

## Development of Linearizing Feedback Control with a Variable Structure Observer for Continuous Stirred Tank Reactors

Bachir Daaou<sup>1,2,\*</sup>, Abdellah Mansouri<sup>2</sup>, Mohamed Bouhamida<sup>2</sup> and Mohammed Chenafa<sup>2</sup>

<sup>1</sup> Department of Sciences and Technology, Ibn-khaldoun University BP 78, Zaaroura Road, Tiaret, Algeria

<sup>2</sup> Department of Electrical Engineering, E.N.S.E.T. Oran, Laboratory of Automatics and Systems Analysis (L.A.A.S) BP 1523 El'M'naouer, Oran, Algeria

**Abstract** This paper deals with the design of an observer-based nonlinear control for continuous stirred tank reactors (CSTR). A variable structure observer is constructed to estimate the whole process state variables. This observer is basically the conventional Luenberger observer with an additional switching term used to guarantee the robustness against modeling errors. The observer is coupled with a nonlinear controller, designed based on input-output linearization for controlling the reactor temperature. The asymptotical stability of the closed-loop system is shown by the Lyapunov stability theorem. Finally, computer simulations are developed for showing the performance of the proposed approach.

**Keywords** variable structure observer, linearizing feedback, global stability, continuous stirred tank reactors

### 1 INTRODUCTION

Continuous stirred tank reactors (CSTR) are commonly used in the process industries. The process in the reactor is usually nonlinear with time-varying parameters. It is necessary to control these reactors to improve their behavior. In recent years, various design methods for nonlinear control strategies have been proposed. Most of them are based on differential geometric concepts [1–5]. This method allows a certain class of systems to be linearized using state feedback and coordinate transformations [6, 7]. Extensions of the method, such as adaptive linearization [8, 9], robust linearization [10], and asymptotically exact linearization [11], account for small model-plant-mismatch.

For the state estimation, many investigations deal with the observation techniques to estimate the state variables in chemical reactors [12–23].

The main purpose of this work is to develop an observer-based nonlinear control scheme for a CSTR. We apply the variable structure observer, as proposed by Walcott *et al.* [24] for estimating the concentration. The controller is constructed through feedback linearization. Since no separation principle exists for nonlinear systems, the study of the asymptotical stability of the closed-loop system including the observer dynamics is to be established, which is the main objective of this work.

In this work, the reactor model is presented. A variable structure observer for estimating concentration is constructed. For the closed loop control, we use Lyapunov argument to prove the closed loop stability. The closed-loop dynamic simulations are developed to illustrate the effectiveness of the proposed approach.

### 2 MATHEMATICAL MODEL OF REACTOR

The model for a first order irreversible exothermic

reaction in a continuous stirred tank reactor (CSTR) is given by

$$\dot{T} = -\frac{UA}{\rho c_p V} (T - T_j) + \frac{F}{V} (T_i - T) - \frac{\Delta H}{\rho c_p} K(T) C_A \quad (1)$$

$$\dot{C}_A = -K(T) C_A + \frac{F}{V} (C_{Ai} - C_A) \quad (2)$$

where  $K(T) = k_0 e^{-\frac{E}{RT}}$ ,  $C_A$  is the outlet concentration of reactant A,  $C_{Ai}$  is the inlet concentration of A,  $T$  is outlet temperature of reactor,  $T_i$  is the inlet temperature,  $T_j$  is the jacket temperature,  $F$  is the feed flow rate to reactor,  $U$  is the overall heat-transfer coefficient,  $A$  is the surface area for heat transfer,  $c_p$  is the heat capacity of feed and product,  $c_{pj}$  is the heat capacity of jacket fluid,  $E$  is the activation energy,  $R$  is the universal gas constant,  $k_0$  is the pre-exponential factor,  $\Delta H$  is the heat of reaction, and  $\rho$  is the density of mixture in the reactor.

The model can be non-dimensionalized by defining following dimensionless variables and parameters

$$x_1 = \frac{T - T_i}{T_i} \gamma, \quad x_2 = \frac{c_A}{c_{Ai}}, \quad u = \frac{\gamma \alpha}{T_i} (T_j - T_i), \quad \tau = \frac{F}{V} t,$$

$$\alpha = \frac{UA}{\rho c_p F}, \quad \beta = \frac{\Delta H c_{Ai}}{\rho c_p T_i} \gamma, \quad \gamma = \frac{E}{RT_i}, \quad \varphi = \frac{V}{F} k_0 e^{-\gamma}$$

where  $x_1$  is the dimensionless reactor temperature,  $x_2$  is the dimensionless conversion and,  $u$  is the measured input.

The dimensionless equations for the CSTR can be written as

$$\dot{x}_1 = \frac{dx_1}{d\tau} = -(1 + \alpha)x_1 - \beta \varphi x_2 K(x_1) + u \quad (3)$$

$$x_2 = \frac{dx_2}{d\tau} = (1 - x_2) - \varphi x_2 K(x_1) \quad (4)$$

$$y = x_1 \quad (5)$$

where  $K(x_1) = \exp\left(\frac{\gamma x_1}{\gamma + x_1}\right)$ .

The reactor parameter values are given in Table 1.

**Table 1** Parameter values of the reactor

| Parameter | Value | Definition                                          |
|-----------|-------|-----------------------------------------------------|
| $\alpha$  | 0.5   | dimensionless heat-transfer coefficient             |
| $\beta$   | 2     | dimensionless heat of reaction                      |
| $\gamma$  | 5     | dimensionless activation energy                     |
| $\varphi$ | 1     | nominal Damköhler number based on the reaction feed |

### 3 OBSERVER DESIGN

The mathematical model of the chemical reactor has the following form

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u + \mathbf{R}\xi(\mathbf{x}) + \mathbf{D} \\ y = \mathbf{C}\mathbf{x}(t) \end{cases} \quad (6)$$

where

$$\mathbf{x} = [x_1, x_2]^T, \quad \mathbf{A} = \begin{bmatrix} -(1+\alpha) & 0 \\ 0 & -1 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} -\beta\varphi \\ -\varphi \end{bmatrix}, \quad \xi(\mathbf{x}) = x_2 K(x_1),$$

$$\mathbf{D} = [0 \quad 1]^T, \text{ and } \mathbf{C} = [1 \quad 0].$$

The main theoretical assumptions for the development of the observer strategy are listed below.

**Assumption 1** The pair  $(\mathbf{A}, \mathbf{C})$  is observable, *i.e.*, there exists a matrix  $\mathbf{G}$  of appropriate dimensions such that the matrix  $\mathbf{A}_0 = \mathbf{A} - \mathbf{G}\mathbf{C}$  is stable and has a Lyapunov matrix  $\mathbf{P}$  satisfying

$$\mathbf{P}\mathbf{A}_0 + \mathbf{A}_0^T \mathbf{P} = -\mathbf{Q} \quad (7)$$

for positive definite design matrix  $\mathbf{Q}$  and the structural constraint

$$\mathbf{C}^T \mathbf{F}^T = \mathbf{P}\mathbf{R} \quad (8)$$

for nonsingular matrix  $\mathbf{F}$ .

**Assumption 2** The dynamics  $\xi(\mathbf{x})$  is bounded,

$$\forall \mathbf{x} \in \mathbb{R}^2, \exists \rho > 0 : |\xi(\mathbf{x})| \leq \rho$$

**Theorem** Under the above assumptions, the nonlinear observer given by

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}u + \mathbf{D} + \mathbf{G}(y - \mathbf{C}\hat{\mathbf{x}}) + \mathbf{v}(t) \quad (9)$$

is an exponential observer for the system, Eq. (6), where

$$\mathbf{v}(t) = \begin{cases} -\rho \frac{\mathbf{P}^{-1} \mathbf{C}^T \mathbf{F}^T \mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)}{\|\mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)\|} & \text{if } \mathbf{C} \tilde{\mathbf{x}}(t) \neq 0 \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

**Proof** Letting  $\tilde{\mathbf{x}} = \mathbf{x} - \hat{\mathbf{x}}$ , we have

$$\dot{\tilde{\mathbf{x}}} = (\mathbf{A} - \mathbf{G}\mathbf{C})\tilde{\mathbf{x}} + \mathbf{R}\xi(\mathbf{x}) - \mathbf{v}(t) \quad (11)$$

$$\dot{\tilde{\mathbf{x}}} = \mathbf{A}_0 \tilde{\mathbf{x}} + \mathbf{R}\xi(\mathbf{x}) - \mathbf{v}(t) \quad (12)$$

Since  $(\mathbf{A}_0 = \mathbf{A} - \mathbf{G}\mathbf{C})$  is Hurwitz, there exists a symmetric positive definite matrix  $\mathbf{P}$  satisfying Eq. (7).

Define  $V(\tilde{\mathbf{x}}) = \tilde{\mathbf{x}}^T \mathbf{P} \tilde{\mathbf{x}}$  as the Lyapunov candidate function. Then its time derivative is

$$\dot{V}(\tilde{\mathbf{x}}) = \dot{\tilde{\mathbf{x}}}^T \mathbf{P} \tilde{\mathbf{x}} + \tilde{\mathbf{x}}^T \mathbf{P} \dot{\tilde{\mathbf{x}}} \quad (13)$$

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}) &= \tilde{\mathbf{x}}^T \mathbf{A}_0^T \mathbf{P} \tilde{\mathbf{x}} + \tilde{\mathbf{x}}^T \xi(\mathbf{x}) \mathbf{P} \tilde{\mathbf{x}} - \mathbf{v}(t)^T \mathbf{P} \tilde{\mathbf{x}} + \\ &\quad \tilde{\mathbf{x}}^T \mathbf{P} \mathbf{A}_0 \tilde{\mathbf{x}} + \tilde{\mathbf{x}}^T \mathbf{P} \mathbf{R} \xi(\mathbf{x}) - \tilde{\mathbf{x}}^T \mathbf{P} \mathbf{v}(t) \end{aligned} \quad (14)$$

$$\dot{V}(\tilde{\mathbf{x}}) = \tilde{\mathbf{x}}^T (\mathbf{P}\mathbf{A}_0 + \mathbf{A}_0^T \mathbf{P}) \tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^T \mathbf{P} \mathbf{R} \xi(\mathbf{x}) - 2\tilde{\mathbf{x}}^T \mathbf{P} \mathbf{v}(t) \quad (15)$$

$$\dot{V}(\tilde{\mathbf{x}}) = -\tilde{\mathbf{x}}^T \mathbf{Q} \tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^T \mathbf{C}^T \mathbf{F}^T \xi(\mathbf{x}) - 2\tilde{\mathbf{x}}^T \mathbf{P} \mathbf{v}(t) \quad (16)$$

To continue the demonstration, there are two cases.

**Case 01**  $\mathbf{C} \tilde{\mathbf{x}}(t) \neq 0$

Then  $\mathbf{v}(t) = \rho \frac{\mathbf{P}^{-1} \mathbf{C}^T \mathbf{F}^T \mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)}{\|\mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)\|}$  and  $\dot{V}(\tilde{\mathbf{x}})$  becomes

$$\dot{V}(\tilde{\mathbf{x}}) = -\tilde{\mathbf{x}}^T \mathbf{Q} \tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^T \mathbf{C}^T \mathbf{F}^T \xi(\mathbf{x}) - 2\rho \|\mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)\| \quad (17)$$

Using Assumption 2, we obtain

$$\dot{V}(\tilde{\mathbf{x}}) \leq -\tilde{\mathbf{x}}^T \mathbf{Q} \tilde{\mathbf{x}} + 2\rho \|\mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)\| - 2\rho \|\mathbf{F} \mathbf{C} \tilde{\mathbf{x}}(t)\| \quad (18)$$

$$\dot{V}(\tilde{\mathbf{x}}) \leq -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 < 0 \quad (19)$$

where  $\lambda_Q^{\min}$  is the minimum eigenvalue of  $\mathbf{Q}$ .

**Case 02**  $\mathbf{C} \tilde{\mathbf{x}}(t) = 0$

In this case, Eq. (17) becomes

$$\dot{V}(\tilde{\mathbf{x}}) \leq -\tilde{\mathbf{x}}^T \mathbf{Q} \tilde{\mathbf{x}}, \quad \dot{V}(\tilde{\mathbf{x}}) \leq -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 < 0 \quad (20)$$

In both cases, the derivative of the Lyapunov function is negative, showing that the state estimation error converges asymptotically towards zero. This completes the proof of the Theorem.

### 4 CONTROL ALGORITHM

We design a control algorithm based on feedback linearization. The model of the chemical reactor, Eqs. (3)–(5), can be written as

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x})u \\ y = x_1 \end{cases} \quad (21)$$

where  $\mathbf{f}(\mathbf{x}) = \begin{bmatrix} -(1+\alpha)x_1 - \beta\varphi x_2 K(x_1) \\ (1-x_2) - \varphi x_2 K(x_1) \end{bmatrix}$ , and

$$\mathbf{g}(\mathbf{x}) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

The relation between system input and the linearizing signal is

$$u = \vartheta + (1+\alpha)x_1 + \beta\varphi x_2 K(x_1) \quad (22)$$

$$\vartheta = \dot{y} \quad (23)$$

It should be noted that the state variables are estimated using an observer, then Eqs. (22) and (23) become

$$u = \vartheta + (1+\alpha)\hat{x}_1 + \beta\varphi\hat{x}_2 K(\hat{x}_1) \quad (24)$$

$$\vartheta = \dot{y} + \left[ -(1+\alpha)x_1 - \beta\varphi x_2 K(x_1) \right] + \left[ (1+\alpha)\hat{x}_1 + \beta\varphi\hat{x}_2 K(\hat{x}_1) \right] \quad (25)$$

$$\vartheta = \dot{y} - (\alpha+1)\tilde{x}_1 - \beta\varphi \left[ x_2 K(x_1) - \hat{x}_2 K(\hat{x}_1) \right] \quad (26)$$

We choose  $\vartheta$  such that the system is closed loop stable and achieves a desired setpoint at temperature.

$$\vartheta = -\delta_1 e_1 - \delta_2 e_2 + \dot{x}_1^d \quad (27)$$

where  $e_1 = \int (x_1 - x_1^d) dt$ ,  $e_2 = x_1 - x_1^d$ , and  $x_1^d$  is the reactor temperature.

The closed-loop error dynamics and observer are given by

$$\begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = -\delta_1 e_1 - \delta_2 e_2 + (\alpha+1)\tilde{x}_1 + \beta\varphi \left[ x_2 K(x_1) - \hat{x}_2 K(\hat{x}_1) \right] \\ \dot{\tilde{\mathbf{x}}} = \mathbf{A}_0 \tilde{\mathbf{x}} + \mathbf{R} \xi(\mathbf{x}) - \mathbf{v}(t) \end{cases} \quad (28)$$

Now consider the following assumption.

**Assumption 3** Function  $\xi(\mathbf{x})$  is globally Lipschitz with respect to  $\mathbf{x}$ , i.e.

$$\forall \mathbf{x} \in \mathbb{R}^2 : \|\xi(\mathbf{x}) - \xi(\hat{\mathbf{x}})\| \leq \mu \|\tilde{\mathbf{x}}\|$$

where  $\mu$  denotes the Lipschitz constants of  $\xi(\mathbf{x})$ .

**Main result** Consider the control law stated in Eq. (24) and the observer Eq. (9) with Eq. (10), if Assumptions 1–3 are satisfied and by selecting  $\delta_1$  and  $\delta_2$  such that all roots of the polynomial  $s^2 + \delta_2 s + \delta_1$  lie in the open left-hand side of the complex plane, the closed loop system described by Eq. (28) is globally asymptotically stable.

**Proof** Consider the following Lyapunov function candidate

$$V(\tilde{\mathbf{x}}, \mathbf{e}) = V_0(\tilde{\mathbf{x}}) + V_c(\mathbf{e}) \quad (29)$$

where  $V_0(\tilde{\mathbf{x}}) = \tilde{\mathbf{x}}^T \mathbf{P} \tilde{\mathbf{x}}$  and  $V_c(\mathbf{e}) = \frac{1}{2}(e_1^2 + e_2^2)$ . The time derivative of the Lyapunov function  $V(\tilde{\mathbf{x}}, \mathbf{e})$  is

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \mathbf{e}) = & -\tilde{\mathbf{x}}^T \mathbf{Q} \tilde{\mathbf{x}} + 2\tilde{\mathbf{x}}^T \mathbf{C}^T \mathbf{F}^T \xi(\mathbf{x}) - \\ & 2\tilde{\mathbf{x}}^T \mathbf{P} \mathbf{v}(t) + e_1 e_2 + e_2 \dot{e}_2 \end{aligned} \quad (30)$$

We have  $V_0(\tilde{\mathbf{x}}) \leq -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 \forall \mathbf{v}(t)$ , then

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \mathbf{e}) \leq & -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 + e_1 e_2 - \delta_1 e_1 e_2 - \delta_2 e_2^2 + \\ & (\alpha+1)\tilde{x}_1 e_2 + \beta\varphi [\xi(\mathbf{x}) - \xi(\hat{\mathbf{x}})] e_2 \end{aligned} \quad (31)$$

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \mathbf{e}) \leq & -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 - \mathbf{e}^T \mathbf{A}_c \mathbf{e} + (\alpha+1)\tilde{x}_1 e_2 + \\ & \beta\varphi [\xi(\mathbf{x}) - \xi(\hat{\mathbf{x}})] e_2 \end{aligned} \quad (32)$$

with  $\mathbf{A}_c = \begin{bmatrix} 0 & -1 \\ \delta_1 & \delta_2 \end{bmatrix} > 0$ .

Using Assumption (3), inequality (32) becomes

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \mathbf{e}) \leq & -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 - \mathbf{e}^T \mathbf{A}_c \mathbf{e} + \\ & (\alpha+1)\tilde{x}_1 e_2 + \beta\varphi \mu \|\tilde{\mathbf{x}}\| e_2 \end{aligned} \quad (33)$$

Knowing that  $\|e_2\| \leq \|\mathbf{e}\|$  and  $\|\tilde{x}_1\| \leq \|\tilde{\mathbf{x}}\|$ , we obtain

$$\begin{aligned} \dot{V}(\tilde{\mathbf{x}}, \mathbf{e}) \leq & -\lambda_Q^{\min} \|\tilde{\mathbf{x}}\|^2 - \lambda_{A_c}^{\min} \|\mathbf{e}\| + \\ & (\alpha+1)\|\tilde{\mathbf{x}}\| \|\mathbf{e}\| + \beta\varphi \mu \|\tilde{\mathbf{x}}\| \|\mathbf{e}\| \end{aligned} \quad (34)$$

where  $\lambda_{A_c}^{\min}$  is the minimum eigenvalue of  $\mathbf{A}_c$ .

Inequality (34) can be rewritten as

$$\dot{V}(\boldsymbol{\eta}) \leq -\boldsymbol{\eta}^T \boldsymbol{\Gamma} \boldsymbol{\eta} \quad (35)$$

with  $\boldsymbol{\eta} = [\tilde{\mathbf{x}} \quad \mathbf{e}]^T$  and  $\boldsymbol{\Gamma} = \begin{bmatrix} \lambda_Q^{\min} & -(\alpha+1) \\ -\beta\varphi\mu & \lambda_{A_c}^{\min} \end{bmatrix}$ .

If  $\lambda_Q^{\min} > \frac{\beta\varphi\mu(\alpha+1)}{\lambda_{A_c}^{\min}}$ , then  $\boldsymbol{\Gamma} > 0$  and  $\dot{V}(\boldsymbol{\eta}) \leq 0$ .

Consequently, asymptotical stability of the closed-loop system is established.

## 5 SIMULATION RESULTS

Simulations, using MATLAB Software Package, are carried out to verify the effectiveness of the proposed method. The values of the model parameters used in simulation are given in Table 1. To evaluate the observer performance, the system is simulated by assuming that the process is excited through a constant input signal  $u = 1.5$ . This variable would be used later as the manipulated variable for control purposes.

The state initial conditions are set to  $\mathbf{x}(0) = [0.15 \quad 0.07]^T$  and  $\hat{\mathbf{x}}(0) = [0.45 \quad 0.35]^T$ . The estimation results obtained are depicted in Figs. 1 and 2. The speed of convergence can be modified by changing the values of the two matrixes  $\mathbf{G}$  and  $\mathbf{Q}$ . If  $\mathbf{Q}$  is fixed and matrix  $\mathbf{G}$  increases, higher speed of convergence is achieved but with undesirable chattering effect.

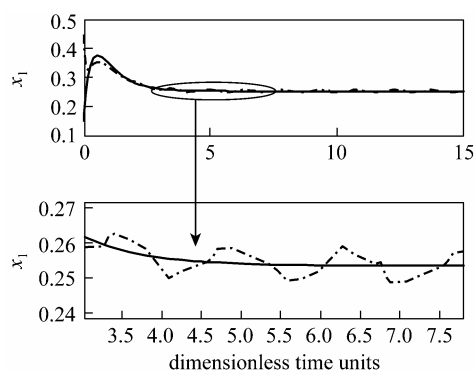


**Figure 1** Actual and estimated dimensionless reactor temperature

— real value; - - - estimated value

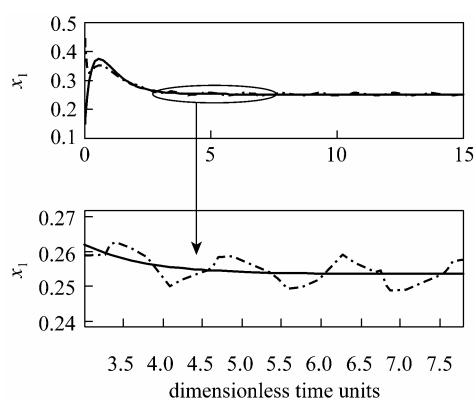


**Figure 2** Actual and estimated dimensionless concentration

— real value; - - - estimated value

Now, we study the performance of the observer by in a closed loop with the nonlinear control. The state initial conditions are set to  $\mathbf{x}(0) = [1.8 \ 0.65]^T$  and  $\hat{\mathbf{x}}(0) = [2.3 \ 0.8]^T$ . Fig. 3 shows the measured temperature and the reference trajectory. The manipulated signal  $u$  is depicted in Fig. 4. It can be seen that the proposed observer/controller structure shows good performance in achieving the output regulation but the

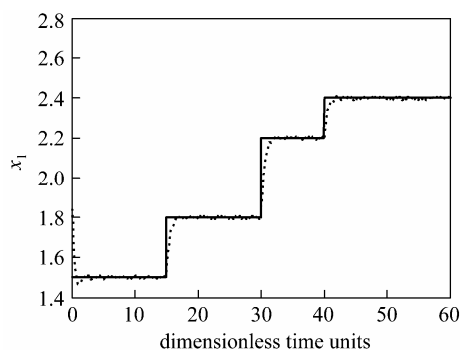


**Figure 3** Closed-loop response

— setpoint; ..... controlled output

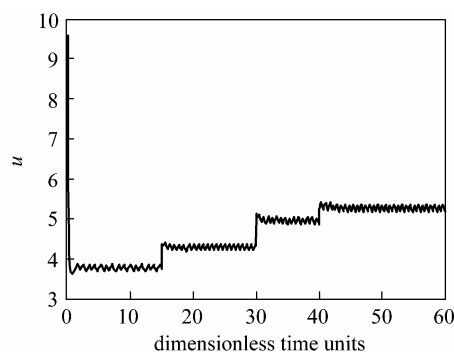


**Figure 4** Control input

control action exhibits chattering, which may be unacceptable in practice. We use the boundary layer approach to eliminate chattering.

Finally, we examine the robustness of the proposed controllers in the presence of the measurement noise and model uncertainty.

**Case 01 Performance analysis in the presence of measurement noise** In this case, white Gaussian noises with variances of  $\pm 5\%$  are simultaneously added to the output measurement. The transient responses of temperature for the controller and their corresponding control actions are shown in Figs. 5 and 6 respectively. The set-point tracking behavior is very satisfactory. Note that the proposed controller maintains the temperature in a small neighborhood of the reference value despite the noise on the measurement.

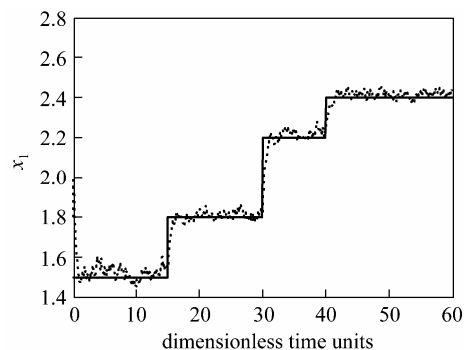


**Figure 5** Closed-loop response in presence of measure noises

— setpoint; ..... controlled output

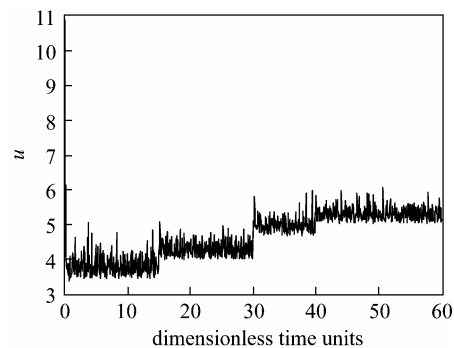


**Figure 6** Control input in presence of measure noises

**Case 02 Performance analysis in the presence of model uncertainty** The major advantage of variable structure observers is that they can be made considerably more robust to parametric uncertainties. For this purpose, we consider a mismatch between the real activation energy and its value in the model. A difference up to 2% between the real parameter and its value in the model is considered. Simulation results are depicted in Figs. 7 and 8. The performance does not degrade significantly because the controller can well estimate the uncertainty.

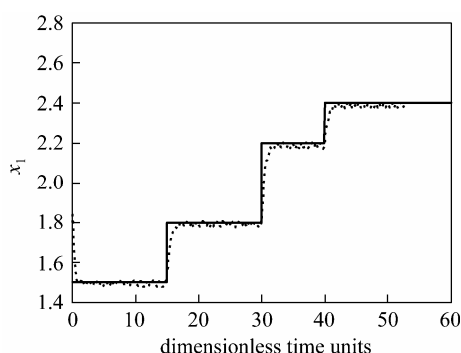


**Figure 7** Controlled dimensionless temperature for 2% increase in the activation energy  
— setpoint; ..... controlled output

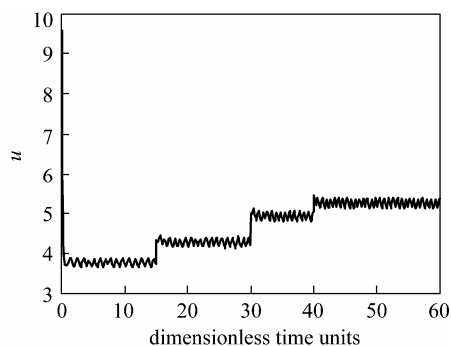


**Figure 8** Control input for 2% increase in the activation energy

## 6 CONCLUSIONS

In this paper, design of an observer-based control scheme using feedback linearization technique for temperature control of CSTR is addressed. The observer proposed in this study is basically the Luenberger observer with an additional switching term used to cope with system nonlinearities. The Lyapunov stability technique is used to establish the asymptotical stability of closed-loop system including the observer dynamics. The closed-loop performance of the controller is illustrated *via* numerical simulations. It is shown that this controller is able to regulate the reactor temperature despite modeling uncertainties and noisy measurements.

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