IJIRR

International Journal of Information Research and Review
Vol. 06, Issue, 06, pp.6347-6350, June, 2019

RESEARCH ARTICLE

ADAPTIVE FUZZY CONTROL FOR CHEMICAL CONTINUOUS STIRRED TANK REACTOR SYSTEM WITH DEAD ZONE INPUT

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ARTICLE INFO

Article History:
Received 20th March, 2019
Received in revised form
17th April, 2019
Accepted 15th May, 2019

Keywords:
Continuous stirred tank reactor,
Adaptive fuzzy control,
Fuzzy logic system, Nonlinear system.

ABSTRACT

This paper presents the flexible adaptive fuzzy control method for chemical continuous stirred tank reactor, one of uncertain nonlinear systems. Objects of this method include input dead zone observed when controlling valve or motor current in practice. Adaptive fuzzy logic system is used to approximate the nonlinear systems. Compared with the previous method, this adaptive fuzzy control approximation is more flexible, so can be extened to the chemical continuous stirred tank reactor with dead zone of valve input control. So, this work observe chemical continuous stirred tank reactor (CSTR) system which can be extended to one with dead zone input and design the adaptive fuzzy controller of this system is designed. Finnaly, the validity of the proposed control method is tested with chemical continuous stirred tank reactor (CSTR) with dead zone input.

INTRODUCTION

Continuous stirred tank reactors (CSTRs) are known to be one of the systems that exhibit complex behavior. Previously, linear control approaches which are derived on the basis of linearized models of the process have been applied to CSTRs (Shi, Zhang *et al.,* 2016; Jiaoa *et al.,* 2014). However, CSTRs are difficult to control effectively using linear techniques due to their inherent nonlinear behavior. The other source of complexity is that it is often desirable to operate CSTRs in an open-loop unstable region due to the suitable reaction behavior there. Therefore, nonlinear design tools such as feedback linearization have been used to provide global stabilization (Yao *et al.,* 2016). Also, various auxiliary solutions have been proposed to overcome inherent drawbacks of the feedback linearization approach. In particular, state observers have been designed to estimate non-measurable states (Xu *et al.,* 2005; Aouaouda *et al.,* 2012; Tong *et al.,* 2016). Also robust techniques have been utilized to reduce the effect of parameter uncertainties (Hua *et al.,* 2008; Hua *et al.,* 2015). Moreover, input constraints and multivariable behavior of CSTRs, encourage the utilization of other advanced controllers (He *et al.,* 2016; Yazdi *et al.,* 2009; Wei Zheng *et al.,* 2018). Yazdi *et al.* presents the problem of controller synthesis with the objective of stabilizing a continuous stirred tank reactor (CSTR) with arbitrary switching between two modes and introducing the concept of modal state feedback linearization, makes two nonlinear state feedback laws and a nonlinear state transformation be synthesized. Also, adaptive dynamic output-feedback control for CSTR with nonlinear uncertaninties and multiple time-delays (Wei Zheng *et al.,* 2018). They used nonlinear discrete-time system with multiple time delays. These didn't consider dead-zone problem. In recent years, the adaptive control of nonlinear systems has achieved progress (Wenshun Lv *et al.,* 2018). Neural networks (NN), universal approximators have been successfully applied to solve the control issue for various kinds of such nonlinear systems because they provide powerful tools for control of uncertain nonlinear system. The nonlinear control scheme using neural networks has been further improved by the introduction of adaptive algorithms for tuning the weighs of NNs (Yang *et al.,* 2017). By employing norms of unknown weight vectors as the estimated parameters, the huge computation problem of this method has also been resolved in (Shi *et al.,* 2016) to a certain extent. The purpose of these methods is toachieve the desired system performance for general type of problems. Many chemical processes include discontinuous actuators, physical constraints or manufacturing distinct phases such as, filling/emptying a reactor or heating/cooling a product. In addition, in the field of practical application, the actuator of the system may encounter dead-zone input nonlinearity phenomena, which is marked by insensitivity for small control input. These phenomena often can be observed in controlling valve, temperature, electric current, etc. Dead zone in the

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actuator degrades the tracking performance of the system and it may even cause the instability of all the system. Most of practical systems may include actuators with dead-zone input. Many results have been obtained for uncertain nonlinear systems with dead-zone input (Wenshun Lv *et al.,* 2018). However, these control algorithms can only be adapted to general nonlinear problems. This paper focuses on solving the well known nonlinear control problem, Chemical continuous stirred tank reactor (CSTR), especially one with dead zone input. Chemical continuous stirred tank reactor (CSTR) is well known nonlinear control problem. Research of this problem has been preceded in advance, but they didn't consider dead zone input. Therefore, Chemical continuous stirred tank reactor (CSTR) with dead zone input is refined for our solver and simulated. The paper is organized as follows. In Section 2, the control problem of the nonlinear system with dead-zone input is formulated. Adaptive fuzzy control scheme is presented in Section 3. Section 4 presents simulation results. Finally, the paper ends with the conclusion in Section 5.

Nonlinear Chemical Continuous Stirred Tank Reactor (CSTR) system with dead zone input: The chemical reaction process of the CSTR is shown schematically in Fig. 1. It consists of a constant volume CSTR fed by a single inlet stream through a selector valve. Suppose that the position of the selector valve at each time is determined by a supervisory mechanism based on an objective. In other words, at each time the reactor is fed by one of the source streams according to the decision made by the supervisor. Since the source streams have different parameters, the parameters of the feed of the reactor can change instantaneously. The reactor is cooled by a coolant stream with a constant flow rate and a variable temperature □$_{□}$(M. B. Yazdi *et al.,* 2009).

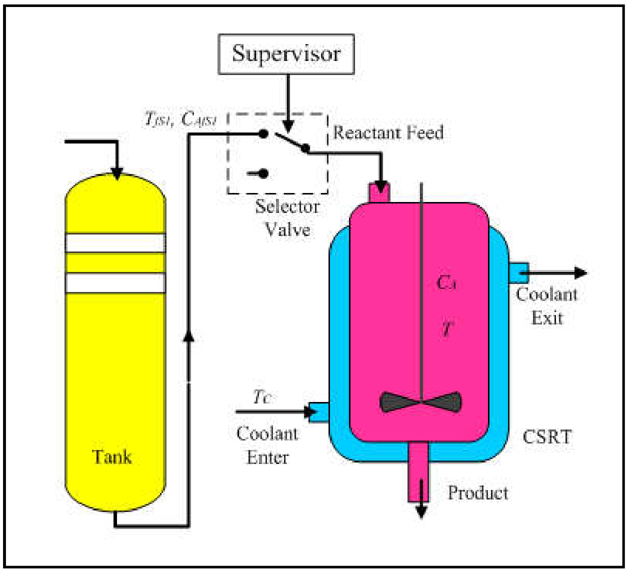

Fig. 1. Schematic diagram of the chemical reaction process

Consider a nonlinear chemical continuous stirred tank reactor (CSTR) system (M. B. Yazdi *et al.,* 2009) as follows:

$$\begin{cases} \dot{C}_A = \frac{q_i}{V}\left(C_{Af_{si}} - C_A\right) - a_0 \exp\left(-\frac{E}{RT}\right) C_A \\ \dot{T} = \frac{q_i}{V}\left(T_{f_{si}} - T\right) - a_1 \exp\left(-\frac{E}{RT}\right) C_A + a_2(T_c - T) \end{cases} \quad \cdots\cdots(1)$$

Where $i = 1{,}2$ is a mode index, f_{si} is a feed stream index, and the use details of *I* and f_{si} were shown in [15]. In this paper, the parameter *I* is chosen as *i*= 1. Therefore, nominal parameters of the process are chosen as volume of reactor V=100L, E/R = 8750K, $a_0 = 7.2 \times 10^{10}$, $a_1 = -1.506 \times 10^{13}$, $a_2 = 2.092$, and parameters of feed stream are choosen as $C_{Af_{s1}} = 1.5molL^{-1}$, $q_1 = 50Lmin^{-1}$, $T_{f_{s1}} = 350K$. C_A, T and T_C are the reactant concentration, reactor temperature and coolant temperature, respectively. For the CSTR system (1), the desired nominal operating values are chosen as C_A^*= 0.5mol/L, T^*= 350 K and T_c^*= 300 K. In this case, defining the state variables, $x_1(t) = T(t) - T^*$, $x_2(t) = C_A(t) - C_A^*$ and the control input $u(t) = T_c(t) - T_c^*$.

Consider the nonlinear chemical stirred tank reactor system with dead zone input in controlling coolant stream temperature, then the system (1) can be rewritten as follows:

$$\begin{cases} \dot{x}_2 = \frac{q_1}{V}\left(C_{Af_{s1}} - C_A^* - x_2\right) - a_0\,(x_2 + C_A^*)\exp\left(-\frac{E}{R(x_1+T^*)}\right) \\ \dot{x}_1 = \frac{q_1}{V}\left(T_{f_{s1}} - T^* - x_1\right) - a_1\,(x_2 + C_A^*)\exp\left(-\frac{E}{R(x_1+T^*)}\right) \\ \qquad +a_2(D(u) + T_c^* - T^* - x_1) \\ y = x_1 \end{cases} \quad \ldots..(2)$$

Where $D(u)$ is the dead-zone characteristic described as

$$D(u) = \begin{cases} \xi_1(u - T_1), & u \geq T_1 \\ 0, & T_1 < u < T_2 \\ \xi_2(u - T_2), & u \leq T_2 \end{cases} \quad \ldots\ldots..(3)$$

where $\xi_1, \xi_2, T_1 > 0$ and $T_2 < 0$ are unknown constants.

Then $D(u)$ can be reformulated as

$$D(u) = \xi(t)u - \varpi(t), \quad \ldots\ldots...(4)$$

Where

$$\xi(t) = \begin{cases} \xi_1, & u \geq T_1 \\ 0, & T_2 < u < T_1 \\ \xi_2, & u \leq T_2 \end{cases}$$

and

$$\varpi(t) = \begin{cases} \xi_1 T_1, & u \geq T_1 \\ 0, & T_2 < u < T_1 \\ \xi_2 T_2, & u \leq T_2 \end{cases}$$

Fuzzy Logic System

The following fuzzy logic systems (FLSs) will be used to approximate the unknown nonlinear function. Choose a collection of fuzzy rules as follows:

R^l: If x_1 is M_1^l and … and x_n is M_n^l,

Then y is U^l, $l \in \{1,2,\ldots,N\}$

where $\tilde{x}_n = [x_1, x_2, \ldots, x_n]^T \in R^n$ and $y \in R$ are the input and the output of the fuzzy system, respectively. M_ℓ^l and U^l denote fuzzy sets composed of fuzzy membership functions $\mu_{M_\ell^l}(\chi_l)$ and $\mu_{U^l}(y)$. *N* is the number of the rules. Through the singleton fuzzier, the product inference and the center-average defuzzifier, the fuzzy logic system is:

$$y(x) = \frac{\sum_{l=1}^{N} \varphi_l \prod_{\ell=1}^{n} \mu_{M_\ell^l}(x_\ell)}{\sum_{l=1}^{N}\left[\prod_{\ell=1}^{n} \mu_{M_\ell^l}(x_\ell)\right]}$$

Where

$\varphi_l = \max_{y \in R} \mu_{U^l}(y)$, $\varphi = (\varphi_1, \varphi_2, \dots, \varphi_N)^T$.
Let

$$R_l(x) = \frac{\prod_{\ell=1}^{n} \mu_{M_\ell^l}(x_\ell)}{\sum_{l=1}^{N} \left[\prod_{\ell=1}^{n} \mu_{M_\ell^l}(x_\ell)\right]},$$

where $R(x) = \left(R_1(x), R_2(x), \dots, R_N(x)\right)^T$. We can override the fuzzy logic system as

$$y(x) = \varphi^T R(x) \qquad \dots\dots\dots\dots\dots\dots\dots(5)$$

The fuzzy membership functions include two sigmoidal functions and four Gaussian functions. These are chosen as

$$\mu_{M_n^1}(x) = (1 + \exp(5x + 10))^{-1}\,,$$
$$\mu_{M_n^k}(x) = exp(-(x + 3.5 - k)^2)\,,$$
$$\mu_{M_n^6}(x) = (1 + \exp(-5x + 10))^{-1}\,, \qquad \dots\dots\dots\dots\dots\dots\dots(6)$$

Simulations

Consider the nonlinear chemical stirred tank reactor system with dead zone input in controlling coolant stream temperature, then the system (1) can be rewritten as follows:

$$\dot{x}_2 = \frac{q_1}{V}\left(C_{Af_{s1}} - x_2 - C_A^*\right) - a_0 \exp\left(-\frac{E}{R(x_1 + T^*)}\right)(x_2 + C_A^*)$$
$$\dot{x}_1 = \frac{q_1}{V}\left(T_{f_{s1}} - x_1 - T^*\right) - a_1 \exp\left(-\frac{E}{R(x_1 + T^*)}\right)(x_2 + C_A^*)$$
$$+a_2(D(u) + T_c^* - T^* - x_1)$$
$$y = x_1$$

where $D(u)$ is defined as (3).

Choose the dead-zone parameters as $T_1 = 1$, $T_2 = -1$, $\xi_1 = \xi_2 = 1.2$.The reference signal is chosen as $y_r = \sin(\frac{t}{2}) + \frac{t}{2}\sin(t)$.

Choose the initial conditions as $x_1(0) = 1/100$, $x_2(0) = 1/100$.

The results of simulation are shown in Figs. 2-4.

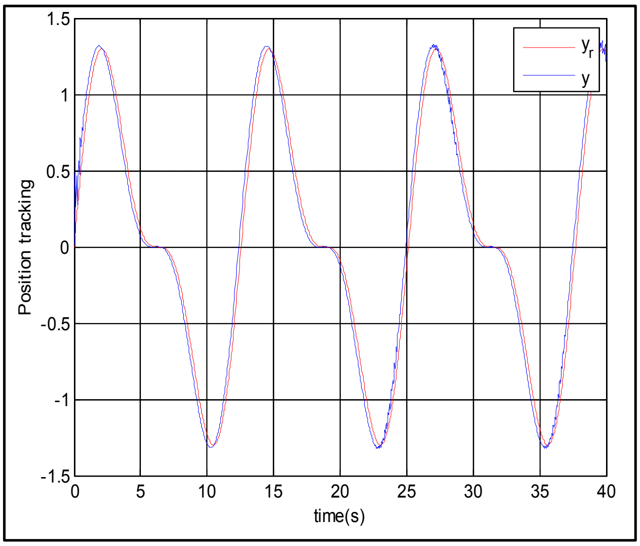

Fig. 2. y and y_r

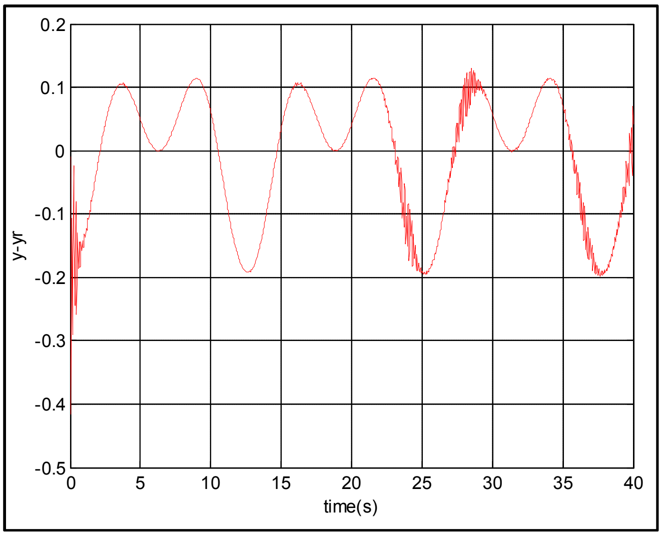

Fig. 3. y-y_r

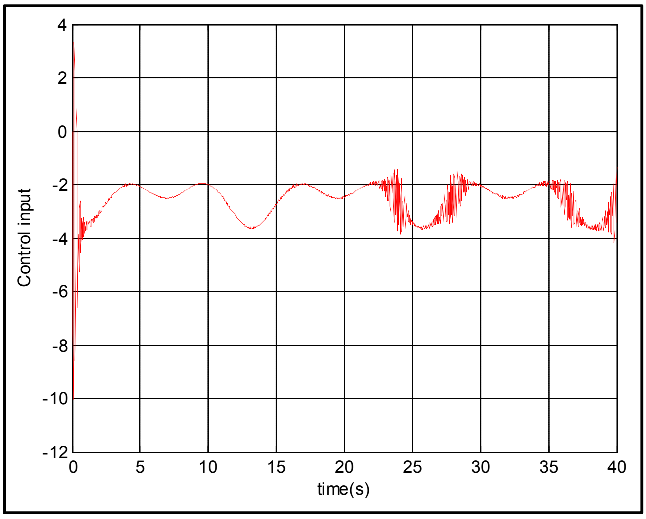

Fig. 4. Control input $u(t) = T_c(t) - T_c^*$.

In general, the reference signal, especially the required temperature is constant value. So the reference signal is chosen as $y_r = 0$.Choose the dead-zone parameters as $T_1 = 1$, $T_2 = -1$, $\xi_1 = \xi_2 = 1.2$.Choose the initial conditions as $x_1(0) = 1/100$, $x_2(0) = 1/100$.

The results of simulation are shown in Figs. 5-7.

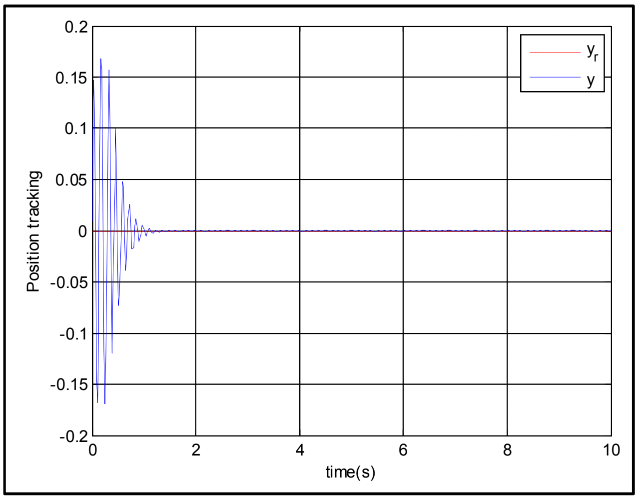

Fig. 5. y and y_r

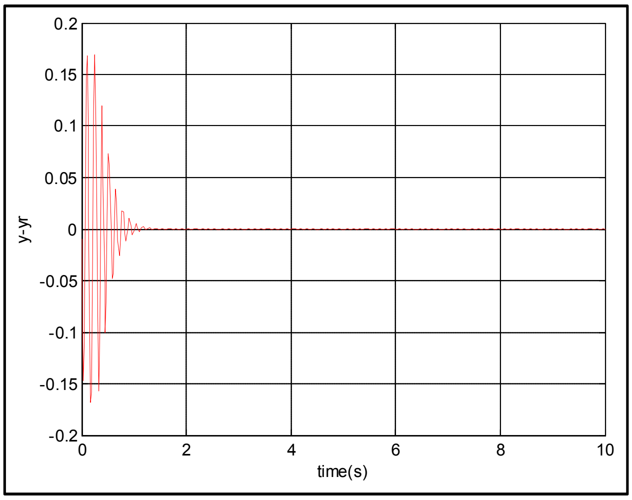

Fig. 6. y-y_r

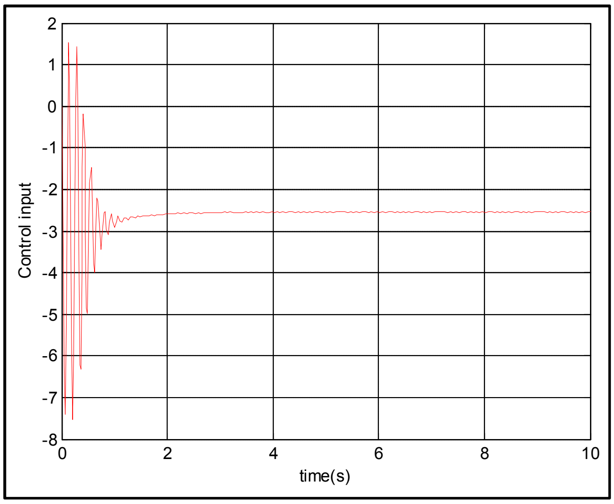

Fig. 7. Control input $u(t) = T_c(t) - T_c^*$.

Conclusion

This paper focused on an adaptive controller of uncertain nonlinear system with deadzone input. Aadaptive fuzzy controller has been constructed to solve the problem of the nonlinear uncertainties. The considered problem is one of the well knowen nonlinear problems, CSTR. Depending on the CSTR defined in the former literatures, new type of CSTR is defined. This CSTR system include dead zone input effect. Contructed adaptive fuzzy controller is applied to the CSTR with dead zone input. Simulation is done with two cases, variable reference signal and constant reference signal. Finally, the simulation results are given to show the effectiveness of the proposed method.

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