Model-free Adaptive Sliding Mode Control for Continuous Stirred Tank Reactor

Jiehua Feng[1], Lei Cao[1], Luning Ma[1], Dongya Zhao[1], Sarah K Spurgeon[1,2]

1. College of Chemical Engineering, China University of Petroleum, Qingdao 266555, P. R. China
E-mail: dyzhao@upc.edu.cn; dongyazhao@139.com

2. Department of Electronic & Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom
E-mail: s.spurgeon@ucl.ac.uk

Abstract: The continuous stirred tank reactor (CSTR) is representative of a typical class of chemical equipment, where the dynamics is strongly nonlinear. Two difficult issues in control of a CSTR are the difficulty of accurate modeling and the suppression of external disturbances. Driven by these challenging issues and demanding expectations around performance levels, this paper proposes a control solution based on the model-free data-driven linearization method and sliding mode control. After giving the corresponding stability proof, the effectiveness of the method is validated by MATLAB simulation. Experimental results are also presented to further test the proposed method.

Key Words: CSTR, adaptive sliding mode control, dynamic linearization, model free control

1 Introduction

The CSTR is one of the most commonly used reactors in the process industry. It has many advantages, such as low cost, high heat transfer capability and product stability. From the perspective of modeling and control, the CSTR exhibits nonlinear behaviour. This renders controller design difficult, especially in the presence of external disturbances. In addition, research studies relating to the control of the CSTR not only have the potential to improve product quality and stability of operation, but also provide added value to wider research on nonlinear process modeling and control [1].

Many efforts have been made to control the CSTR. Besides traditional PID control [2], many other control algorithms such as model predictive control [3], anti-jamming control [4] and fuzzy control [5] have been successfully applied to the CSTR. A predictive control approach has been developed to tackle the control problem in the presence of temperature delay effects which is based on fuzzy modelling, early prediction and rolling optimization [6]. A robust adaptive control scheme has been proposed in the literature [7] which can guarantee the convergence of parameter estimates and the stability of the closed-loop system. A new robust control strategy has been presented based on the theory of cooperative control in [8]. However, these methods require that the model is known. This study focuses on designing a model free controller with strong robustness.

Variable structure control with a sliding mode is a widely used control method, which can effectively solve the problem of controlling uncertain nonlinear systems [9]. In the sliding mode, the system is completely robust against matched disturbances. By designing the sliding mode appropriately, the control performance can be achieved independently of the disturbance, which provides advantages such as rapid response and insensitivity to a class of uncertainty and disturbances whilst being simple to implement. There are many successful applications of sliding mode control to CSTR. An output feedback terminal sliding mode control (TSMC) is proposed to estimate the system states and stabilize the system output tracking error to zero in finite time [10] . A sliding mode predictive control (SMPC) algorithm has been applied to the CSTR in [11] . A sliding mode control to achieve asymptotic tracking in the presence of disturbances is designed in [12]. The aforementioned approaches require the use of the CSTR dynamic model in the controller design which may be difficult to obtain accurately in practice. Model-free adaptive control [13–17] (MFAC) is a method that does not requires any information on the mathematical model. It has been successfully applied to control problems in the fields of oil refining, chemical, electrical, light industry and urban road systems. Since model free adaptive control does not need the mathematical model, some algorithms have been developed in this area [18–20]. However the existing methods have not been applied to CSTR and verified experimentally.

In many practical engineering systems, real-time controller implementations are computer based and the design of discrete time control systems becomes of interest. However, for discrete time systems, the reaching law based sliding mode control may only achieve quasi-sliding motion [21–23]. The adaptive discrete time sliding mode control approach [24–26] can ensure the system exhibits good performance without large chattering. This paper proposes an adaptive model-free control algorithm by combining discrete time sliding mode control and the partial form dynamic linearization method. The goal is to develop a control paradigm which does not require a dynamic model and ensures the system yields good performance without inducing excessive chattering.

The rest of this paper is organized as follows. In section 2, the dynamic linearization method is given for the CSTR. In Section 3, a model-free controller is designed based on a discrete sliding mode control approach and the stability is analyzed. In Section 4, case studies are used to validate the effectiveness of the proposed approach. In Section 5, experimental studies are used to further validate the proposed method. Finally, some concluding remarks are made in Section 6.

This work is partially supported by the National Nature Science Foundation of China under Grant 61473312 and the Changjiang Scholar Project.

2 Partial Form Dynamic Linearization (PFDL) Method for CSTR

Informed by the dynamics of the CSTR reaction, the dimensionless dynamic model from [27] is used:

$$\begin{aligned} x_1(k+1) &= [-x_1(k) + D_a(1-x_1(k))\exp(\frac{\gamma x_2(k)}{\gamma + x_2(k)})]T \\ &\quad + x_1(k) \\ x_2(k+1) &= [-x_2(k) + bD_a(1-x_1(k))\exp(\frac{\gamma x_2(k)}{\gamma + x_2(k)})]T \\ &\quad + [\beta(u(k) - x_2(k) + d(k))]T + x_2(k) \\ y(k) &= x_2(k) \end{aligned} \tag{1}$$

where $x_1, x_2 \in R$ are the states, which respectively represent the dimensionless concentration and temperature. The input of the CSTR is the flow of the jacket water and this is denoted $u(k)$. The sampling time is given by T.

Assumption 1. $x_1(k)$ and $x_2(k)$ are measurable. The CSTR system is observable and controlled.

(1) can be written as:

$$\begin{aligned} y(k+1) = &f(y(k), \cdots, y(k-n_y), \\ &x_1(k), \cdots, x_1(k-n_y), \\ &u(k), \cdots, u(k-n_u)) \end{aligned} \tag{2}$$

where $f(\cdot)$ denotes an unknown nonlinear function.

Let $\mathbf{U}_L(k) \in R^L$ be a vector consisting of all control input signals within the time window $[k-L+1, k]$,

$$\mathbf{U}_L(k) = [u(k), \cdots, u(k-L+1)]^T \tag{3}$$

where $\mathbf{U}_L(k) = \mathbf{0}$ for $k \leq 0$, L is a constant to control the input linearization length, and **0** is a zero vector of dimension L.

Assumption 2. (2) is generalized Lipschitz, i.e., for any $k_1 \neq k_2$, $k_1, k_2 \geq 0$, and $\mathbf{U}_L(k_1) \neq \mathbf{U}_L(k_2)$, there is

$$|\Delta y(k+1)| \leq b \left\| \Delta \mathbf{U}_L(k) \right\| \tag{4}$$

where $\Delta y(k+1) = y(k+1) - y(k)$, $\Delta \mathbf{U}_L(k) = \mathbf{U}_L(k) - \mathbf{U}_L(k-1)$, and b is a positive constant.

Assumption 3. The partial derivative of $f(\cdot)$ with respect to the control input signal $u(k), \cdots, u(k-L+1)$ of the system is continuous.

Remark 1. Assumption 2 is a restriction on the output variation of the CSTR system whereby the variation in the bounded output is generated by a change in the the bounded input. Assumption 3 holds for a broad class of nonlinear systems including the CSTR.

Lemma 1[28]. For the nonlinear discrete-time CSTR system shown in (2), if the Assumptions 1-3 are satisfied, when $\|\Delta \mathbf{U}_L(k)\| \neq 0$, there must be a pseudo gradient (PG), so that

$$\Delta y(k+1) = \theta_{p,L}^T(k) \Delta \mathbf{U}_L(k) \tag{5}$$

with bounded $\theta_{p,L}^T(k) = [\theta_1(k), \cdots \theta_L(k)]^T$.

(5) is a partial form dynamic linearization for the CSTR which defines a linearized equation using a data-driven approach. This reduces to some extent the modeling effort required to determine (1).

3 Model-Free Adaptive Sliding Mode Controller Based on Partial Form Dynamic Linearization (MFASMC-PFDL)

The system tracking error of the CSTR is defined as:

$$e(k) = y_d(k) - y(k) \tag{6}$$

where $y_d(k)$ is a given desired trajectory. The control objective is to stabilize the tracking error $e(k)$ to zero asymptotically. Define the sliding mode as:

$$s(k) = ce(k) \tag{7}$$

where c is a positive constant. In order to determine a sliding mode control, it is first necessary to define a reachability condition. Discrete sliding mode design frequently adopts the exponential reaching law which is given by:

$$s(k+1) - s(k) = -qTs(k) - \varepsilon T sgn(s(k)) \tag{8}$$

The discrete reaching law shown in (8) has many advantages. The performance is determined by the parameters defining the reaching rate as well as the sampling period of the discrete time system, but the system may exhibit large chattering. The ideal ε should be time varying, so that ε is larger when the system is far away from the sliding mode but decreases as the sliding mode is attained [29]. Motivated by the above, the reaching law can be designed as:

$$s(k+1) - s(k) = -qTs(k) - \frac{|s(k)|}{2} T sgn(s(k)) \tag{9}$$

where $q > 0$.

According to (6), (7), (9):

$$\begin{aligned} y_d(k+1) - y(k+1) = &\frac{1-qT}{c} s(k) \\ &- \frac{|s(k)|}{2c} T sgn(s(k)) \end{aligned} \tag{10}$$

A estimation criterion function is proposed to estimate the PG $\theta_{p,L}(k)$:

$$\begin{aligned} J(\theta_{p,L}(k)) = &\left| y(k) - y(k-1) - \theta_{p,L}^T(k) \Delta \mathbf{U}_L(k) \right|^2 \\ &+ \mu \left\| \theta_{p,L}(k) - \hat{\theta}_{p,L}(k-1) \right\|^2 \end{aligned} \tag{11}$$

where μ is a positive constant to express the weighting factor, $\hat{\theta}_{p,L}(k-1)$ is the estimation value of $\theta_{p,L}(k-1)$.

Under an optimal condition $\frac{\partial J(\theta_{p,L}(k))}{\partial \theta_{p,L}(k)} = 0$:

$$\begin{aligned} \hat{\theta}_{p,L}(k) = \hat{\theta}_{p,L}(k-1) + &\frac{\eta \Delta \mathbf{U}_L(k-1)}{\mu + \|\Delta \mathbf{U}_L(k-1)\|^2} \cdot \\ &\left[y(k+1) - y(k) - \hat{\theta}_{p,L}^T(k-1) \Delta \mathbf{U}_L(k-1) \right] \end{aligned} \tag{12}$$

where the step-size factor $\eta \in (0, 2]$.

Considering the estimation ability of the algorithm (12) in some special cases, the following reset algorithm is proposed:

$$\hat{\theta}_{p,L}(k) = \hat{\theta}_{p,L}(1) \tag{13}$$

if $\text{sgn}(\hat{\theta}_{p,L}(k)) \neq \text{sgn}(\hat{\theta}_{p,L}(1))$, $\left\| \hat{\theta}_{p,L}(k) \right\| \leq \varepsilon$, or $\|\Delta \mathbf{U}_L(k-1)\| \leq \varepsilon$, where ε is a small positive constant and $\hat{\theta}_{p,L}(1)$ is the initial value of $\hat{\theta}_{p,L}(k)$.

Integrating (5) and (10), the MFASMC-PFDL algorithm can be expressed as:

$$\begin{aligned} u(k) = u(k-1) + \frac{1}{\theta_1(k)} & [y_d(k+1) - y(k) \\ -\frac{1-qT}{c}s(k) & + \frac{|s(k)|}{2c}Tsgn(s(k)) \\ -\theta_2(k)\Delta u(k-1) - \cdots & - \theta_L(k)\Delta u(k-L+1)] \end{aligned} \quad (14)$$

where the $\hat{\theta}_{p,L}(k)$ depends on (12) and (13).

Remark 2. The desired trajectory $y_d(k)$ is frequently constant for the CSTR. This means that the temperature of the CSTR needs to be stabilized to a constant. In the model (1), D_a is a small positive constant representing the Damkohler number.

Theorem 1. If (2) satisfies Assumptions 1-3, the MFASMC-PFDL algorithm (14) can render $e(k)$ asymptotically stable and $x_1(k)$ will be bounded.

Proof: In order to prove the stability of the MFASMC-PFDL algorithm, an estimate of the boundedness of the PG has been given in the literature [30]. The stability of the discrete sliding mode is shown as follows.

Choose a Lyapunov candidate function:

$$V(k) = s^2(k) \quad (15)$$

When $\Delta V(k) < 0$ is satisfied, any initial state tends to the switching surface $s(k)$, where $\Delta V(k) = s^2(k+1) - s^2(k)$. The conditions for convergence are therefore

$$s^2(k+1) < s^2(k) \quad (16)$$

From (16), the reaching condition for the discrete time sliding mode can be expressed as:

$$\begin{aligned} [s(k+1) - s(k)]\, sgn(s(k)) < 0 \\ [s(k+1) + s(k)]\, sgn(s(k)) > 0 \end{aligned} \quad (17)$$

For the discrete reaching rate, the following equations are available.

$$\begin{aligned} [s(k+1) - s(k)]sgn(s(k)) &= -qTs(k)sgn(s(k)) \\ &- \frac{|s(k)|}{2}Tsgn(s(k))sgn(s(k)) \\ &= -(q+0.5)T\,|s(k)| < 0 \end{aligned} \quad (18)$$

$$\begin{aligned} [s(k+1) + s(k)]sgn(s(k)) &= 2s(k)sgn(s(k)) \\ &- qTs(k)sgn(s(k)) \\ &- \frac{|s(k)|}{2}Tsgn(s(k))sgn(s(k)) \\ &= (2 - 0.5T - qT)\,|s(k)| > 0 \end{aligned} \quad (19)$$

where $T < \frac{4}{1+2q}$.

The result shows the correctness of (16), that is, $\lim_{t\to\infty} s(k) \to 0$. So $\lim_{t\to\infty} e(k) \to 0$ can be obtained from (7).

Based on the analysis above, $TD_a \exp(\frac{\gamma x_2(k)}{\gamma + x_2(k)})$ is also bounded due to the boundedness of $x_2(k)$.

Let $C_1 = TD_a \exp(\frac{\gamma x_2(k)}{\gamma + x_2(k)})$, $C = 1 - T - C_1$, it is obvious that $C_1 > 0$ and $0 < C < 1$.

According to (1):

$$\begin{aligned} x_1(k+1) &= \left[-x_1(k) + D_a(1 - x_1(k))\exp(\frac{\gamma x_2(k)}{\gamma + x_2(k)})\right]T \\ &\quad + x_1(k) \\ x_1(k+1) &= (-T - C_1 + 1)x_1(k) + C_1 \\ x_1(k+1) &= Cx_1(k) + C_1 \end{aligned} \quad (20)$$

Using iteration

$$\begin{aligned} x_1(k) &= C^{k-1}x_1(0) + C_1\frac{1 - C^{k-1}}{1 - C} \\ \lim_{k\to\infty} x_1(k) &= \frac{C_1}{1 - C} \end{aligned} \quad (21)$$

where $x_1(0)$ is the initial condition of $x_1(k)$. Hence x_1 is bounded and Theorem 1 is proved; the stability of the closed-loop system is guaranteed.

4 Simulation Analysis

In view of the need for complicated controller parameter settings and the poor robustness of PID schemes for the CSTR, an adaptive PID controller based on RBF network tuning (APID-RBF) has been previously proposed in the literature [31]. In this section, the performance of the MFASMC-PFDL and APID-RBF algorithms are tested by using the model (1). The performance of the two controllers is compared by evaluating J and δ , where $J = \int_0^\infty te^2dt$ and δ is the system overshoot.

The parameters of the model (1) were selected as: $\beta = 0.3$, $\gamma = 20.0$, $b = 8.0$, $D_a = 0.078$. The initial conditions are chosen as $x_1 = 0.5, x_2 = 3$ and the given desired trajectory is chosen as $y_d(k) = 4$.

Case 1. There is no external disturbance, that is, $d(k)= 0$.

Fig. 1 shows the two controllers can guarantee x_2 converges to the desired trajectory. Fig. 2 and Fig. 3 show the convergence of x_1 and the boundedness of the control input. At the same time, it can be seen that $J(\mathrm{APID-RBF}) = 2.3213$, $\delta(\mathrm{APID-RBF}) = 0$, $J(\mathrm{MFASMC-PFDL}) = 0.5434$, $\delta(\mathrm{MFASMC-PFDL}) = 0$. The results show that the MFASMC-PFDL has better overall performance. Specifically, it achieves a faster response. For the APID-RBF controller, the control performance can be improved by adjusting the parameters, but the control input will have a larger overshoot, which will cause damage to the actual CSTR device, where the constraints on the the valve that controls the water flow to the jacket are pertinent.

Case 2. Performance in the presence of a rectangular wave disturbance as shown in Fig. 7.

Fig. 4 shows the two controllers can guarantee x_2 converges to the desired trajectory. Fig. 5 and Fig. 6 show the convergence of x_1 and the boundedness of control input. It can be obtained that $J(\mathrm{APID-RBF}) = 4.4391$, $\delta(\mathrm{APID-RBF}) = 2.34\%$, $J(\mathrm{MFASMC-PFDL}) = 0.5676$, $\delta(\mathrm{MFASMC-PFDL}) = 0.25\%$. The results show that the MFASMC-PFDL has better overall performance and the system overshoot is smaller. The MFASMC-PFDL guarantees that the level of chattering is acceptable in the presence of the rectangular wave disturbance as shown in Fig.6.

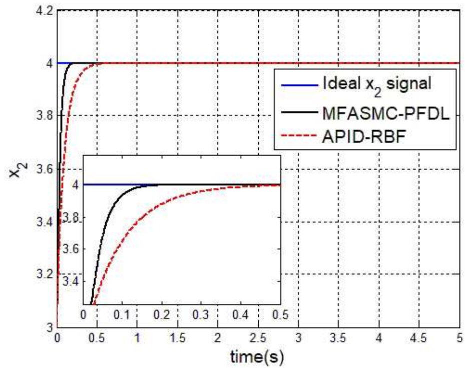

Fig. 1: x_2 performance of the two algorithms for the nominal CSTR system without disturbance

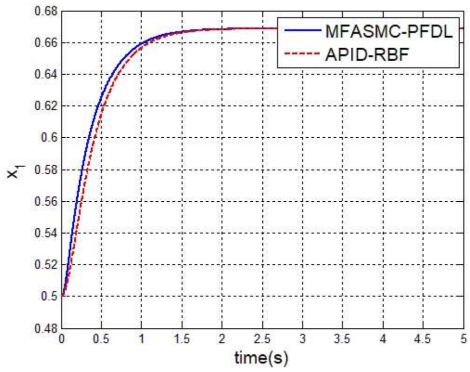

Fig. 2: x_1 performance of the two algorithms for the nominal CSTR system without disturbance

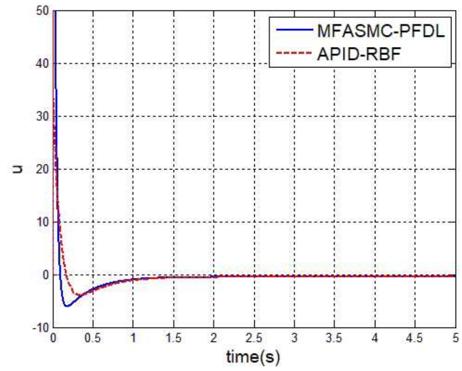

Fig. 3: The control input of the two algorithms for the nominal CSTR system without disturbance

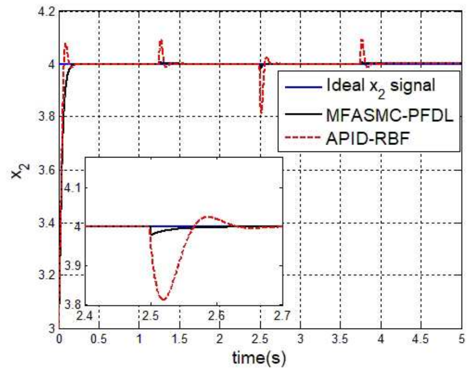

Fig. 4: x_2 performance of the two algorithms for the CSTR system in the presence of rectangular wave disturbance

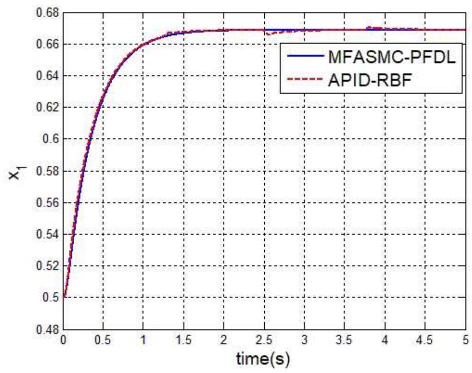

Fig. 5: x_1 performance of the two algorithms for the CSTR system in the presence of rectangular wave disturbance

Case 3. Performance in the presence of a sine wave disturbance as shown in Fig. 11.

Fig. 8 shows the two controllers can guarantee x_2 converges to the desired trajectory. Fig. 9 and Fig. 10 show the convergence of x_1 and the boundedness of control input. It can be seen that $J(\mathrm{APID-RBF}) = 1.0559$, $\delta(\mathrm{APID-RBF}) = 2.37\%$, $J(\mathrm{MFASMC-PFDL}) = 0.5256$, $\delta(\mathrm{MFASMC-PFDL}) = 0.25\%$. The results show that the MFASMC-PFDL has better overall performance while the system overshoot is smaller. At the same time, the MFASMC-PFDL does not induce chattering in the presence of the sine wave disturbance as shown in Fig. 10.

Based on the analysis of the above three cases, the MFASMC-PFDL approach exhibits robustness while ensuring acceptable performance in terms of chattering in the presence of external disturbances.

5 Experimental Verification

In this section, the performance of the MFASMC-PFDL algorithm is experimentally tested on a CSTR. The experimental operating interface is shown in Fig. 12. The esterification of sodium hydroxide with ethyl acetate is carried out in the CSTR. The purpose of this experiment is to stabilize the temperature of the CSTR from 40 degrees Celsius to 30 degrees Celsius.

In the experiment, the cooling water flow in the jacket is used as the control input u and the reactor temperature is the control output y. The controller is designed using the presented MFASMC-PFDL approach. As can be seen from Fig. 13, the temperature of the reactor finally stabilizes to the desired temperature after four fluctuations. This is because the chemical reaction is an exothermic reaction, and the material has been preheated. The cooling of the jacketed water and reaction heat must achieve dynamic balance. In the experiment, the water temperature of the jacket is not completely constant and other external disturbances exist. The practicability and robustness of the proposed MFASMC-PFDL method is verified.

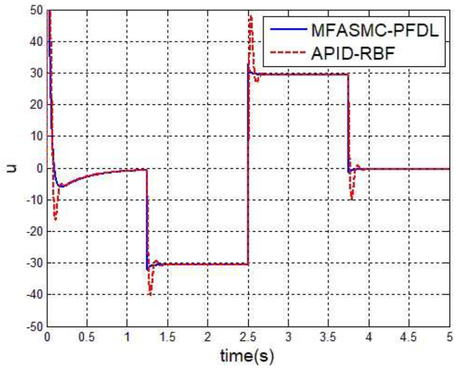

Fig. 6: The control input of the two algorithms for the CSTR system in the presence of rectangular wave disturbance

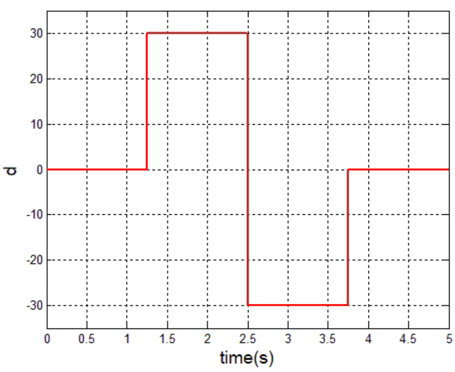

Fig. 7: The rectangular wave disturbance

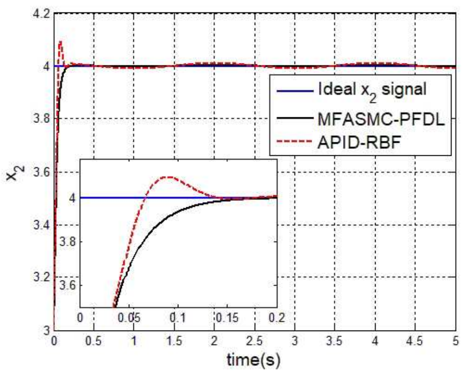

Fig. 8: x_2 performance of the two algorithms for the CSTR system in the presence of sine wave disturbance

6 Conclusion

In this paper, a MFASMC-PFDL controller is proposed by combining the dynamic linearization method from discrete time nonlinear systems and sliding mode control. The corresponding stability analysis is given to provide a theoretical foundation for the results. The effectiveness of the proposed method is validated by a detailed numerical simulation. The MFASMC-PFDL method shows strong robustness in the presence of external disturbances, while ensuring acceptable levels of chattering. The experimental testing further demonstrates the proposed approach. Future work will consider the performance indicators for a variety of con-

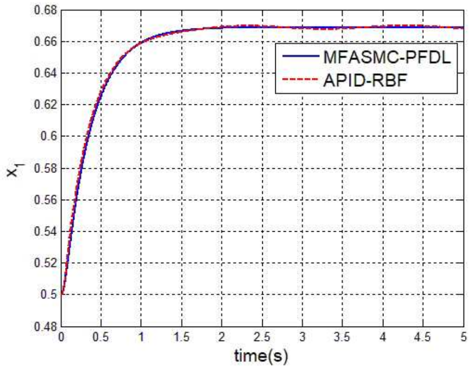

Fig. 9: x_1 performance of the two algorithms for the CSTR system in the presence of sine wave disturbance

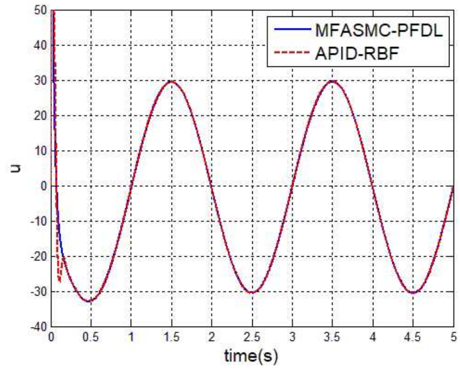

Fig. 10: The control input of the two algorithms for the CSTR system in the presence of sine wave disturbance

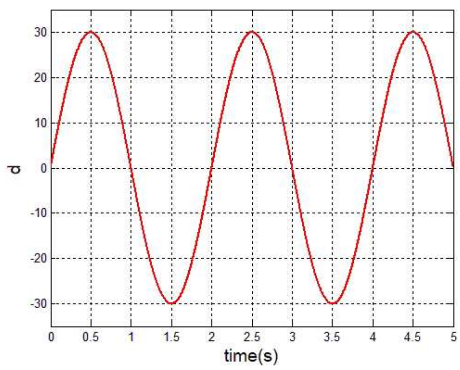

Fig. 11: The sine wave disturbance

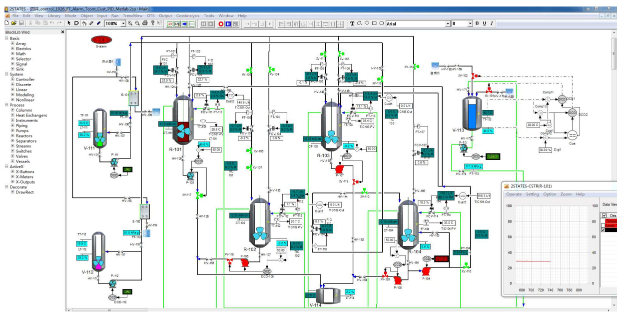

Fig. 12: The experimental operating interface

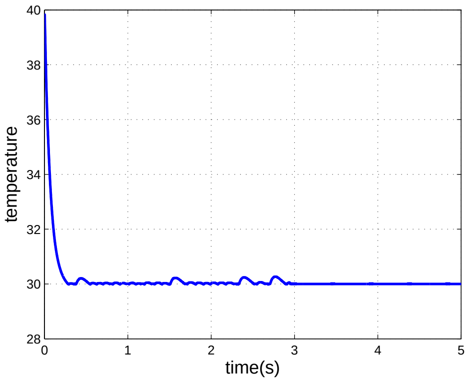

Fig. 13: The temperature performance of the MFASMC-PFDL controller

trollers, especially the sliding mode control, while using the experimental platform for verification of the results obtained in theory and simulation.

References

[1] L. Ma, X. Yang, D. Zhao, et al. "Disturbance observer based sliding mode control for a continuous stirred tank reactor (CSTR)," *Control Conference (CCC), 2017 36th Chinese. IEEE*, 2017: 3748-3753.

[2] B. Dey, L.Roy, " A Comparative Study on Temperature Control of, CSTR using PI Controller, PID Controller and PID, (Two Degree of Freedom) Controller," *International Journal of Electronics and Computer Science Engineering*, 2014, 3(1).

[3] F. Wu, "LMI-based robust model predictive control evaluated on an industrial CSTR model," *International Conference on Control Applications. IEEE*, 1992:609-614.

[4] H. Niu, C. Liu, Y. Zhang , et al. "The bifurcation analysis and chaos anti-control of a differential-algebraic system," *IEEE Fifth International Conference on Bio-Inspired Computing: Theories and Applications. IEEE*, 2010:104-108.

[5] M. Mohammadzaheri, L. Chen, "Double-command fuzzy control of a nonlinear CSTR," *Conference on Industrial Electronics and Applications. IEEE*, 2008:659-664.

[6] M. Jalili-Kharaajoo, " Predictive control of a continuous stirred tank reactor based on neuro-fuzzy model of the process," *Sice 2003 Conference. IEEE*, 2003:3277-3282 Vol.3.

[7] P. Yuan , B. Zhang, Mao Z Z, "A robust adaptive controller for Hammerstein nonlinear systems," *International Journal of Control Automation and Systems*, 2017, 15(2):656-667.

[8] S. Rastegar , A. Rui , J. Sadati , et al. " A novel robust control scheme for LTV systems using output integral discrete-time synergetic control theory," *European Journal of Control*, 2017, 34:39-48.

[9] C. Edwards , S K. "Spurgeon Sliding mode control: theory and applications," *Crc Press*, 1998.

[10] D. Zhao, Q. Zhu, and J. Dubbeldam, "Terminal sliding mode control for continuous stirred tank reactor," *Chemical Engineering Research and Design*, vol. 94, pp. 266–274, 2015.

[11] W. Garcła-Gabłn ,J E. Normey-Rico , "Camacho E F. SLIDING MODE PREDICTIVE CONTROL OF A DELAYED CSTR," *Ifac Proceedings Volumes*, 2006, 39(10):246-251.

[12] M C. Colantonio ,A C. Desages , "Romagnoli J A, et al. Nonlinear Control of a CSTR: Disturbance Rejection Using Sliding Mode Control," *Industrial and Engineering Chemistry Research*, 1995, 34(7):2383-2392.

[13] H. Zhang, J. Zhou, Q. Sun, et al. "Data-Driven Control for Interlinked AC/DC Microgrids Via Model-Free Adaptive Control and Dual-Droop Control," *IEEE Transactions on Smart Grid*, 2017, PP(99):1-15.

[14] Z. Dong, Y. Pan , Z. Zhang, et al. "Model-free adaptive control law for nuclear superheated-steam supply systems," *Energy*, 2017.

[15] Y. Zhu , Z. Hou , F. Qian , et al. "Dual RBFNNs-Based Model-Free Adaptive Control With Aspen HYSYS Simulation," *IEEE Transactions on Neural Networks and Learning Systems*, 2017, 28(3):759.

[16] Z. Wang, D. He , X. Zhu , et al. "Data-Driven Model-Free Adaptive Control of Particle Quality in Drug Development Phase of Spray Fluidized-Bed Granulation Process," *Complexity*, 2017, 2017(1):1-17.

[17] M. Tao , Z. Ke , Y. Yu . "System identification and model-free adaptive control of once-through steam generator in nuclear power," *International Conference on Mechatronics and Automation. IEEE*, 2017:1256-1261.

[18] E G. Nabati , S. Engell . "Data-driven adaptive robust control of a CSTR," *Electrotechnical Conference. IEEE*, 2012:946-949.

[19] T. Wonghong , S. Engell. "DApplication of a New Scheme for Adaptive Unfalsified Control to a CSTR," *Ifac Proceedings Volumes*, 2008, 41(2):13247-13252.

[20] A. Mizov "A Model-Free Control Algorithm Derived Using the Sliding Model Control Method," *Dissertations and Theses - Gradworks*, 2015.

[21] C. Milosavljevic "Perunicic-Drazenovic B, Veselic B, et al. Sampled Data Quasi-Sliding Mode Control Strategies," *International Conference on Industrial Technology. IEEE*, 2006:2640-2645.

[22] C Y. Chan "Discrete adaptive quasi-sliding mode control," *International Journal of Control*, 1999, 72(4):365-373.

[23] T. Liu , H. Tang . "Quasi-Sliding Mode Control Based on Reduced Order Mode," *International Conference on Control, Automation and Artificial Intelligence*, 2017.

[24] H. Li , P. Shi , D. Yao . " Adaptive Sliding-Mode Control of Markov Jump Nonlinear Systems With Actuator Faults,"*IEEE Transactions on Automatic Control*, 2017, 62(4):1933-1939.

[25] X. Guo , J. Wang , F. Liao , et al. "Distributed Adaptive Sliding Mode Control Strategy for Vehicle-Following Systems With Nonlinear Acceleration Uncertainties,"*IEEE Transactions on Vehicular Technology*, 2017, 66(2):981-991.

[26] R. Karthikeyan , K. Anitha. "Chaos Control in Fractional Order Smart Grid with Adaptive Sliding Mode Control and Genetically Optimized PID Control and Its FPGA Implementation,"*Complexity*, 2017:1-18.

[27] M C. Colantonio , A C. Desages , "Romagnoli J A, et al. Nonlinear Control of a CSTR: Disturbance Rejection Using Sliding Mode Control,"*Industrial and Engineering Chemistry Research*, 1995, 34(7):2383-2392.

[28] S T. Jin, Z S. Hou, R H. Chi, et al. "Data-driven model-free adaptive iterative learning control for a class of discrete-time nonlinear systems," *Control Theory and Applications*, 2012, 29:1001-1009.

[29] C L. Zhai, Z M.Wu. "Design of variable structure control for uncertain discrete time systems,"*Automation Journal*, 2000, 26 (2): 184-191.

[30] Y. Zhu, Z. Hou. "Controller compact form dynamic linearization based model free adaptive control,"*Decision and Control. IEEE*, 2012:4817-4822.

[31] J K. Liu. "Advanced PID control MATLAB simulation,"*Electronics and Industry Press*, 2004.