DESIGN OF A SLIDING MODE CONTROL SYSTEM BASED ON AN IDENTIFIED SOPDT MODEL

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Abstract: Based on an identified SOPDT model, a designed optimal sliding surface and the use of a delay-ahead predictor, a novel and systematic sliding mode control system design methodology is proposed for the regulation of chemical processes. The convergence property of the closed-loop system is guaranteed theoretically through satisfying a sliding condition and the control system performance is examined with some typical chemical processes. Besides, with the concept of delay equivalent, a simple technique is presented such that the proposed sliding mode control scheme can be utilized directly to handle with the regulation control of non-minimum phase processes.

Keywords: sliding mode control, predictor, optimal sliding surface, non-minimum phase, SOPDT model.

1. INTRODUCTION

Due to its simplicity and the capability of representing the process dynamics more accurately than a first-order plus dead-time (FOPDT) model, the second-order plus dead-time (SOPDT) model is widely adopted for process modeling and is then enhanced for controller design. Up to date, many identification methods for estimating the SOPDT model parameters have been proposed in the literature, and based on SOPDT model various controller design methodologies have been presented (Hwang, 1993; Sung et al., 1996; Jahanmiri and Fallahi, 1997; Wang et al., 2001). Based on a single closed-loop test, Hwang (1993) presented an adaptive pole design method for PID controllers. Sung et al. (1996) presented a relay feedback test with combining a P controller to identify a SOPDT model, and then an automatic tuning rule for PID controller was proposed for on-line application. With an alternative identification method for SOPDT model, Jahanmiri snd Fallahi (1997) conveyed the concept of Internal Model Control (IMC) to improve the performance of a PID controller. Wang et al. (2001) proposed a simple closed-loop identification method for SOPDT and based on the model a PID auto-tuning strategy is applied.

In general, for on-line control the identification of a SOPDT model is usually accomplished in a single test by using either a closed-loop or open-loop identification method and thereafter the identified model is directly used for the tuning of a linear controller, such as PID-type controllers. This kind of approach is simple and straightforward. However, if uncertainties exist in the identification phase, an inaccurate SOPDT model may give rise to a poorly designed linear controller and therefore may lead to unsatisfactory control performance. The performance degradation is mainly due to that the uncertainties in a process are usually not explicitly considered when applying the identification-then-tune methods.

Recently, there is increasing interest in the development of robust control system for processes having uncertainties. The sliding mode control strategy appears to be one of the most promising model-based approaches to the control of uncertain processes. To account for system's input-delay, Camacho et al. (1999) and Camacho and Smith (2000) proposed the synthesis of a sliding mode controller based on an FOPDT model. Their approaches resulted in a fixed structure controller with a set of tuning equations being formulated as a function of the model's characteristic parameters. Hu et al., (2000) adopted linear matrix inequality technique and a sliding mode control method to handle a class of uncertain time-delay systems. Based on the Lyapunov theorem, Chou and Cheng (2001) proposed an adaptive variable structure control strategy to stabilize a class of perturbed time-varying delay systems. Their method does not require the upper bound of perturbations and the performance of the system can be obtained by pre-specifying a set of suitable eigenvalues. Although these approaches have potential to deal with uncertainties and state delay, they do not consider the compensation for input-delay as a whole. For the issue of dealing with input-delay, Kojima et al. (1994) explored the H_∞ stabilization problem of uncertain input-delay systems. More recently, Roh and Oh (1999; 2000) investigated the feasibility of the sliding surface with

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including a predictor to compensate for the input delay of the system.

In this paper, we propose a simple and novel sliding mode control system for the regulation of chemical processes. Based on an identified SOPDT model, a delay-ahead predictor is developed for state estimation and a correction term from the measured process output is incorporated to enhance the prediction accuracy of the process states. With the help of state predictor and a designed optimal sliding surface, a sliding mode controller that is able to account for model uncertainties can be easily constructed and implemented. The robust stability as well as the system behavior of the closed-loop system is analyzed through guaranteeing the sliding condition. Besides, in this paper the presented scheme is further extended to one that is able to deal with the process having inverse response. The effectiveness and applicability of the proposed scheme is tested with some typical processes, including an underdamped process with long dead-time, an overdamped high order process and a non-minimum phase one. The performance comparisons with some existing SOPDT-based techniques are also included for evaluation.

The remainder of this paper is organized as follows. In the next section, the predictor design, sliding mode controller design methodology as well as the optimal sliding surface design has been presented. Besides, for extension to non-minimum phase process, a simple strategy is introduced. The subsequent section performs extensive simulations to demonstrate and verify the proposed scheme. Finally conclusion remarks are made.

2. A SLIDING MODE CONTROL TECHNIQUE

In this section, we devote to develop a sliding mode control scheme for the regulation of chemical processes. In essence, the sliding mode control is a kind of model-based scheme, and the SOPDT model is the most widely used process model especially for the underdamped process and the high-order process which has the same multiple poles. Therefore, in what follows we shall present a systematic sliding mode controller design methodology based on an identified SOPDT model.

2.1 Predictor design based on an identified SOPDT model.

Consider an identified, stable SOPDT model as follows:

$$\widetilde{G}(s) = \frac{b_1}{s^2 + a_2 s + a_1} e^{-\theta s} \tag{1}$$

In order to deal with the input delay and hence facilitate the design of a sliding mode control system, we shall first discuss the development of a delay-ahead predictor based on the SOPDT model. To proceed, we convert the above model into an equivalent state space model as

$$\dot{\widetilde{x}}_1(t) = \widetilde{x}_2(t) \tag{2a}$$

$$\dot{\widetilde{x}}_2(t) = -a_1\widetilde{x}_1(t) - a_2\widetilde{x}_2(t) + b_1 u(t-\theta) \tag{2b}$$

$$\widetilde{y}(t) = \widetilde{x}_1(t) \tag{2c}$$

where $\widetilde{x}_1$ and $\widetilde{x}_2$ are the states, and $\widetilde{y}$ and u are, respectively, the model output and control input. By removing the time-delay from the above model, we can construct a delay-ahead prediction model as

$$\dot{x}_1^*(t) = x_2^*(t) \tag{3a}$$

$$\dot{x}_2^*(t) = -a_1 x_1^*(t) - a_2 x_2^*(t) + b_1 u(t) \tag{3b}$$

$$y^*(t) = x_1^*(t) \tag{3c}$$

In order to improve the accuracy of the state prediction, especially in the face with modelling errors and unmeasured disturbance, the following correction from the measured process output can be used for practical implementation

$$\hat{x}_1(t+\theta|t) = x_1^*(t) + y(t) - \widetilde{x}_1(t) \tag{4a}$$

and

$$\hat{x}_2(t+\theta|t) = x_2^*(t) \tag{4b}$$

where $y(t)$ is the actual process output and $\hat{x}_1(t+\theta|t)$ is the predicted output at time $t+\theta$ based on the information available at time t. By the comparison of Eqs. (2) and (3), it follows that $x^*(t) = \widetilde{x}(t+\theta)$ if the predictor is initialized as $x^*(0) = \widetilde{x}(\theta)$. This initialization can be achieved at steady state because in this case $\widetilde{x}(\theta) = \widetilde{x}(0)$. Hence, in the absence of plant/model mismatch the prediction model yields the plant state one time delay ahead, i.e. $\hat{x}(t+\theta|t) = \widetilde{x}(t+\theta)$. The presented prediction model, which is delay free, can facilitate the design of a sliding controller for SOPDT model.

2.2 Sliding mode controller design.

Having characterized the prediction model, we shall discuss in this subsection the design of a delay-ahead sliding mode controller. To account for model uncertainties in the controller design, we consider the following uncertain model

$$\dot{x}_1^*(t) = x_2^*(t) \tag{5a}$$

$$\begin{aligned}\dot{x}_2^*(t) = &-(a_1 + \Delta a_1)x_1^*(t) - (a_2 + \Delta a_2)x_2^*(t) \\ &+ (b_1 + \Delta b_1)u(t)\end{aligned} \tag{5b}$$

where Δa_1, Δa_2 and Δb_1 are the variations of model parameters. To begin with, we rewrite the uncertain model as

$$\dot{x}_1^*(t) = x_2^*(t) \tag{6a}$$

$$\dot{x}_2^*(t) = -a_1 x_1^*(t) - a_2 x_2^*(t) + b_1 u(t) + h(\mathbf{x}^*, t) \tag{6b}$$

where

$$h(\mathbf{x}^*, t) = -\Delta a_1 x_1^*(t) - \Delta a_2 x_2^*(t) + \Delta b_1 u(t) \tag{7}$$

is the term containing the uncertainties. Let the hard constraint of the control input be

$$|u(t)| \le \bar{u} \tag{8}$$

and therefore the upper bound function, $h_{\max}(\cdot)$, of $h(\cdot)$ can be estimated as

$$\left|h(\mathbf{x}^*,t)\right| \le h_{\max}(\mathbf{x}^*,t) \tag{9}$$

where

$$h_{\max}(\mathbf{x}^*,t) = \sup\left|\Delta a_1 x_1^*(t)\right| + \sup\left|\Delta a_2 x_2^*(t)\right| + \max\left|\Delta b_1\right|\overline{u} \tag{10}$$

Next, let's choose a sliding function as follows:

$$\delta = c_1 x_1^*(t) + c_2 x_2^*(t) \tag{11}$$

The following theorem presents a sliding mode controller for the considered uncertain model.

Theorem 1: The following control law

$$\begin{aligned} u(t) &= b_1^{-1}[a_1 x_1^*(t) + (a_2 - c_2^{-1}c_1)x_2^*(t)] \\ &\quad - (b_1 c_2)^{-1}(\alpha + \overline{h}(\mathbf{x}^*,t))\mathrm{sign}(\delta) \end{aligned} \tag{12}$$

admit the uncertain system of (5) to satisfy the sliding condition of $\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}\delta^2 \le -\alpha\left|\delta\right|$, where α is the pre-specified positive constant regarding to the system performance and $\overline{h}(\mathbf{x}^*,t) = \left|c_2\right| h_{\max}(\mathbf{x}^*,t)$

Proof: See Appendix A.

The fundamental idea behind the use of the zero level set of the auxiliary output, denoted by $\Sigma = \left\{\mathbf{x}^* \middle| \delta = 0\right\}$, as a sliding surface (switching manifold) is to force the controlled motion to adopt Σ as an integrated manifold. When the system trajectory is outside the manifold, the strategy forces the states toward the design sliding surface. Upon reaching Σ fast switching takes place in the immediate vicinity of Σ, which tries to keep the trajectory constrained to Σ. To eliminate the undesirable switching (chattering phenomena) of the manipulated variable, it is practical to replace the sign function in (12) by a saturation function, $\mathrm{sat}(\delta/\beta)$, which is defined by

$$\mathrm{sat}(\delta/\beta) = \begin{cases} \delta/\beta, & \text{if } \left|\delta/\beta\right| < 1 \\ \mathrm{sign}(\delta/\beta), & \text{if } \left|\delta/\beta\right| \ge 1 \end{cases} \tag{13}$$

where $\beta > 0$ represents the boundary layer thickness. Here, it should be noted that the selection of the sliding function may affect the control performance since it is involved in the controller. In general, the selection of β represents the trade-off between the high performance and the extent of the chattering attenuation. To achieve optimal performance, we discuss in the following subsection the design of an optimal sliding function for practical application.

2.3 Optimal sliding function design.

Let's introduce a performance index as follows:

$$J = \int_{t_s}^{t} \mathbf{x}^*(t)\mathbf{Q}\,\mathbf{x}^*(t)\mathrm{d}t \tag{14}$$

where $\mathbf{x}^*(t) \equiv [x_1^*(t) \quad x_2^*(t)]^T$, t_s is the beginning time of the sliding motion, and $\mathbf{Q} = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix}$ is a positive define, symmetric matrix, i.e. $q_{12} = q_{21}$ and $q_{11}q_{22} - q_{12}^2 > 0$. Also, let an auxiliary variable, v, be given by

$$v = x_2^*(t) + \frac{q_{12}}{q_{22}}x_1^*(t) \tag{15}$$

The performance function can thus be rewritten as

$$J = \int_{t_s}^{t} (q_{11}^* x_1^{*2}(t) + q_{22}v^2(t))\mathrm{d}t \tag{16}$$

where $q_{11}^* = q_{11} - q_{12}^2/q_{22}$. Then, with the definition of v, and from Eq. (15), we have

$$\dot{x}_1^*(t) = a_1^* x_1^*(t) + v \tag{17}$$

where $a_1^* = -q_{12}/q_{22}$. The optimal control law for the above dynamic equation with the performance index of (16) is given by (Sage and White, 1977)

$$v = -\frac{p}{q_{22}}x_1^*(t) \tag{18}$$

where p is the positive root of the quadratic polynomial $p^2 - 2a_1^* q_{22} p - q_{22} q_{11}^* = 0$, i.e. $p = -q_{12} + \sqrt{q_{11}q_{22}}$. By inserting Eq. (15) into the above optimal solution, we can conclude that a set of optimal sliding coefficients, c_1 and c_2, are given by $c_1 = \sqrt{q_{11}q_{22}}$ and $c_2 = q_{22}$.

2.4 Practical implementation.

With the output correction of Eq. (4), the control law of (12) can be implemented with the replacement of $\mathbf{x}^*(t)$ by $\hat{\mathbf{x}}(t+\theta \mid t)$. Thus, for practical implementation the control law is formulated as

$$\begin{aligned} u(t) &= b_1^{-1}[a_1\hat{x}_1(t+\theta \mid t) + (a_2 - c_2^{-1}c_1)\hat{x}_2(t+\theta \mid t)] \\ &\quad - (b_1 c_2)^{-1}(\alpha + \overline{h}(\hat{\mathbf{x}}(t+\theta \mid t),t))\mathrm{sign}(\hat{\delta}) \end{aligned} \tag{19}$$

where the sliding function $\hat{\delta}$ is given by

$$\hat{\delta} = c_1\hat{x}_1(t+\theta \mid t) + c_2\hat{x}_2(t+\theta \mid t) \tag{20}$$

The schematic diagram of the proposed sliding mode control system is depicted in Fig. 1.

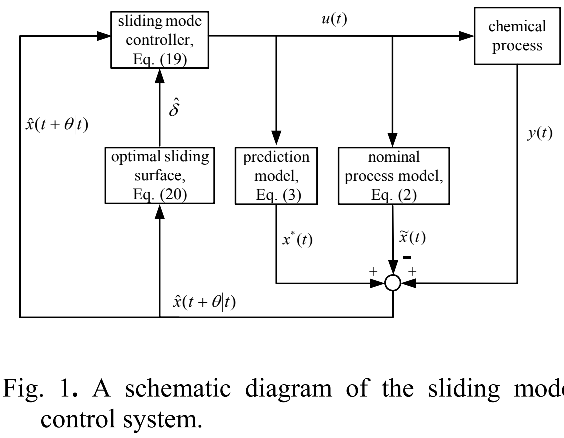

Fig. 1. A schematic diagram of the sliding mode control system.

2.5 Extension to non-minimum phase processes.

If the process has inverse response, we can identify the process as a SOPDT model with a right-half-plane (RHP) zero. For example, we can apply the identification method of Park et al. (1998) to give a model of the form

$$\widetilde{G}(s)=\frac{-b_2 s+b_1}{s^2+a_2 s+a_1}e^{-\theta s} \tag{21}$$

Then, by using the equivalent time-delay concept of Sung and Lee (1996)

$$\exp(-\theta_{\text{equivalent}}s)\cong 1-\theta_{\text{equivalent}}s \tag{22}$$

the above non-minimum phase model can be transformed to a standard SOPDT model as

$$\overline{G}(s)=\frac{b_1}{s^2+a_2 s+a_1}e^{-(\theta+\frac{b_2}{b_1})s} \tag{23}$$

Therefore, based on the above equivalent SOPDT model, the proposed sliding mode control scheme can applied directly to non-minimum phase processes.

3. SIMULATION STUDIES

To verify the effectiveness and applicability of the proposed approach, we apply it to some typical chemical processes, including an underdamped process with long dead time, an overdamped high order process and a non-minimum phase system. The performance comparisons with the SOPDT model-based techniques of Sung et al. (1996) and Jahanmiri and Fallahi (1997) are included for evaluation. For the later simulation studies, we assume that the hard input constraint is $|u(t)|\le 1$, i.e., $\overline{u}=1$. Also, the parameters of the sliding mode controller are set to be $\alpha=0.1$ and $\beta=0.4$. To demonstrate the ability of output regulation by the proposed approach, we further assume that the system outputs are perturbed to move away from their steady states with the magnitude of +1.0 initially in the Examples 3.1 and 3.2, and -0.2 in the Example 3.3.

Example 3.1 Underdamped second-order with long deadtime process.

$$G_p(s)=\frac{1}{9s^2+2.4s+1}e^{-5s} \tag{24}$$

To apply the proposed scheme, we first convey a system identification technique to this system. With the closed-loop identification technique of Park et al. (1998), the SOPDT model parameters are given by $a_1=0.1111$, $a_2=0.2667$, $b_1=0.1111$ and $\theta=5$. For sliding mode controller design, we assume that each of these model parameters has 25% variations from its estimated values. Also, let $\mathbf{Q}=\begin{bmatrix}0.03 & 0\\ 0 & 2\end{bmatrix}$, then we arrive at a set of optimal sliding coefficients as $c_1=0.2449$ and $c_2=2$. Having previous information for design, one can easily implemented a sliding mode control system for this process. Fig. 2 depicts the output regulation results and the produced control input. The performance of the proposed scheme with arbitrary sliding coefficients is also included for comparison. From this figure, it is shown clearly that the proposed scheme provides a smoother and faster control performance as compared with the ISE optimal PID (Sung et al., 1996) and an IMC-PID scheme (Jahanmiri and Fallahi, 1997). The design of an optimal sliding surface for the sliding controller apparently results in a better performance than the arbitrary one does. Also observed is that the IMC-PID scheme of Jahanmiri and Fallahi (1997) produces more vigorous control input which violates the hard constraints and therefore results in a more oscillatory system output. On the contrary, there is no violation of the input hard constraint by applying the proposed technique since the input range can be pre-considered in the design stage. To verify the ability of handling with process uncertainties, we assume that the identified model remains unchanged, while the dynamics of the actual plant vary to $G_p(s)=\frac{1}{11s^2+2s+1}e^{-6s}$. Fig. 3 depicts the system performance in the face with this plant/model mismatch. The simulation results show clearly that the proposed scheme is still very robust in response to the plant uncertainties, while the IMC-PID leads to undesirable oscillation.

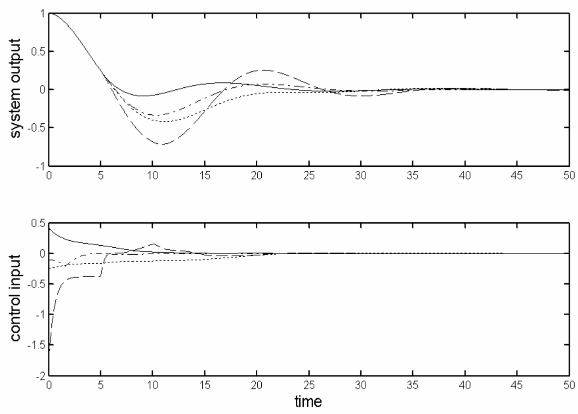

Fig. 2. Closed-loop system performance of Example 3.1. ——— the proposed approach with an optimal sliding surface; -·-·-·- the proposed approach with arbitrary sliding coefficients ($c_1=1$ and $c_2=2$); -------Jahanmiri and Fallahi (1997); ········Sung et al. (1996).

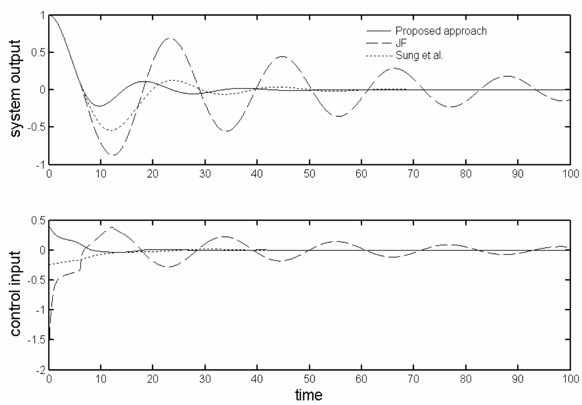

Fig. 3. Closed-loop system performance of Example 3.1 in the face with plant/model mismatch.

Example 3.2 High-order with deadtime process.

$$G_p(s) = \frac{1}{s^5 + 5s^4 + 10s^3 + 10s^2 + 5s + 1} e^{-2s} \quad (25)$$

By using the technique of Park et al. (1998) to this process, the SOPDT model parameters are identified as $a_1 = 0.2291$, $a_2 = 0.8465$, $b_1 = 0.2291$ and $\theta = 3.3$. Similarly, we consider 25% parameter variations in the design of the sliding controller. Let $\mathbf{Q} = \begin{bmatrix} 0.3 & 0 \\ 0 & 1.2 \end{bmatrix}$ for this process, we have the optimal sliding coefficients of $c_1 = 0.6$ and $c_2 = 1.2$. From Fig. 4, it is also observed that the closed-loop control performance by the proposed approach is smoother than both the methods of Sung et al. (1996) and Jahanmiri and Fallahi (1997). To evaluate the ability of handling process uncertainties, we further assume that the process dynamics change to

$$G_p(s) = \frac{1}{s^5 + 3s^4 + 12s^3 + 9s^2 + 6s + 1} e^{-2.5s} \quad (26)$$

but the identified model remains unchanged. The simulation results shown in Fig. 5 again corroborate the effectiveness and robustness of the proposed scheme in the face with uncertainties.

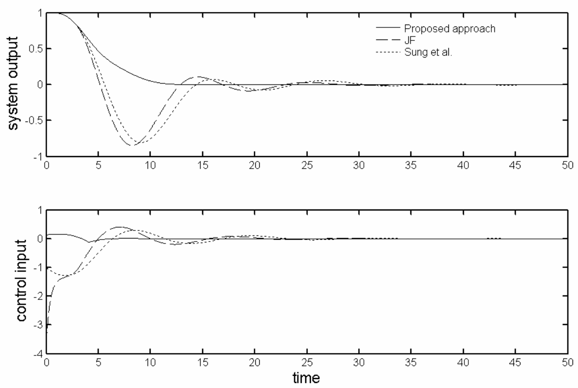

Fig. 4. Closed-loop system performance of Example 3.2.

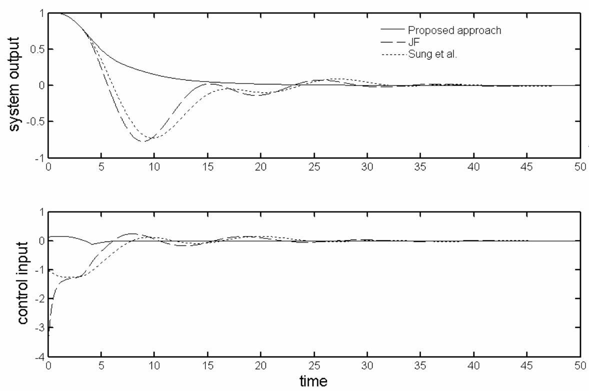

Fig. 5. Closed-loop system performance of Example 3.2 in the face with plant/model mismatch.

Example 3.3 Non-minimum phase process.

$$G_p(s) = \frac{-s + 0.5}{s^4 + 5s^3 + 8.75s^2 + 6.25s + 1.5} e^{-2s} \quad (27)$$

To apply the proposed scheme to this non-minimum phase process, we first identify the process model as in the form of Eq. (21). By applying the identification technique of Park et al. (1998), we have the model parameters as $a_1 = 0.4417$, $a_2 = 1.2915$, $b_1 = 0.1473$, $b_2 = 0.2249$ and $\theta = 2.5387$. Therefore an equivalent SOPDT model can be given by

$$\overline{G}_p(s) = \frac{0.1473}{s^2 + 1.2915\, s + 0.4417} e^{-4.0655s} \quad (28)$$

Now, by considering 25% parameter variations and choosing $\mathbf{Q} = \begin{bmatrix} 1.5 & 0 \\ 0 & 1.2 \end{bmatrix}$, we can construct a sliding mode control system for this non-minimum phase system. From Fig. 6, it is evident that the proposed scheme rapidly forces the system output back to its set-point. In contrast, both the approaches of Sung et al. (1996) and Jahanmiri and Fallahi (1997) results in serious oscillation in the process output as well as the produced control input. For the case that the process dynamics vary to

$$G_p(s) = \frac{-1.2s + 0.5}{s^4 + 6s^3 + 7.5s^2 + 5.5s + 1.5} e^{-2.5s} \quad (29)$$

the simulation results shown in Fig. 7 reveal that the proposed control strategy still gives to robust system performance, while both the linear techniques of Sung et al. (1996) and Jahanmiri and Fallahi (1997) become quite unstable by the influence of this significant plant/model mismatch.

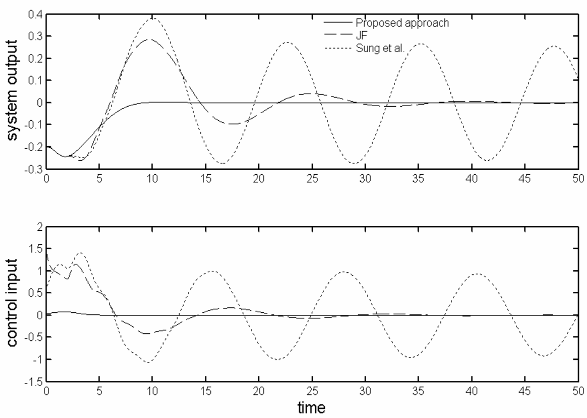

Fig. 6. Closed-loop system performance of Example 3.3.

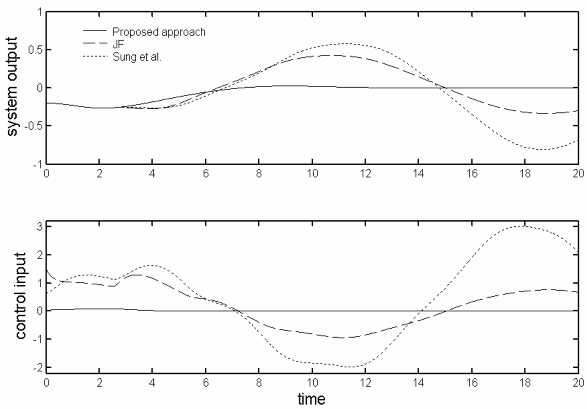

Fig. 7. Closed-loop system performance of Example 3.3 in the face with plant/model mismatch.

4. CONCLUSIONS

This paper has presented a systematic and novel model-based control system for the regulation of chemical processes. Based on an identified SOPDT model, a delay-ahead predictor and a designed optimal sliding surface, a sliding mode control scheme has been developed. The stability of the closed-loop system as well as the control performance is guaranteed with satisfying a sliding condition. Besides, with the concept of delay equivalent, the presented scheme can be easily extended to deal with the regulation problem of processes having inverse response. The effectiveness and applicability of the proposed sliding mode control technique has been tested with some typical plants. Moreover, performance comparisons with some existing SOPDT-based techniques are included for further evaluation. Extensive simulation results reveal that the proposed sliding mode control scheme appears to be a simple, robust and powerful approach to the regulation control of chemical processes.

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Appendix A: Proof of the sliding condition

By taking time derivative of the sliding function (11) and inserting the control law of (12), we have

$$\begin{aligned}\dot{\delta} &= c_1\dot{x}_1^*(t) + c_2\dot{x}_2^*(t) \\ &= c_1 x_2^*(t) + c_2\{-a_1 x_1^*(t) - a_2 x_2^*(t) + b_1[b_1^{-1}(a_1 x_1^*(t) \\ &\quad + (a_2 - c_2^{-1}c_1)x_2^*(t)) - (b_1 c_2)^{-1}(\alpha + \bar{h}(\mathbf{x}^*,t))\mathrm{sign}(\delta)] \\ &\quad + h(\mathbf{x}^*,t)\} \\ &= -(\alpha + \bar{h}(\mathbf{x}^*,t))\mathrm{sign}(\delta) + c_2 h(\mathbf{x}^*,t)\end{aligned} \qquad (A1)$$

Further, by checking

$$\begin{aligned}\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}\delta^2 &= \delta\cdot\dot{\delta} = -\alpha|\delta| - \bar{h}(\mathbf{x}^*,t)|\delta| + \delta c_2 h(\mathbf{x}^*,t) \\ &= -\alpha|\delta| - \bar{h}(\mathbf{x}^*,t)|\delta|\left(1 - \frac{\delta c_2 h(\mathbf{x}^*,t)}{|\delta|\bar{h}(\mathbf{x}^*,t)}\right) \\ &= -\alpha|\delta| - \bar{h}(\mathbf{x}^*,t)|\delta|\left(1 - \frac{\delta c_2 h(\mathbf{x}^*,t)}{|\delta||c_2|h_{\max}(\mathbf{x}^*,t)}\right) \\ &\le -\alpha|\delta|\end{aligned} \qquad (A2)$$

it is shown obviously that the sliding condition is satisfied.

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