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논 문
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A Robust Sliding Mode Controller for Unmatched Uncertain Severe Sate Time-Delay Systems

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Abstract - This note is concerned with a robust sliding mode control(SMC) for a class of unmatched uncertain system with severe commensurate state time delay. The suggested method is extended to the control of severe state time delay systems with unmatched uncertainties except the matched input matrix uncertainty. A transformed sliding surface is proposed and a stabilizing control input is suggested. The closed loop stability together with the existence condition of the sliding mode on the proposed sliding surface is investigated through one Lemma and two Theorems by using the Lyapunov direct method with the concept of the control Lyapunov function instead of complex Lyapunov-Kravoskii functionals. Through an illustrative example and simulation study, the usefulness of the main results is verified.

Key Words : State time delay, Variable structure system, Sliding mode control, Unmatched uncertainty

1. Introduction

The stability analysis and robust controller design for uncertain time delay systems is now open problem[1]. A various industrial system for example the turbojet engine, electrical network, nuclear reactor, rolling mill, and chemical process, etc have the characteristics of the time delay. These time delay can result in the instability and poor performance[2]. Until now, there are many stability analysis and robust controller design algorithms for time delay systems such as Smith predictor[3], feedback stabilization[4]-[7], robust H_∞ [8][9], Lyapunov -Razumikhin[10], Lyapunov-Krasovskii[11]-[14], linear matrix inequality(LMI)[8][15] [27], adaptive control[16], backstepping[17][18], passivity-based[19], and sliding mode control(SMC)[19]-[30], etc[31][32]. Those have their merits and demerits. Smith-predictor to cancel the effect of time delay is known to lead to poor control performance when the model is imperfect. Among them, the sliding mode control(SMC) can provide the effective means to the problem of controlling uncertain dynamical systems under parameter variations and external disturbances[33][34], even uncertain time delay systems[1][19]-[30]. In [20], a new robust stability criterion for uncertain time-delay systems was given and the sliding mode control was proved to be applicable by Shyu and Yan in 1993. Khazali proposed an integral output feedback variable structure system for uncertain time-delay systems[21] in which Khazali tried to overcome some of the system's structural constraints. To uncertain input delay system, a sliding mode control applied by Hu, Basker and Crisalle[22] and Roh and Oh[23]. For multi input systems with multiple state delays without uncertainties, a sliding mode controller was designed in [24] by Jafarov. In [25], a memoryless robust sliding mode control design method was presented for a class of uncertain time delay systems with multiple fixed state delays by Li and Decarlo. For linear system with both input and state delays, a sliding mode control was proposed without uncertainties by Xia, Han, Jia in 2002 in [26]. Using an LMI approach, a robust sliding mode control was designed for uncertain time-delay systems by Xia and Jia in [27]. For the tracking control of a class of nonlinear uncertain system with state time delays, a new sliding mode controller was presented by Pan in 2007 in [28]. A optimal sliding mode for a class of nonlinear systems with time delay without uncertainties was proposed by using the successive approximation approach in [29]. For uncertain stochastic delay systems, a robust H_∞ controller is designed by using the sliding mode control, in which, the restrictive assumption is removed and the design method provides control scheme for finite-time stabilization of stochastic delay systems[30].

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In this note, a new robust sliding mode control is presented for severe state time delay systems with unmatched system matrix uncertainty and disturbance and matched input matrix uncertainty. A useful lemma which will be needed in the proof of the stability is stated. A new transformed sliding surface is proposed and a corresponding stabilizing control input is suggested. Using the concept of control Lyapunov function, the existence condition of the sliding mode and closed loop stability is proved. This approach is a delay independent analysis. To show the validity of the proposed algorithm, an illustrative example is given.

2. Main Results of a Sliding Mode Controller

Consider the unmatched uncertain linear differential-difference equations with state severe commensurate state time delay

$$\dot{x}(t) = (A_0 + \Delta A_0)x(t) + (A_1 + \triangle A_1)x(t-h) + (B_0 + \Delta B)u + \Delta D(t) \tag{1}$$

$$x(t) = \varphi(t) \quad \forall t \in [-h, 0] \tag{2}$$

where $x \in R^n$ is the state, $\varphi(t)$ is the initial condition, $h > 0$ is the finite severe delay of the system maybe time-varying or unknown, $u \in R^1$ is the control input, $A_0 \in R^{n\times n}$ and $A_1 \in R^{n\times n}$ are the nominal system matrices, maybe those are unstable, $B_0 \in R^{n\times 1}$ is the nominal input matrix, $\triangle A_0$ and $\triangle A_1$ are the unmatched system matrix uncertainty, $\Delta D(t)$ is unmatched external disturbance, and $\triangle B$ is the matched input matrix uncertainty, respectively, those uncertainties and disturbance are bounded. The following assumptions are made.

Assumption A1: The pair (A_0, B_0) is completely controllable

Assumption A2: The matching condition is imposed on only the uncertainty $\triangle B$

$$R\{\triangle B\} \in R\{B_0\} \tag{3}$$

where $R\{\cdot\}$ means the range space of the matrix.

The following assumption is made for analyzing the algorithm with delay independent approach.

Assumption A3: It is assumed that

$$(CB_0)^{-1} C \triangle B = \triangle I < \delta < 1 \tag{4}$$

is satisfied for a non zero element row vector C.

Assumption A4[10]: The matrix A_1 satisfies the matching condition i.e.

$$R\{A_1\} \in R\{B_0\} \tag{5}$$

Assumption A5: The system (1) has only the equilibrium point at zero in state space.

Assumption A6: The time delay state $x(t-h)$ is available or measurable

And the time delay state $x(t-h)$ satisfies the following lemma

Lemma 1: If $x(t) \to 0$ as $t \to \infty$ then $x(t-h) \to 0$ as $t \to \infty$ for any finite value h.

Proof: it is clear itself.

Because the time delay system is a nonlinear system, the Lyapunov stability theorem for nonlinear systems which will be needed is stated as follows:

Theorem 1[35]: Assume that, in a neighborhood of the equilibrium 0, there exists a positive scalar function with first order derivatives and a class K function α, β, and γ such that $\forall x \neq 0$

a. $0 < \alpha(\|x\|) \leqq V(x,t) \leqq \beta(\|x\|)$ (6)

b. $\dot{V} \leqq -\gamma(\|x\|) < 0$ (7)

then, the equilibrium 0 is uniformly asymptotically stable

Proof: See Chapter 4 in [35]

The suggested sliding surface is the linear combination of the full state variable and transformed as[36]

$$s = (CB_0)^{-1} C \cdot x(t) \tag{8}$$

The time derivative of the proposed sliding surface is as follows:

$$\begin{aligned} \dot{s} &= (CB_0)^{-1} C \cdot \dot{x}(t) \\ &= (CB_0)^{-1} C(A_0 + \Delta A_0)x(t) + (CB_0)^{-1} C(A_1 + \Delta A_1)x(t-h) \\ &\quad + (CB_0)^{-1} C(B_0 + \Delta B)u(t) + (CB_0)^{-1} C \Delta D(t) \\ &= (CB_0)^{-1} C(A_0 + \Delta A_0)x(t) + (CB_0)^{-1} C(A_1 + \Delta A_1)x(t-h) \\ &\quad + (I + \Delta I)u(t) + (CB_0)^{-1} C \Delta D(t), \quad \Delta I = (CB_0)^{-1} C \Delta B \end{aligned} \tag{9}$$

The equivalent control input is obtained from $\dot{s} = 0$ as follows:

$$\begin{aligned} u_{eq} = &-(I + \Delta I)^{-1} (CB_0)^{-1} C(A_0 + \Delta A_0)x(t) \\ &-(I + \Delta I)^{-1} (CB_0)^{-1} C(A_1 + \Delta A_1)x(t-h) \\ &-(I + \Delta I)^{-1} (CB_0)^{-1} C \Delta D(t) \end{aligned} \tag{10}$$

This input can not be implemented because of the uncertainties and disturbances. Therefore the SMC control input is proposed as follows:

$$\begin{aligned} u(t) = &-K_0 \cdot x(t) - \Delta K_0 \cdot x(t) - K_1 \cdot x(t-h) \\ &- \Delta K_1 \cdot x(t-h) - K_2 \cdot s - \triangle K_2 \cdot sign(s) \end{aligned} \tag{11}$$

where K_0, K_1, and K_2 are the constant gains, ΔK_0, ΔK_1 and ΔK_2 are the switching gains, respectively. The constant gains K_0, K_1, and K_2 are selected as follows:

$$K_0 = (CB_0)^{-1} CA_0 \tag{12}$$

$$K_1 = (CB_0)^{-1} CA_1 \tag{13}$$

$K_2 > 0$ such that

$$[A_0 + A_1, \quad B_0(K_0 + K_2(CB_0)^{-1} C)] \text{ is stable} \tag{14}$$

The switching gains ΔK_0, ΔK_1 and ΔK_2 are chosen as follows:

$$\triangle K_0 = [\triangle k_{0j}]$$

$$\triangle k_{0j} \begin{cases} \geq \dfrac{\max\{(CB_0)^{-1} C \triangle A_0 - \triangle I (CB_0)^{-1} CA_0\}_j}{\min\{I + \triangle I\}} & sign(sx_j(t)) > 0 \\ \leq \dfrac{\min\{(CB_0)^{-1} C \triangle A_0 - \triangle I (CB_0)^{-1} CA_0\}_j}{\min\{I + \triangle I\}} & sign(sx_j(t)) < 0 \end{cases}$$

$$j = 1, 2, \ldots, n \tag{15}$$

$$\triangle K_1 = [\triangle k_{1j}]$$

$$\triangle k_{1j}\begin{cases} \geq \dfrac{\max\{(CB_0)^{-1}C\triangle A_1 - \triangle I(CB_0)^{-1}CA_1\}_j}{\min\{I+\triangle I\}} & sign(sx_j(t-h))>0 \\ \leq \dfrac{\min\{(CB_0)^{-1}C\triangle A_1 - \triangle I(CB_0)^{-1}CA_1\}_j}{\min\{I+\triangle I\}} & sign(sx_j(t-h))<0 \end{cases}$$

$$j=1,2,...,n \tag{16}$$

$$\triangle K_2\begin{cases} \geq \dfrac{\max\{(CB_0)^{-1}C\Delta D(t)\}}{\min\{I+\Delta I\}} & sign(s)>0 \\ \leq \dfrac{\min\{(CB_0)^{-1}C\Delta D(t)\}}{\min\{I+\Delta I\}} & sign(s)<0 \end{cases} \tag{17}$$

By the suggested control input, (11)-(17), the time derivative of the proposed sliding surface, (10), becomes as follows:

$$\begin{aligned} \dot{s} = &(CB_0)^{-1}C(A_0+\Delta A_0)x(t) \\ &+(CB_0)^{-1}C(A_1+\Delta A_1)x(t-h)+(CB_0)^{-1}C\triangle D(t) \\ &-(I+\Delta I)[K_0x(t)+\Delta K_0x(t)+K_1x(t-h) \\ &+\triangle K_1x(t-h)+K_2s+\triangle K_2sign(s)] \end{aligned} \tag{18}$$

$$\begin{aligned} = &(CB_0)^{-1}CA_0x(t)-K_0x(t)+(CB_0)^{-1}CA_1x(t-h) \\ &-K_1x(t-h)+(CB_0)^{-1}C\Delta A_0x(t)-\triangle IK_0x(t) \\ &-(I+\Delta I)\Delta K_0x(t)+(CB_0)^{-1}C\Delta A_1x(t-h) \\ &-\triangle IK_1x(t-h)-(I+\Delta I)\Delta K_1x(t-h) \\ &-(I+\Delta I)K_2s+(CB_0)^{-1}C\Delta D(t)-(I+\Delta I)\triangle K_2sign(s) \end{aligned} \tag{19}$$

By the relationship of (12) and (13), the equation (19) becomes

$$\begin{aligned} \dot{s} = &(CB_0)^{-1}C\Delta A_0x(t)-\triangle IK_0x(t)-(I+\Delta I)\Delta K_0x(t) \\ &+(CB_0)^{-1}C\Delta A_1x(t-h)-\triangle IK_1x(t-h) \\ &-(I+\Delta I)\Delta K_1x(t-h)-(I+\Delta I)K_2s+(CB_0)^{-1}C\Delta D(t) \\ &-(I+\Delta I)\triangle K_2sign(s) \end{aligned} \tag{20}$$

Theorem 2: With the suggested sliding surface (9) and proposed control input (11)-(17), the closed loop system of (1) is asymptotically stable to $s(t)=0$ and finally zero in state space and the existence condition of the sliding mode on $s(t)=0$ is satisfied.

Proof: The proof is straightforward. Instead of complex Lyapunov-Krasovskii functionals[13][14], take a Lyapunov candidate function as

$$\begin{aligned} V(x(t)) &= \frac{1}{2}s^Ts = \frac{1}{2}x^T(t)C^T(CB_0)^{-1^T}(CB_0)^{-1}Cx(t) \\ &= x^T(t)Px(t)>0 \end{aligned} \tag{21}$$

$$P=C^T(CB_0)^{-1^T}(CB_0)^{-1}C>0 \tag{21a}$$

The derivative of a Lyapunov candidate function is as follows:

$$\begin{aligned} \dot{V}(x(t)) &= s^T \cdot \dot{s} \\ &= (CB_0)^{-1}C\Delta A_0x(t)s-\triangle IK_0x(t)s-(I+\Delta I)\Delta K_0x(t)s \\ &\quad+(CB_0)^{-1}C\Delta A_1x(t-h)s-\triangle IK_1x(t-h)s \\ &\quad-(I+\Delta I)\Delta K_1x(t-h)s-(I+\Delta I)K_2s^2 \\ &\quad+(CB_0)^{-1}C\Delta D(t)s-(I+\Delta I)\triangle K_2sign(s)s \end{aligned} \tag{22}$$

From the gain inequality (14)-(17), then one can obtain the following equation

$$\dot{V}(x(t)) = s^T \cdot \dot{s} \leqq -(1-\delta)K_2s^2<0 \tag{23}$$

The existence condition of the sliding mode on $s(t)=0$ is proved for the uncertain severe time delay system. By Theorem 1, $V(x)\to 0$ as $t\to\infty$ which menas that $x(t)\to 0$ as $t\to\infty$. By Lemma 1, also $x(t-h)\to 0$ as $t\to\infty$ independently the finite h, which completes the proof of the theorem.

3. Illustrative Example

Consider a second order severe state time delay uncertain system:

$$\begin{aligned} \begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = &\begin{bmatrix}1 & 1+0.2\sin(x_1(t)) \\ 1+0.3\sin(t) & 2+0.6\sin^2(5t)\end{bmatrix}x(t) \\ &+\begin{bmatrix}0.3\sin(x_1(t-h)) & 0 \\ 10+0.3\sin(5t) & 2+0.4\sin(5t)\end{bmatrix}x(t-h) \\ &+\begin{bmatrix}0\\ 2+0.2\sin(3t)\end{bmatrix}u+\begin{bmatrix}0.3\sin(x_2(t))+0.2\sin(x_2(t-h)) \\ 0\end{bmatrix} \end{aligned} \tag{24}$$

where the nominal parameter A_0, A_1, and B_0, unmatched uncertainties $\triangle A_0$, $\triangle A_1$, and $\triangle D(t)$, matched uncertainty $\triangle B$ are

$$A_0=\begin{bmatrix}1&1\\1&2\end{bmatrix},\ A_1=\begin{bmatrix}0&0\\10&2\end{bmatrix}\ \ B_0=\begin{bmatrix}0\\2\end{bmatrix} \tag{25}$$

$$\triangle A_0=\begin{bmatrix}0 & 0.2\sin(x_1) \\ 0.3\sin(t) & 0.6\sin(3t)\end{bmatrix},$$

$$\triangle A_1=\begin{bmatrix}0.2\sin(x_1(t-h)) & 0 \\ 0.3\sin(5t) & 0.4\sin(7t)\end{bmatrix},$$

$$\triangle D(t)=\begin{bmatrix}0.3\sin(x_2(t))+0.2\sin(x_2(t-h)) \\ 0\end{bmatrix},\quad \triangle B=\begin{bmatrix}0\\0.2\sin(3t)\end{bmatrix}$$

Since A_0 has the eigenvalues at 0.382 and 2.618, A_0 is unstable. However, Assumption A1 is satisfied. $\triangle B$ and A_1 satisfies Assumption A2 and Assumption A4, respectively. The Assumption 3 is satisfied since $(CB_0)^{-1}C\triangle B=0.1\sin(3t)\leqq 0.1<1$. The non zero stable coefficient of the transformed sliding surface is determined as

$$(CB_0)^{-1}C=\frac{1}{2}[3\ \ 1]=[1.5\ \ \ 0.5] \tag{26}$$

The selected gains in the control input are as follows:

$$K_0=(CB_0)^{-1}CA_0=\frac{1}{2}[3\ \ \ 1]\begin{bmatrix}1&1\\1&2\end{bmatrix}=[2\ \ \ 2.5] \tag{27}$$

$$K_1=(CB_0)^{-1}CA_1=\frac{1}{2}[3\ \ \ 1]\begin{bmatrix}0&0\\10&2\end{bmatrix}=[5\ \ \ 1] \tag{28}$$

$$K_2=5>0 \tag{29}$$

$$\triangle k_{01}=\begin{cases}2.1 & \text{if } sx_1>0\\ -2.1 & \text{if } sx_1<0\end{cases} \tag{30}$$

$$\triangle k_{02}=\begin{cases}2.2 & \text{if } sx_2>0\\ -2.2 & \text{if } sx_2<0\end{cases} \tag{31}$$

$$\triangle k_{11}=\begin{cases}1.1 & \text{if } sx_1(t-h)>0\\ -1.1 & \text{if } sx_1(t-h)<0\end{cases} \tag{32}$$

$$\triangle k_{12}=\begin{cases}2.3 & \text{if } sx_2(t-h)>0\\ -2.3 & \text{if } sx_2(t-h)<0\end{cases} \tag{33}$$

$$\triangle K_2=\begin{cases}1.8 & \text{if } s>0\\ -1.8 & \text{if } s<0\end{cases} \tag{34}$$

The simulation is carried out under 1[msec] sampling time and with $x(0)=[10\ \ 0]^T$ initial state. For $x(t)=[10\ \ 0]^T\ \ \forall t\in[-h,0]$, Fig. 1 shows the output responses of x_1, x_2, $x_1(t-h)$, and $x_2(t-h)$ for $h=1$[sec] and for all unmatched uncertainties and disturbance.

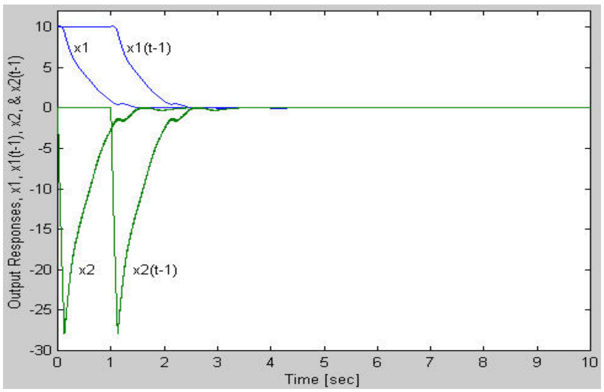

Fig. 1 Output responses of x_1, x_2, $x_1(t-1)$, and $x_2(t-1)$ for $x(t)=[10\quad 0]^T\quad \forall t\in[-1,0]$

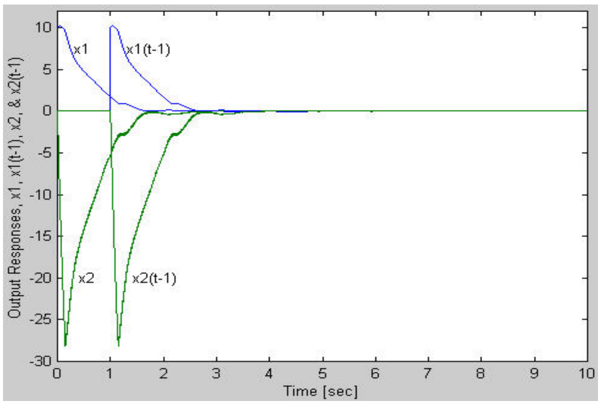

Fig. 2 Output responses of x_1, x_2, $x_1(t-1)$, and $x_2(t-1)$ for $x(t)=[0\quad 0]^T\quad \forall t\in[-1,0]$

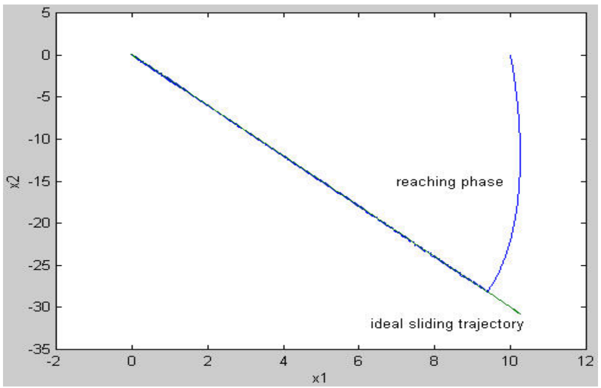

Fig. 3 Phase trajectory with the ideal sliding trajectory

During first delay time, the delay state plays a role of the disturbance however all state variables converge to zeros. For $x(t)=[0\quad 0]^T\quad \forall t\in[-1,0]$ Fig. 2 shows the output responses of x_1, x_2, $x_1(t-1)$, and $x_2(t-1)$. The phase trajectory with the ideal sliding trajectory is shown in Fig. 3. The sliding surface and control input is depicted in Fig. 4 and Fig. 5, respectively. For severe time delays $h=2$ and $h=3$ [sec], the output responses of x_1, x_2, $x_1(t-h)$, and $x_2(t-h)$ are shown in Fig. 6 and Fig. 7, respectively. As shown in these figures, for different severe state time delays, all the output responses converge to zeros as $t\to\infty$ by the suggested designed algorithm.

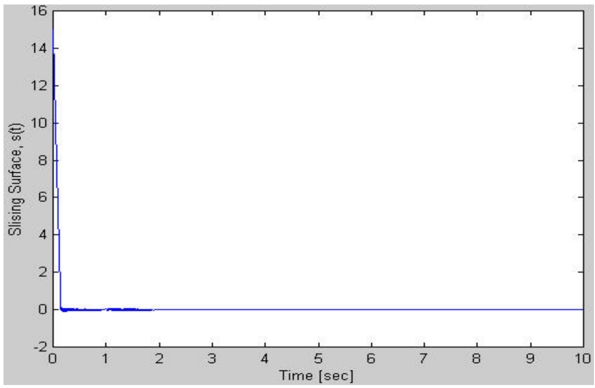

Fig. 4 Sliding surface time trajectory

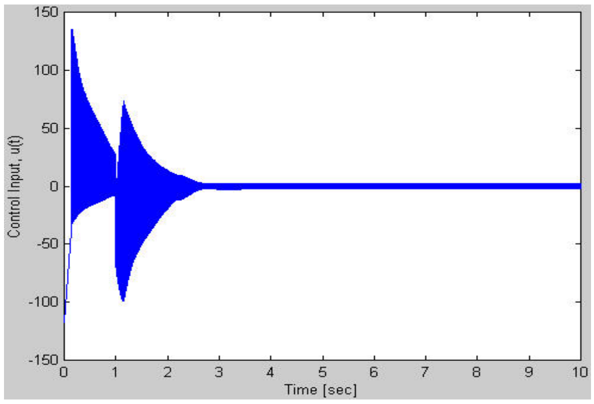

Fig. 5 Control input time trajectory

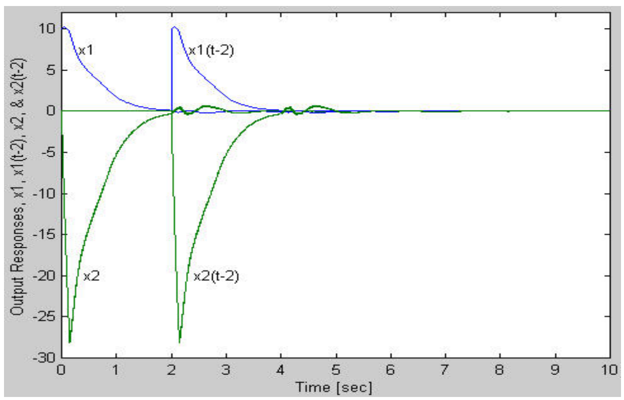

Fig. 6 Output responses of x_1, x_2, $x_1(t-2)$, and $x_2(t-2)$ for $h=2$

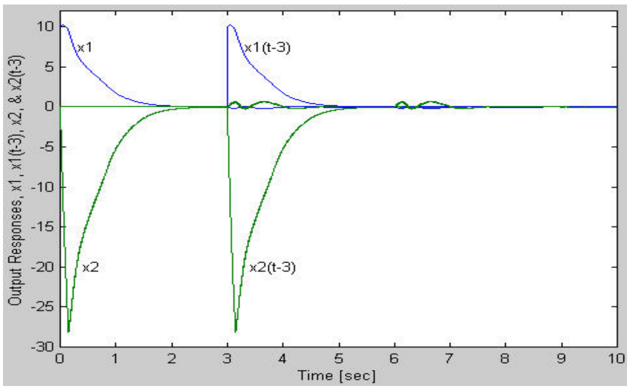

Fig. 7 Output responses of x_1, x_2, $x_1(t-3)$, and $x_2(t-3)$ for $h=3$

4. Conclusions

In this note, a robust sliding mode controller is proposed for a class of unmatched uncertain severe commensurate state time delay systems. The proposed method is extended to the control of severe commensurate state time delay systems with unmatched uncertainties except the matched input matrix uncertainty. The transformed sliding surface is suggested as the linear combination of full state. A stabilizing corresponding control input is proposed. The gain selection rule for the proposed control input is suggested. The existence condition of the sliding mode on the suggested sliding surface is proven via Theorem 1 and Theorem 2. The stability of the closed loop system with the stabilizing corresponding control input and the transformed sliding surface is investigated through Lemma 1, Theorem 1, and Theorem 2, in which, the Lyapunov direct method and concept of control Lyapunov function is used instead of complex Lyapunov-Krasovskii functionals. This approach is the delay independent one rather than the delay dependent one. An illustrative example with a design example and simulation study is presented to show the validity of the algorithm. Furthermore, the proposed method is promising and easy to implement.

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