LPF

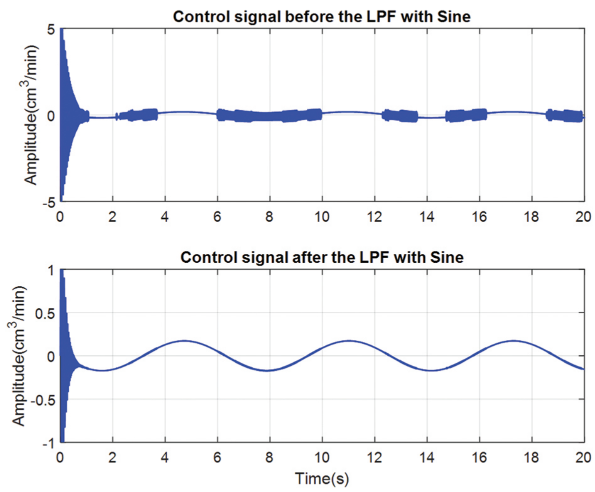


**Fig. 10.** Control signal of the AFSMC _ LPF before and after the filter with Sine

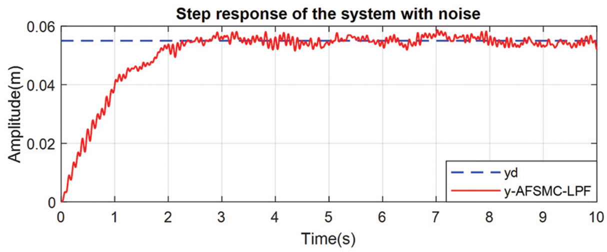


**Fig. 11.** Step response of the AFSMC _ LPF with Band Limited White Noise

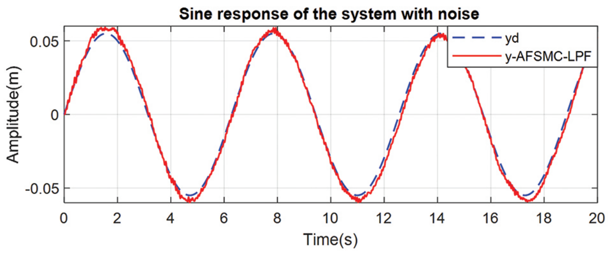


**Fig. 12.** Sine response of the AFSMC _ LPF with Band Limited White Noise

## 5. CONCLUSIONS

This paper presents the design of the adaptive sliding mode control based on the fuzzy logic and the low pass filter for the two-tank interacting system. The sliding mode controller is designed to ensure the actual liquid level of the system converges to the reference in a finite time. The fuzzy logic is used to approximate the function $f(\mathbf{x})$ in the SMC law and the LPF reduces the effect of chattering to a great extent. Responses and control input for AFSMC _ LPF with and without filter are presented. Simulation results with MATLAB/Simulink shown that the AFSMC _ LPF efficient, robust and suitable in liquid level control of the two-tank interacting system. The actual liquid level of the system tracks to the desired input in a finite time (Fig. 7) without the overshoot, the rising time achieves 2.187(s), the settling time is about 3.9133(s) and the steady state error converges to 0. These criteria (Table 3) of the proposed controller are better than the SMC controller, SMC using conditional integrators and fuzzy control. The amplitude of the control signal with yd=0.055m and yd=sine (±0.055m) after passing the low pass filter is reduced about 5 times (Fig. 8, 10). The step and sine response of the AFSMC _ LPF with Band Limited White Noise still converge to the reference signal in the finite time (Fig. 11, 12). In the future, this research will use the intelligent algorithms to optimize the fuzzy system and experiment with real models.

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