Journal of Automation and Control, 2015, Vol. 3, No. 1, 1-9
Available online at http://pubs.sciepub.com/automation/3/1/1

DOI:10.12691/automation-3-1-1

A Novel Approach in Design of Model-free Fuzzy Sliding Mode Controller to SISO Chemical Processes

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Received December 06, 2014; Revised December 26, 2014; Accepted January 07, 2015

Abstract Sliding Mode Control (SMC) is a powerful methodology in the field of nonlinear feedback control with feature of proven robustness, performance and stability in the face of system nonlinearity and modeling uncertainties. Unfortunately, pure SMC controller suffers from two important problems; chattering phenomenon and formulation of equivalent dynamics. The aim of this paper is to design a novel model-free Fuzzy Sliding Mode Control (FSMC) to solve these drawbacks. In this method the equivalent component of the SMC is estimated using an auto-adjustable fuzzy inference system in order to remedy the model dependency problem and robustness improvement. Also, in this method the conventional switching component of the SMC is developed using additional saturation function to eliminate the chattering completely. Eventually, for verification, the proposed controller is implemented on an isothermal van de vusse reactor as a high nonlinear chemical process, subjected by unknown disturbance. It is revealed that the purposed method can improve system's robustness and transient performance effectively in terms of complete suppression of the chattering and disturbance, specially, in the face of extra disturbances and reduction in settling time and percentage of overshoot in comparison with the two other model-free FSMC and Classical PID control.

Keywords: *model-free Fuzzy Sliding Mode Control, chattering elimination, model dependency, unknown disturbance, robustness, transient performance*

Cite This Article: M. Khodadadi, M. Shahbazian, and M. Aghajani, "A Novel Approach in Design of Model-free Fuzzy Sliding Mode Controller to SISO Chemical Processes." *Journal of Automation and Control*, vol. 3, no. 1 (2015): 1-9. doi: 10.12691/automation-3-1-1.

1. Introduction

Sliding Mode Control (SMC) is known because of its salient feature in robustness in the face of high nonlinearity, modeling uncertainties and disturbances with quick response [1,2,3]. Hence, this methodology has been developed during last three decades in the nonlinear control area. The SMC control law consists of two component; continuous and switching (discontinuous) controllers [2]. The discontinuity of the switching component causes the structure of the SMC control action to be consisted of a set of smooth functions. The controller's structure is allowed to change with infinite frequency at any instant between these smooth members in accordance with the situation of state vector with respect to the predefined state dependent sliding surface [3,4]. The purpose of this switching is to enforce and derive the system's state trajectory to reach the sliding surface in finite time (reaching mode or approaching regime) [5]; and then, enforce the trajectory to remain and slide on this surface as a manifold toward set-point (sliding mode) [6]. During the sliding mode, the motion of the system's state trajectory is sustained under modeling errors and disturbances [2]. However, *chattering* and *requirement of SMC to model of the plant* are known as main problems which can restrict applications of the original SMC [7]. "*Chattering phenomenon*" is the high frequency oscillation of the state trajectory near the sliding surface which is created in the presence constrained frequency switching in original SMC [2]. This harmful phenomenon produces high heat in electronic circuits and extreme erosion in moving parts of mechanical devices [8]. To overcome the chattering, commonly, the boundary layer (BL) approach is used as a signal filter for alleviation of the control signal in the thin layer around the sliding surface. However, it results in the quasi sliding mode [5] and loss of the asymptotic tracking. Specially, by consideration of the large enough boundary layer thickness and high switching gain in the presence of extra bound of modeling uncertainties and disturbances, the B.L. may cause a considerable tracking error [9,10] even, the chattering on the boundary [11]. To eliminate the drawbacks of the B.L., several methods has been proposed such as varying boundary layer and switching gain for instance [9-13]. The continuous part of the SMC is *model dependent*, thus in the presence of the complex or ill-defined process or large range of uncertainties, this dependency can degrade the system's performance [7], [14]. Fuzzy Logic Control methodology (FLC) based on fuzzy set theory [15] is designed in a form of inferential rules based on some qualitative expert knowledge about plant under control. Because of its model free feature, it is implemented generally on ill-modeled or parameter-fluctuated plants to improve control system's performance [16]. Integrating of the FLC with the SMC which collects the excellent features of both original SMC and FLC [17] capable to solve the problems of the original SMC (chattering, model dependency). This integrating is done commonly in two ways [18]: Sliding Mode Fuzzy Control ***(SMFC)*** and Fuzzy Sliding Mode Control ***(FSMC)*** which have been widely used in recent years such as [7,19]. In this paper, a novel model free-FSMC is proposed which can be specially implemented for process control to improve the robustness. In this new strategy, the continuous control is estimated and updated online by fuzzy methodology to remedy the model dependency problem and removing of steady state error. Also, the traditional switching control is developed using additional filter-like saturation function to avoid the chattering. This paper is organized as follows: In section 2 the SMC is presented; the new model-free FSMC methodology is illustrated in section 3; in section 4, the proposed FSMC is implemented and its capability is verified; eventually, in the section 5 the paper is concluded.

2. Pure Sliding Mode Control

Let an n^{th} order single input nonlinear system defined as [2]

$$x^{(n)} = f(X,t) + b(X,t)u(t) + d(t) \qquad (1)$$

Where, $X(t) = \left[x, \dot{x}, \ddot{x}, \dddot{x} \ldots, x^{n-1}\right]^T$ is the state vector and scalar x is the control variable. Scalar u(t) is the control action. $f(X,t), b(X,t)$ are generally nonlinear functions which are uncertain and bounded by continuous functions $F(X,t)$, $b_{\min}(X,t)$, $b_{\max}(X,t)$ respectively and are estimated as $\hat{f}, \hat{b}$ as follows:

$$\left|\hat{f}(X,t) - f(X,t)\right| \le F(X,t) \qquad (2)$$

$$0 \le b_{\min}(X,t) \le b(X,t) \le b_{\max}(X,t) \qquad (3)$$

$$\hat{b}(X,t) = \sqrt{b_{\min}(X,t) b_{\max}(X,t)} \qquad (4)$$

$$\beta(X,t) = \frac{b_{\max}(X,t)}{b_{\min}(X,t)} \qquad (5)$$

Also, the disturbance d(t) is upper bounded by D.

$$0 \le |d(t)| \le D \qquad (6)$$

Switching (sliding) function or sliding variable [5,11] is defined in the state space $R^{(n)}$ as:

$$s(X,t) = \left(\frac{d}{dt} + \lambda\right)^{(n-1)} e(t) \qquad (7)$$

$$E(t) = X(t) - X_d(t) = \left[e, \dot{e}, \ddot{e} \ldots, e^{n-1}\right]^T \qquad (8)$$

Here, $E(t)$ is the tracking error vector in the output state where $X_d(t)$ is the reference state vector and tuning factor λ is strictly positive. For second order systems (n=2), Eq. (7) gives the switching function as:

$$s = \dot{e} + \lambda e \qquad (9)$$

By choosing the Lyapunov function as:

$$V(s) = \frac{1}{2}s^2 \qquad (10)$$

For stability and to achieve invariant and null value sliding variable, it gives the switching (reaching) condition as:

$$\dot{V}(s) = s.\dot{s} \le -\eta|s| \qquad (11)$$

Here, η is a positive fixed parameter.

2.1. SMC's Control Law

In the sliding mode, the controller satisfies the confinement of scalar sliding surface at zero:

$$\dot{s} = \ddot{e} + \lambda\dot{e} = 0 \qquad (12)$$

Substituting Eq. (7) in Eq. (1), gives the approximation of continuous control law as [20]:

$$u_{eq} = \frac{-\hat{f} + \ddot{x}_d - \lambda\dot{e}}{\hat{b}} \qquad (13)$$

Here, u_{eq} is the continuous (equivalent) control (element) [2] which is the system's dynamic in the sliding mode [21]. By substituting Eq. (9) into the reaching condition Eq. (11) and use of Eq. (1) the control law is obtained as [20]:

$$u = \frac{-\hat{f} + \ddot{x}_d - \lambda\dot{e}}{\hat{b}} - k_s \operatorname{sgn}(s) \qquad (14)$$

$$u = u_{eq} + u_s \qquad (15)$$

Thereby, the reaching mode will be assured. Here, u_s is the discontinuous (switching, relay or robustness) control (term) [11] and k_s is the positive switching gain. The severity of the reaching mode depended on this gain [22] which is bounded as follows:

$$k_s(X,t) \ge \beta(X,t)(F(X,t) + \eta) + (\beta(X,t) - 1)\left|u_{eq}\right| \qquad (16)$$

2.2. Boundary Layer (BL) Technique and its Problems

In pure SMC, there is restricted frequency and non-instantaneous control switching in the sliding regime thus instead of ideal sliding mode, the state trajectory oscillates and chatters around the sliding surface with high frequency as depicted in Figure 1. The main causes of this non ideal switching are discretized (digital) implementation of the SMC's control law or neglected high frequency un-modeled dynamics (such as actuator's dynamics and time delays) [1,2,5,8,21]. The Boundary Layer (B.L) devise is the common filtering techniques to produce the smoothed control signal within a thin layer about the sliding surface [2] to suppress the chattering.

This is done using a continuous approximated saturation function such as linear type sat (instead of the discontinuous signum function sgn (as:

$$B(t) = \{X, ||s(X,t)| \le \varnothing\} \tag{17}$$

$$sat\left(\frac{s}{\varnothing}\right) = \begin{cases} \mathrm{sgn}(s) & if\ |s| \ge \varnothing \\ \frac{s}{\varnothing} & if\ |s| < \varnothing \end{cases} \tag{18}$$

Where $\varnothing$ is thickness of the boundary layer $B(t)$. However, this technique causes the tracking error which is limited to the precision of ϵ [2,23].

$$\epsilon = \frac{\varnothing}{\lambda^{n-1}} \tag{19}$$

Here, ϵ is named the width of the boundary layer

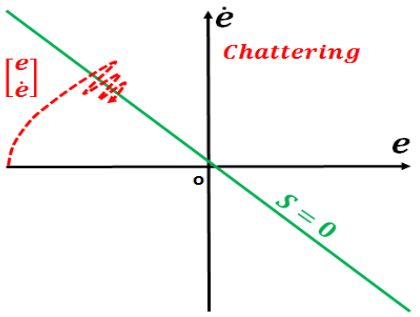

Figure 1. Chattering phenomenon as a result of non-ideal switching [23]

It is notable that, if the modeling uncertainties or disturbances vary in large range in the system, it should be assigned the *high enough switching gain* to improve tracking error and afterward, in order to prevent the chattering due to high gain, the *thickness of the boundary layer* should be assigned *large enough*, but, this devise may result in off-set considerably [9]. Furthermore, it may replace the chattering on the boundary [11]. To solve these drawbacks, time varying thickness has been proposed by several researchers, for instance in [9]. However, the varying boundary layer may result in a large ϵ for some systems [11]. In [11] the saturation function (18) was replaced with a new continuous function with fixed $\varnothing$ based on system dynamics.

In this paper every chattering will be avoided using the large enough and constant boundary layer thickness together with additional saturation function. Moreover, the steady state error as second problem of the boundary layer will be remedied by an auto adjustable fuzzy equivalent control.

3. The Proposed FSMC

In this section, a novel model-free FSMC strategy is proposed to assurance system's robustness and improved performance. Firstly, the equivalent control is designed by a fuzzy inferential system. Afterward online tuning method is devised for it such that the uncertainty of this dynamic depended part of the FSMC be eliminated, thereby, the steady state error will be canceled completely. Secondly, new switching control is designed by aim of complete elimination of the chattering. It is done by developing conventional switching function with additional saturation function of the sliding variable rate of change. The proposed FSMC controller is constructed as follows (see Figure 2):

$$u_{(k)} = u_{eq\ fuzzy(k)} + u_{s(k)} \tag{20}$$

Where, $u_{s(k)}$ and $u_{eq\ fuzzy(k)}$ are the switching control and fuzzy equivalent control respectively. $u_{(k)}$ is the FSMC output signal as the process input.

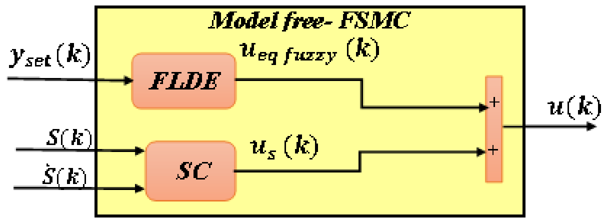

Figure 2. Model free -FSMC controller's elements: Fuzzy Logic Dynamics Estimator (FLDE) and developed Switching Control (SC)

3.1. Design of Equivalent Control of Proposed Model-free FSMC

The SMC whose equivalent part is formulated based on the *approximated model* of the process such as First Order Plus Dead Time (FOPDT) may be robust against inevitable un-modeled uncertainties arises from this modeling process [22], parameters variation and disturbances, but, if the modeling uncertainties vary in large range, the performance of controller will be degraded such that the SMC with conventional alleviated switching function may result in extreme steady state error and chattering on the boundary as mentioned in section 2.2. In this sub-section it is attempted to solve these problems. It is done by estimation of the equivalent part of the SMC using a fuzzy logic inference system based on system's behavior on the steady state condition. Afterward, atuning method is introduced for online adjusting of this fuzzy estimator based on the *difference between output of the SMC and output of its equivalent part* by aim of complete cancellation of this difference (or uncertainty) at steady state condition.

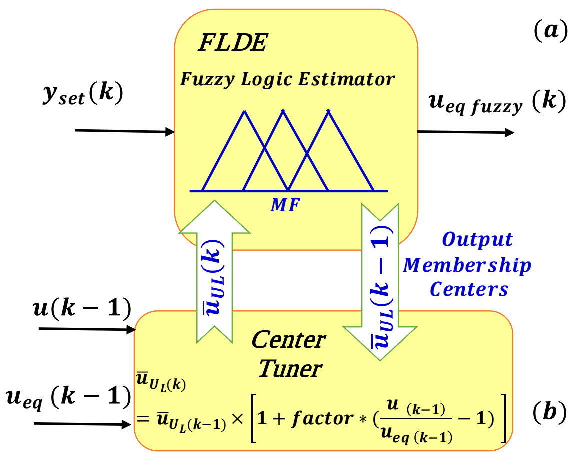

Figure 3. a) FLDE with auto adjustable membership functions centers **b)** Center Tuner for membership functions

3.1.1. The Proposed Methodology

For estimation of the equivalent control u_{eq} a *SISO Fuzzy Logic Dynamic Estimator* (*FLDE*) is designed based on *steady-state I/O* data of underlying plant (u_{ss}, y_{set}) which are used as centers of *O/I* membership functions. These centers are as free parameters which can be updated online by center tuner as depicted in Figure 3.

3.1.2. FLDE Design Procedure

Design of the FLDE is done through two steps; offline predesign step and online tuning step as follows:

Step I) Offline Predesign of pure FLDE

To design the FLDE, *output/input* the offline collected data of the process under control in relevant to the steady-state condition $\left(y_{ss}, u_{ss}\right)$ are used. These data are yielded through sensors in the full range of plant operation (which can be obtained from expert knowledge of process engineer). These data are assigned as the primary (pure) input/output centers of the membership functions $(\bar{y}_{A_L}, \bar{u}_{U_L})$ of the pure FLDE. The centers of the output membership function are free to tune online. Fuzzy reference (set-point) value y_{set} and equivalent control u_{eq} are defined with 8 linguistic labels. Triangular Membership Functions (MF) are chosen for the fuzzy variables. One dimensional rule base of the FLDE are given in Table 1, for instance, two typical rules are as follows:

$$\begin{aligned} &IF\ \ y_{set\ fuzzy}\ \ is\ small\ THEN\ u_{eq\ fuzzy}\ is\ small. \\ &IF\ \ y_{set\ fuzzy}\ \ is\ big\ THEN\ u_{eq\ fuzzy}\ is\ big. \end{aligned} \quad (21)$$

Mamdani product inference engine and Center Average Defuzzifier are used for FLDE estimator. Input and output fuzzy sets are as follows:

Input fuzzy sets:

A_1=Zero; A_2=Very-small; A_3=Small; A_4=Medium; A_5=Big; A_6=Very-Big; A_7=Very Very Big; A_8=Ultra Big

Output fuzzy sets:

U_1=Zero; U_2=Very-small; U_3=Small; U_4=Medium; U_5=Big; U_6=Very Big; U_7=Very Very Big; U_8=Ultra Big

Step II) FLDE's Free Parameters Auto Adjustment

The centers of output membership functions of the FLDE $\bar{u}_{U_L}$ (as free parameters) can be adjusted online based on elimination of difference between output of the SMFC $u_{(k)}$ and output the continuous controller $u_{eq(k)}$. These free parameters are tuned online as follows (see Figure 3):

$$\bar{u}_{U_L(k+1)} = \bar{u}_{U_L(k)} \times \left[1 + factor * reg_{(k)}\right] \quad (22)$$

$$reg_{(k)} = \frac{u_{(k)}}{u_{eq(k)}} - 1 \quad (23)$$

Here, $L = 1:M$ and M is the number of rules.

Also, k is the time-interval at time kT_s and T_s is the sampling period. factor is constant step size. As it is evident, the updating process is not iterative in each sampling period and the centers are updated once per each sampling, thus it is not too time-consuming process and therefore is feasible in practice. While the sliding variable remains at null value, the FLDE membership centers will be invariant but once a deviation is occurred in the sliding variable, the center tuner will attempt to compensate the difference between the FLDE output and the FSMC output automatically, such that the tracking error will be disappeared finally.

Table 1. One dimensional Fuzzy rule base for FLDE. Linguistic variables: B=big, M=medium, S=small, Z=zero, V=very, U=ultra

$y_{setfuzzy}(k)$	Z	VS	S	M	B	VB	VVB	UB
$u_{eqfuzzy}(k)$	Z	VS	S	M	B	VB	VVB	UB

3.2. Design of Developed Switching Control

To design the Switching Control (SC) of the proposed FSMC, in accordance with the Figure 4 an alleviated switching control with sigma saturation function $-k_s \frac{s}{|s| + \varnothing_1}$ is developed by augmenting new sigma saturation function $-k_s \frac{\dot{s}}{|\dot{s}| + \varnothing_2}$ in order to prevent the chattering as follows:

$$u_S = -k_s\left(\frac{s}{|s| + \varnothing_1} + \frac{\dot{s}}{|\dot{s}| + \varnothing_2}\right) \quad (24)$$

Here, k_s are the switching gain and $S, \dot{S}$ are the sliding variable and its rate of change respectively and $|S|, |\dot{S}|$ are their absolute values. $\varnothing_1$, $\varnothing_2$ are constant tuning parameters.

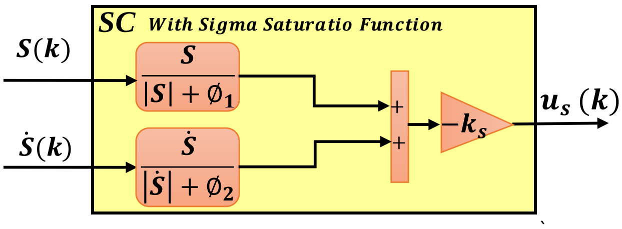

Figure 4. Developed switching control by additional Sigma Function

By choosing the large enough tuning parameter together with the additional sigma function the any chattering and fluctuation (around the sliding surface and on the boundary) which mentioned in sub-section 2.2 will be inhibited completely. It is worth noting that, the source of the chattering are determinant factors in choosing of the $\varnothing_1$, $\varnothing_2$ for example the greater time delay causes the choosing of larger tuning parameters. Also, the steady state error as the second problem of the boundary layer approach specially, if the large thickness is chosen will be eliminated by online tuning of the FLDE as mentioned in in subsection 3.1.

4. Simulation

4.1 Case Study

In this subsection, an isothermal Van de Vusse reactor [24] is chosen as a benchmark for validation of the performance of the proposed model free-FSMC. This high non-linear process is done in the continuous stirred tank reactor (CSTR) in the presence of inverse response behavior, input-delay(dead-time), affected by unmeasured disturbances [25,26]. This reactor is characterized by the following chemical reactions:

$$A \xrightarrow{k1} B \xrightarrow{k2} C \quad (25)$$

$$2A \xrightarrow{k3} D \quad (26)$$

Here, the component A is the reactant (feed of the reactor), B is the main product and C are the undesirable products. k_1, k_2 and k_3 are constants of the reaction rate. The control of the cyclopentenol (B) production from cyclopentadiene (A) by acid-catalyzed electrophilic addition of water in dilute solution is considered [27]. In this process the cyclopentanediol (C) and dicyclopentadiene (D) are as by-products. The reaction rates of A and B (molar rate per unit volume) are as follows:

$$r_A = -k_1 C_A - k_3 {C_A}^2 \quad (27)$$

$$r_B = k_1 C_A - k_2 C_B \quad (28)$$

The mole balances for components A and B are as follows:

$$\frac{dC_A}{dt} = \frac{F}{V}\left(C_{A,Feed} - C_A\right) - k_1 C_A - k_3 {C_A}^2 \quad (29)$$

$$\frac{dC_B}{dt} = -\frac{F}{V} C_B + k_1 C_A - k_2 C_B \quad (30)$$

Here, C_A and C_B are the concentrations of the components A, B and F is the molar feed flow rate, consists of pure A. It is supposed that, variation in the feed concentration (disturbance) $C_{A,Feed}$ is unknown. The reactor has constant volume. The density of the solution is assumed to be constant. The $\frac{F}{V}$ is control variable which is controlled by manipulating of dilution rate $\frac{F}{V}$ (see Figure 5). It is worth noting that, this process exhibits a change in sign of gain at peak conversion level of the operating curve. As depicted in Figure 6 it has non-minimum-phase behavior for operation to the left of this peak and minimum phase for operation to the right [14]. Thus, the maximum value of manipulated variable is upper bounded to $\frac{F_{peak}}{V} = 1.3\,\text{min}^{-1}$. The Kinetic parameters of the reaction and process variables are given in Table 2. The MATLAB software was used for simulation and numerical solving the equations of system's dynamics exhibited by Eq. (29), Eq. (30). Also, it is supposed that digital implementation with the sampling time $T_s = 1\text{sec}$ and the process time delay are the source of the chattering in this process and the actuator dynamics is assumed to be ideal.

In Accordance with the Figure 6 if the system affected by variation of the feed concentration, the operation curve will be changed, accordingly the FLDE which is designed based on the input/output data of the process under condition $C_{A\,feed} = 10 molL^{-1}$ will have uncertainty.

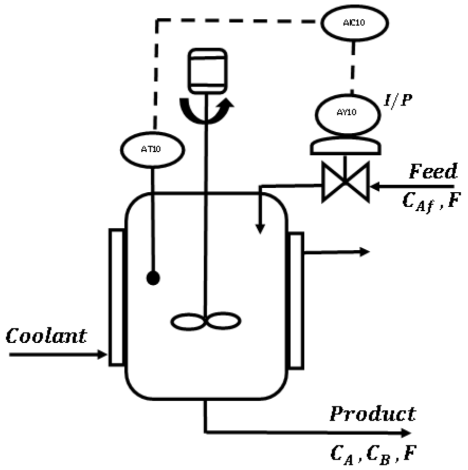

Figure 5. Schematic- isothermal CSTR [28]

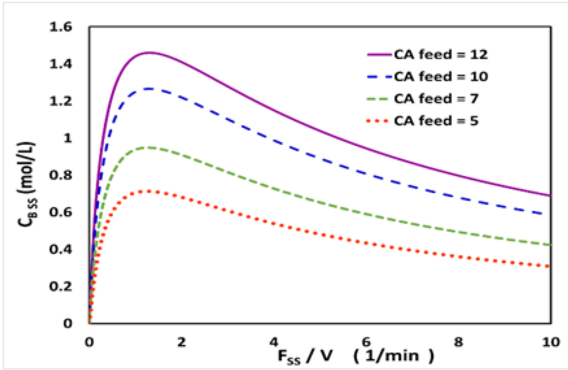

Figure 6. Steady-slate relationships: concentration of product C_{BSS} as a function of the dilution rate $\frac{F_{SS}}{V}$ and $C_{A,Feed}$ [29]

Table 2. Operating parameters of Van De Vusse reactor [14,25]

Parameter	Description	Value
$C_{A,Feed}$	feed concentration	10 molL^{-1}
V	volume of reactor	1.0 L
ρ	mixture density	0.9342 kg L^{-1}
k_1	reaction rate constant	50 h^{-1}
k_2	reaction rate constant	100 h^{-1}
k_3	reaction rate constant	10 Lmol^{-1}h^{-1}

4.2. Numerical Parameters

The sliding variable and the state error is defined as follows:

$$s = e_B, e_B = y - y_{set} = c_B - c_{Bset} \quad (31)$$

Here, C_{Bset} is the set-point concentration.

$$s_{max} = e_{Bmax} = 1.266 \quad (32)$$

$$\dot{s}_{max} = \dot{e}_{B\,max} = 0.024 \quad (33)$$

From the operating curve depicted in Figure 6, in accordance with the $C_{A\,feed}(=10molL^{-1})$, the pick concentration is $C_{Bmax} = 1.266 molL^{-1}$.

4.2.1. FLDE's Fuzzy Memory Table

The steady state I/O value of the reactor as the centers of O/I memberships of the FLDE are given in Table 3.1-

Table 3.2. These date were generated by steady state simulation of the process dynamics by MATLB software.

Table 3.1. One dimensional Fuzzy rule base for FLDE

$y_{setfuzzy}(k)$	0	0.2504	0.4341	0.6914
$u_{eqfuzzy}(k)$	0	0.05	0.1	0.2

Table 3.2. One dimensional Fuzzy rule base for FLDE

$y_{setfuzzy}(k)$	1.117	1.1786	1.2345	1.266
$u_{eqfuzzy}(k)$	0.5714	0.7	0.9	1.3

4.2.2 Coefficient Factors of Controllers:

The constants of the proposed model free-FSMC and 3 other controllers which are used for comparison are given as follows. These constant values were yielded from trial and error manually to achieve the best performance:

Controllers:

I) FSMC1: In this controller, equivalent component is pure FLDE (without tuning) and sigma saturation function with fixed tuning parameter is used for its switching control as follows:

$$u = FLDE_{pure} - K_s \frac{s}{|s| + \varnothing_1} \tag{34}$$

To achieve robustness in the face of any large feed concentration fluctuation, the great enough switching gain should be chosen, thus the maximum dilution rate $1.3min^{-1}$ is considered for K_s. The tuning parameter $\varnothing_1$ is computed as 0.40 by trial and error by getting the compromise between tracking error reduction and chattering reduction.

II) FSMC2: This controller is developed of FSMC1 by augmenting additional sigma function as follows:

$$u = FLDE_{pure} - K_s \left(\frac{s}{|s| + \varnothing_1} + \frac{\dot{s}}{|\dot{s}| + \varnothing_2}\right) \tag{35}$$

By supposition $K_s = 1.3$ same as switching gain of the FSMC1. The tuning parameters $\varnothing_1, \varnothing_2$ should be chosen large enough and small enough respectively as $\varnothing_1 = 0.3$ and $\varnothing_2 = 0.036$ to assure prevention of the chattering completely and $\varnothing_1$ should be small enough to achieve better tracking error in comparison with the FSMC1 in the presence of break-like function $\frac{\dot{s}}{|\dot{s}| + \varnothing_2}$.

III) Proposed FSMC: This controller is developed of FSMC2 by auto-adjusting of it equivalent control FLDE as follows:

$$u = FLDE_{autu-tuned} - K_s \left(\frac{s}{|s| + \varnothing_1} + \frac{\dot{s}}{|\dot{s}| + \varnothing_2}\right) \tag{36}$$

The gain K_s is chosen again as 1.3 and $\varnothing_1, \varnothing_2$ and step-size factor are computed as 1.0, 0.0312 and 0.0585 respectively by trial and error by getting the compromise between the achievement of the fast disturbance rejection and prevention of the chattering.

IV) Classical PID Controller:

The tuning parameters of the PID controller are considered as $K_c = 0.7045$; $K_i = 0.9607$; $K_d = 0.0822$ which are computed based on the tuning formulas for Dahlin synthesis [30] to achieve smoother responses than Ziegler-Nichols tuning method. It is done at operating point: $u = 0.2042L\min^{-1}$; $C_B = 0.7$ and $C_A = 1.5714molL^{-1}$.

4.3. Performance Evaluation

The set-point tracking and disturbance rejection performances of the proposed FSMC are evaluated in comparison with 3 other controllers mentioned in previous section. Integral of Absolute Error (IAE), Tracking Error (TE), Settling-Time ST (time taken for the output to reach 95% or 102% of the change in set-point), over shoot percentage and chattering control are used for verification.

$$IAE = \sum_{t=1}^{N} |C_B(t) - C_{Bset}(t)|.\Delta t \tag{37}$$

4.3.1. Set-point Tracking Performance

To verify the servo tracking performance, the set-point value C_{Bset} is changed step-like from 0.7 $mol.L^{-1}$ to 1.117 $mol.L^{-1}$ from t=0 min to t=15 min. According to Figure 7, and Table 4 it is clearly observed that the proposed method improved transient performance significantly. As it is shown, the settling time were reduced in comparison with the other controllers and less percentage of the overshoot was achieved than SMC1,2. By the SMC2,l ower settling time and percentage of the over shoot were achieved than FSMC1. The PID controller is better than others in term of lower percentage of the overshoot. Moreover, in terms of steady state error, similar performance was achieved by controllers. In accordance with the Figure 7 (b),(c), the proposed method and FSMC2 which were reinforced with the additional alleviated switching term, have less aggressiveness control action to achieve more stable reaching mode near the sliding surface to reduce the chattering thereby which percentage of the overshoot was reduced in comparison with SMC1.

Table 4. Set-point tracking performance of the proposed SMFC in comparison with the other controllers, in relevant to step-like change in Set-point from t=0 min to t=10 min

	PID	FSMC1	FSMC2	Proposed FSMC
IAE	23.67	23.01	15.29	15.22
TE	-1.5E-5	-6.5E-5	1.3E-6	1.6E-13
ST (sec)	116	296	128	84
Overshoot (%)	0.8	27.1	10.4	5.8

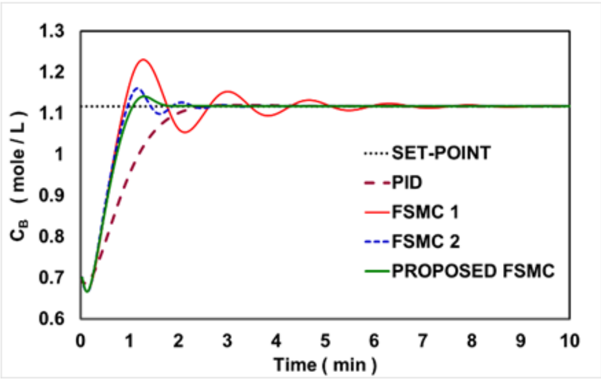

Figure 7(a). Control variable

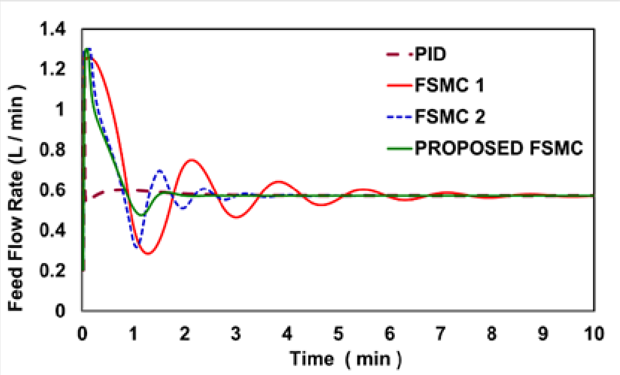

Figure 7 (b). Control action(Feed stream flow rate)

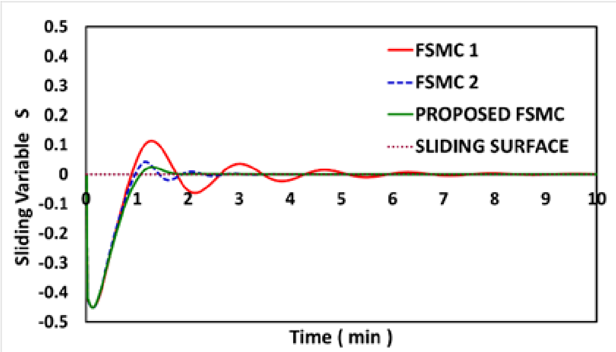

Figure 7 (c). Sliding variable

Figure 7. Set-point-tracking performance

4.3.2 The Regulatory Performance in Load Rejection.

To evaluate the superior robustness of the proposed controller, the feed concentration is changed step-like by +50% and -10% from t=5 min to t=10 min and t=20 min to t=25 min respectively while the set-point value is set in $C_{Bset} = 1.117 molL^{-1}$ as shown in Figure 8. As well depicted in Figure 9 and Table 5, the proposed controller rejected the disturbance successfully in comparison with the other controllers. In Figure 9(a),(c), it is depicted that the proposed FSMC rejected the disturbance completely without any chattering occurrence. The FSMC2 only succeeded in chattering elimination and its performance in rejection of disturbance is not acceptable specially, against large disturbance (50%) against which considerable tracking error (0.0782) was resulted in. The FSMC1 not only didn't succeed in disturbance rejection with tracking error (0.10) similar to FSMC2 but also, only succeeded to eliminate the chattering against small disturbance such that in the face of the large disturbance (50%) it resulted in oscillatory motion of the sliding variable trajectory in the boundary layer, however this oscillation was evanesced and damped finally. The classical PID controller is not sensitive against disturbance and is not robust controller. According to Figure 9(b) the control action of the proposed FSMC was updated successfully until the uncertainty of the FLDE was rejected eventually. It was updated powerfully from 0.571 $L/\min$ to 0.264 $L/\min$ and 0.571 $L/\min$ to 0.810 $L/\min$ against 50% and -10% change in feed concentration respectively. As it is revealed in Figure 9(b),(c) not only the proposed FSMC control action was updated, but also it attempted to break the fast motion of the sliding variable trajectory near the sliding surface to avoid the chattering occurrence similar to FSMC2.

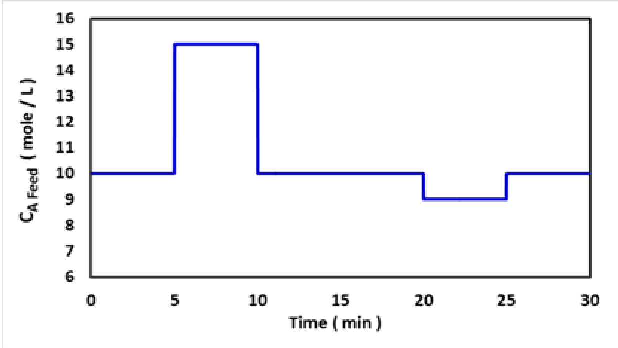

Figure 8. Step-like change in feed concentration (Disturbance)

Table 5. Load rejection performance of the proposed FSMC in comparison with other controllers in relevant to the step-like change in feed concentration from t=5 min to t=10 min

	PID	FSMC1	FSMC2	Proposed FSMC
IAE	19.99	29.76	22.88	4.59
TE	0.0016	0.1022	0.0782	2.3E-5

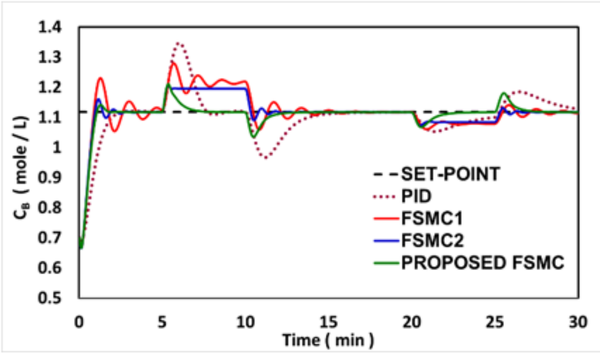

Figure 9 (a). Control variable

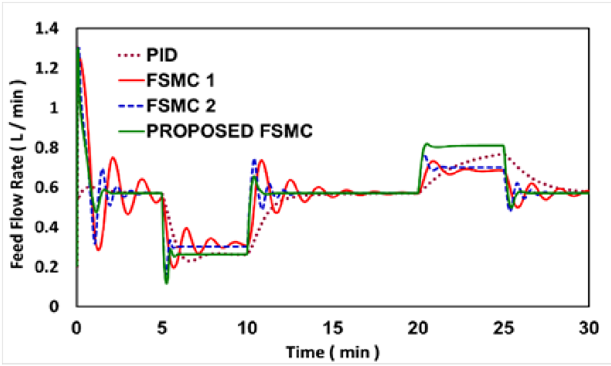

Figure 9 (b). Control action

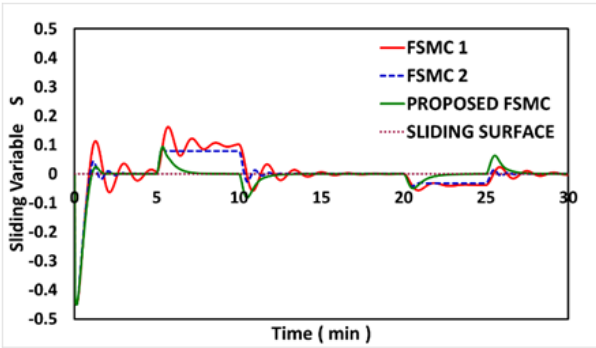

Figure 9 (c). Sliding variable

Figure 9. Disturbance rejection and system regulation performance

It is worth noting that, in accordance with the Figure 10, choosing the small tuning parameter $\varnothing_1 = 0.7$ causes the controller action be speeded up such that disturbance is suppressed faster but at cost of increasing the percentage of the overshoot in servo tracking (5.8% to 25%). Also, larger value of $\varnothing_1$ results in complete inhibiting of the overshoot occurrence (5.8% to 0 %) but at cost of slower response and slower disturbance rejection. These two performance (faster response without any overshoot) is not achieved simultaneously while $\varnothing_1$ is fixed or while sigma functions of switching control in proposed method be combined by constant weighting coefficient. To achieve these performances simultaneously, these sigma function can be integrated with time varying weighting coefficient or tuning parameter $\varnothing_1$ can be allowed to be time varying.

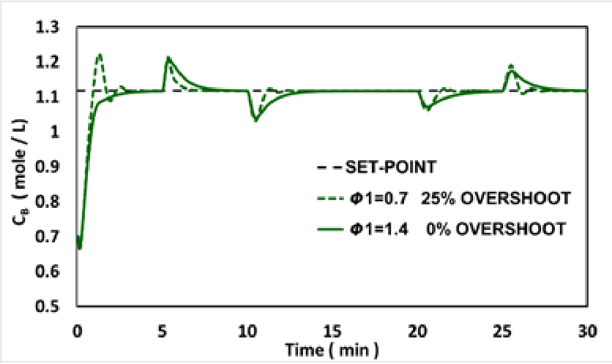

Figure 10. A compromise between overshoot prevention and robustness improvement

5. Conclusions

A novel approach to model-free FSMC was introduced in this paper in order to solve the problems of the pure-SMC can be applied specially in SISO process control. An auto-adjustable fuzzy logic dynamic estimator (FLDE) was proposed in order to improve the robustness in the face of unmeasured disturbances. Also the conventional switching control with large enough boundary layer was reinforced by adding a new saturation function for chattering elimination completely. The proposed method was implemented on an isothermal Van de vusse reactor. The results obviously confirmed the superiority of the new proposed methodology in comparison with two new FSMC and a classical PID control. Robustness was improved effectively specially, in the face of extra disturbances. Also, chattering was removed completely. Moreover, by the proposed method, significant enhancement in transient performance was achieved in terms of shorter settling time with lower overshoot. For further development, the switching control of the proposed method can be developed using fuzzy time varying weighting factor to achieve faster response without any overshoot. Also, we are going to investigate development of the proposed method to apply in MIMO process.

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