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Design of Fuzzy Output Feedback Controller for The Nonlinear Systems with Time-Delay

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Abstract

This paper proposes a design method of a fuzzy output feedback controller for the nonlinear systems with the unknown time-delay. Recently, Cao *et al.* proposed a stabilization method for the nonlinear time-delay systems using a fuzzy controller when the time-delay is known. However, the time-delay is likely to be unknown in practical. We represent the nonlinear systems with the unknown time-delay by Takagi-Sugeno (T-S) fuzzy model and design the fuzzy observer and the parallel distributed compensation (PDC) law based on this observer. By applying Lyapunov-Krasovskii theorem to the closed-loop system, the sufficient condition for the asymptotic stability of the equilibrium point is derived and converted into the linear matrix inequality (LMI) problem.

Keywords : T-S fuzzy system, time-delay, output feedback control, LMI

1. Introduction

Some kind of systems, such as chemical process, rolling mill systems and hydraulic systems, are affected by the time-delay in state or input and it has been shown that the time-delay may induce complex behaviors such as oscillations, or the degradation of the performance. Even worse, a small delay can destabilize some kind of systems [5]. Therefore, the possible time-delay should be taken into consideration in the controller design for the nonlinear systems with the time-delay.

The systems with the time-delay can be categorized into two groups : the neutral type and the retarded type [6]. Generalizations of the Lyapunov method for both of the types have been proposed. In particular, a class of quadratic Lyapunov-Krasovskii functionals has been widely used [10], [11]. For example, Bliman proposed a condition of the delay-independent stability of neutral or retarded type systems in [6]. Su *et al.* suggested a delay-dependent stability criterion for a class of uncertain linear time-delay systems [9].

On the other hand, fuzzy logic has been used to cope with the nonlinear system control problem. Among various kinds of fuzzy methods, Takagi-Sugeno (T-S) fuzzy system is widely accepted as a tool for the design and the analysis of fuzzy control systems [7].

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The applications of the T-S models to the various kinds of nonlinear systems can be found in many literatures [1], [3], [7], [8], [14]. In T-S fuzzy model, the local dynamics in different state space regions are represented by the linear models. The overall model of the system is achieved by fuzzy "blending" of these linear models. The T-S fuzzy model can express a highly nonlinear functional relation with comparatively a small number of implications of rules [12].

Recently, T-S fuzzy control theory has been applied to the nonlinear time-delay system control in some literatures [1], [2], [3]. In [1], Cao *et al.* proposed a fuzzy observer and parallel distributed compensation (PDC) controller based on this observer for the time-delay systems. Lee *et al.* proposed a constructive algorithm to design an output feedback robust H_∞ controller for the uncertain fuzzy dynamic system with the time-delayed state [2]. Recently, Zhang Yi *et al.* derived the conditions for global exponential stability of free fuzzy systems with the uncertain delays [3].

In this paper, we propose a new fuzzy controller and a fuzzy observer for the nonlinear system with the unknown time-delay. The advantage of the proposed fuzzy controller and the fuzzy observer over the reference [1] is that the proposed observer does not require the exact information of the time-delay. In fact, it is not easy to know or measure the time-delay exactly. So, we assume that the time-delay is time-varying and unknown in this paper. In the course of stability analysis, the sufficient condition for the asymptotic stability of the equilibrium point is recast into the linear matrix inequalities (LMI) problem [13].

This paper is organized as follows. In section 2, some preliminaries for T-S model of the nonlinear systems with time-delay are given. The stability analysis of the whole closed-loop system with the proposed controller and the observer is given in chapter 3. The validity and the effectiveness of the proposed method are examined through the computer simulation in chapter 4. Finally, some concluding remarks are presented in chapter 5.

Notations The following general notations will be used throughout the paper. $\mathbf{R}$ denotes the set of real numbers, $\mathbf{R}^n$ denotes the n dimensional Euclidean space. The notation $X \geq Y$ (respectively, $X > Y$), where X and Y are symmetric matrices, means that the matrix $X-Y$ is positive semi-definite (respectively, positive definite). $C_{n,\tau} = C([-\tau,0],\mathbf{R}^n)$ denotes the Banach space of continuous vector functions mapping the interval $[-\tau,0]$ into $\mathbf{R}^n$ with the topology of uniform convergence. The following norms will be used: $\|\cdot\|$ refers to either the Euclidean vector norm or the induced matrix 2-norm; $\|\phi\|_c = \sup_{-\tau\leq t\leq 0}\|\phi(t)\|$ stands for the norm of a function $\phi \in C_{n,\tau}$. Moreover, we denote by $C^v_{n,\tau}$ the set defined by $C^v_{n,\tau} = \{\phi \in C_{n,\tau} : \|\phi\|_c < v\}$, where v is a positive real number.

2. Overview

T-S fuzzy system can represent a general class of nonlinear systems. Using T-S model, we can represent a nonlinear system with the time-delay as follows:

IF-THEN form

$$R_i : \text{If } z_1(t) \text{ is } M_{i1} \text{ and } z_2(t) \text{ is } M_{i2}, \cdots, z_p(t) \text{ is } M_{ip}$$
$$\text{Then } \dot{x}(t) = A_i x(t) + A_{di} x(t-\tau) + B_i u(t) \qquad (1)$$
$$y(t) = C_i x(t)$$

with the initial condition

$x(t_0+\theta) = \phi(\theta)$, $\forall\theta \in [-\tau,0]$; $(t_0,\phi) \in \mathbf{R}^+ \times C^v_\tau$

where, $x(t) \in \mathbf{R}^n$ is the state vector, $z = [z_1, z_2, \ldots, z_p]$ are the measurable premise variables, $R_i\ (i=1,2,\ldots,r)$ is the i th fuzzy rule, r is the number of rule, $M_{i1}, M_{i2}, \ldots, M_{in}$ are fuzzy sets. The time-delay $\tau(t) \leq \tau_0$ is the unknown bounded time-varying delay in the state and it is assumed that

$$\dot{\tau}(t) \leq \beta < 1 \qquad (2)$$

that is, the derivative of the time-varying delay function is continuous and bounded. $\phi(t)$ represents a vector-valued initial continuous function. The output of the above fuzzy system is inferred as follows:

Input-Output form

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))[A_i x(t) + A_{di} x(t-\tau(t)) + B_i u(t)] \qquad (3)$$

where $h_i(z(t))$ is the fuzzy basis functions such that

$$h_i(z(t)) = \frac{w_i(z(t))}{\sum_{i=1}^{r} w_i(z(t))}, \quad h_i(z(t)) \geq 0, \quad \sum_{i=1}^{r} h_i(z(t)) = 1 \qquad (4)$$

with

$$w_i(z(t)) = \prod_{j=1}^{n} M_{ij}(z_j(t)), \ \sum_{i=1}^{r} w_i(z(t)) > 0, \ w_i(z(t)) > 0 \qquad (5)$$

3. Design of fuzzy controller and observer

In [8], the authors proposed a fuzzy controller based on the fuzzy observer. In [1], the authors extended the results of [8] to the nonlinear systems with the known time-delay. But, the time-delay is likely to be unknown in practice. This fact makes it difficult for the observer and controller to be applied to the actual case.

In this section, therefore, a new fuzzy feedback controller and a fuzzy observer with the estimated time-delay are proposed. The proposed fuzzy observer is described by following fuzzy rules :

i th observer rule :

$$R_i : \text{If } z_1(t) \text{ is } M_{i1} \text{ and } z_2(t) \text{ is } M_{i2}, \cdots, z_p(t) \text{ is } M_{ip}$$
$$\text{Then } \dot{\hat{x}}(t) = A_i \hat{x}(t) + A_{di} \hat{x}(t-\hat{\tau}(t)) + B_i u(t) + L_i(y(t)-\hat{y}(t))$$
$$y(t) = C_i \hat{x}(t)$$
$$(6)$$

Notice that $\hat{\tau}(t)$ is the estimated time-delay, and it can be regarded as zero if no relevant information about the plant is available. The overall fuzzy observer can be arranged as

$$\dot{\hat{x}}(t) = \sum_{i=1}^{r} h_i(z(t))[A_i \hat{x}(t) + A_{di} \hat{x}(t-\hat{\tau}(t)) + B_i u(t) + L_i(y(t)-\hat{y}(t))] \qquad (7)$$

where, $\hat{y}(t) = \sum_{i=1}^{r} h_i(z(t)) C_i \hat{x}(t)$.

In the same manner, we design the controller as

$$u(t) = -\sum_{i=1}^{r} h_i(z(t)) K_i \hat{x}(t) \qquad (8)$$

The closed-loop system is represented by the following augmented state equation.

$$\begin{bmatrix}\dot{x}(t)\\ \dot{\hat{x}}(t)\end{bmatrix}=\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(z(t))h_j(z(t))\left\{\begin{bmatrix}A_i & -B_iK_j\\ L_iC_j & A_i-B_iK_j-L_iC_j\end{bmatrix}\begin{bmatrix}x(t)\\ \hat{x}(t)\end{bmatrix}+\begin{bmatrix}A_{di} & 0\\ 0 & A_{di}\end{bmatrix}\begin{bmatrix}x(t-\tau)\\ \hat{x}(t-\hat{\tau})\end{bmatrix}\right\} \tag{9}$$

Define $x-\hat{x}=\tilde{x}$, then the closed-loop systems are arranged as

$$\dot{\xi}(t)=\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(z(t))h_j(z(t))\{\overline{A}_{ij}\xi(t)+\overline{A}_{d1i}\xi(t-\tau)+\overline{A}_{d2i}\xi(t-\hat{\tau})\} \tag{10}$$

where, $\xi(t)=[x^T(t)\ \tilde{x}^T(t)]^T$ and

$$\overline{A}_{ij}=\begin{bmatrix}A_i-B_iK_j & B_iK_j\\ 0 & A_i-L_iC_j\end{bmatrix}, \tag{11}$$

$$\overline{A}_{d1i}=\begin{bmatrix}A_{di} & 0\\ A_{di} & 0\end{bmatrix},\ \overline{A}_{d2i}=\begin{bmatrix}0 & 0\\ -A_{di} & A_{di}\end{bmatrix} \tag{12), (13}$$

Now we introduce a lemma which will be used in the proof of the following theorem.

Lemma 1 [3] Let Q be any of a $n\times n$ matrix. For any constant $k>0$ and any symmetric positive matrix $T>0$, the following inequality is satisfied.

$$2x^TQy\le kx^TQT^{-1}Q^Tx+\frac{1}{k}y^TTy\quad\text{for}\ \forall x,y\in\mathbf{R}^n \tag{14}$$

■

The following theorem provides the stability condition of the systems composed of the plant (3), the controller (8) and the observer (7).

Theorem 1 Let us consider the closed-loop system (10) composed of the plant (3), the controller (8) and the observer (7). If there exist symmetric and positive-definite matrices Q and S such that the following matrix inequalities hold for $\forall i,\ j\in\{1,2,\ldots,r\}$, then the equilibrium point of the whole system is asymptotically stable in the large.

i)

$$\begin{bmatrix}\overline{A}_{ii}Q+Q\overline{A}_{ii}^T+\overline{A}_{d1i}S^{-1}\overline{A}_{d1i}^T+\overline{A}_{d2i}S^{-1}\overline{A}_{d2i}^T & Q\\ Q & -\frac{1-\beta}{2}S^{-1}\end{bmatrix}<0 \tag{15}$$

ii)

$$\begin{bmatrix}2(\overline{A}_{ij}+\overline{A}_{ji})Q+2Q(\overline{A}_{ij}+\overline{A}_{ji})^T+(\overline{A}_{d1i}+\overline{A}_{d1j})S^{-1}(\overline{A}_{d1i}+\overline{A}_{d1j})^T+(\overline{A}_{d2i}+\overline{A}_{d2j})S^{-1}(\overline{A}_{d2i}+\overline{A}_{d2j})^T & 4Q\\ 4Q & -2(1-\beta)S^{-1}\end{bmatrix}<0,\quad i<j \tag{16}$$

proof : Let the quadratic Lyapunov-Krasovskii functional as

$$V(\xi(t))=\xi^T(t)P\xi(t)+\frac{1}{1-\beta}\left\{\int_{t-\tau}^{t}\xi^T(\sigma)S\xi(\sigma)d\sigma+\int_{t-\hat{\tau}}^{t}\xi^T(\sigma)S\xi(\sigma)d\sigma\right\} \tag{17}$$

Obviously, there exist σ_1 and σ_2 such that

$$\sigma_1\|\xi(t)\|^2\le V(\xi(t))\le\sigma_2\|\xi(t)\|^2 \tag{18}$$

The time derivative of V is

$$\begin{aligned}\dot{V}&=\xi^T(t)P\dot{\xi}(t)+\dot{\xi}^T(t)P\xi(t)\\&+\frac{1}{1-\beta}\{\xi^T(t)S\xi(t)-(1-\dot{\tau})\xi^T(t-\tau)S\xi(t-\tau)\\&+\xi^T(t)S\xi(t)-(1-\dot{\hat{\tau}})\xi^T(t-\hat{\tau})S\xi(t-\hat{\tau})\}\\&=\sum_{i=1}^{r}h_i^2(z(t))\{\xi^T(t)[\overline{A}_{ii}^TP+P\overline{A}_{ii}]\xi(t)\\&+2\xi^T(t)P\overline{A}_{d1i}\xi(t-\tau)+2\xi^T(t)P\overline{A}_{d2i}\xi(t-\hat{\tau})\}\\&+2\sum_{i<j\le r}h_i(z(t))h_j(z(t))\left\{\xi^T(t)[(\frac{\overline{A}_{ij}+\overline{A}_{ji}}{2})^TP\right.\\&+P(\frac{\overline{A}_{ij}+\overline{A}_{ji}}{2})]\xi(t)+2\xi^T(t)P(\frac{\overline{A}_{d1i}+\overline{A}_{d1j}}{2})\xi(t-\tau)\\&\left.+2\xi^T(t)P(\frac{\overline{A}_{d2i}+\overline{A}_{d2j}}{2})\xi(t-\hat{\tau})\right\}+\frac{1}{1-\beta}\{2\xi^T(t)S\xi(t)\\&-(1-\dot{\tau})\xi^T(t-\tau)S\xi(t-\tau)-(1-\dot{\hat{\tau}})\xi^T(t-\hat{\tau})S\xi(t-\hat{\tau})\}\end{aligned} \tag{19}$$

Using Lemma 1, the above equation can be upper-bounded as

$$\begin{aligned}\dot{V}\le&\sum_{i=1}^{r}h_i^2(t)\{\xi^T(t)[\overline{A}_{ii}^TP+P\overline{A}_{ii}]\xi(t)+\xi^T(t)P\overline{A}_{d1i}S^{-1}\overline{A}_{d1i}^TP\xi(t)\\&+\xi^T(t-\tau)S\xi(t-\tau)+\xi^T(t-\hat{\tau})S\xi(t-\hat{\tau})\\&+\xi^T(t)P\overline{A}_{d2i}S^{-1}\overline{A}_{d2i}^TP\xi(t)\}\\&+2\sum_{i<j\le r}h_i(t)h_j(t)\left\{\xi^T(t)[(\frac{\overline{A}_{ij}+\overline{A}_{ji}}{2})^TP+P(\frac{\overline{A}_{ij}+\overline{A}_{ji}}{2})]\xi(t)\right.\\&+\xi^T(t)P(\frac{\overline{A}_{d1i}+\overline{A}_{d1j}}{2})S^{-1}(\frac{\overline{A}_{d1i}+\overline{A}_{d1j}}{2})^TP\xi(t)\\&+\xi^T(t)P(\frac{\overline{A}_{d2i}+\overline{A}_{d2j}}{2})S^{-1}(\frac{\overline{A}_{d2i}+\overline{A}_{d2j}}{2})^TP\xi(t)\\&\left.+\xi^T(t-\tau)S\xi(t-\tau)+\xi^T(t-\hat{\tau})S\xi(t-\hat{\tau})\right\}\\&+\frac{1}{1-\beta}\{2\xi^T(t)S\xi(t)-(1-\dot{\tau})\xi^T(t-\tau)S\xi(t-\tau)\\&-(1-\dot{\hat{\tau}})\xi^T(t-\hat{\tau})S\xi(t-\hat{\tau})\}\end{aligned}$$

(20)

Since the derivative of the time-delay and that of the estimated time-delay are bounded as in (2), we get

$$\dot{V} \le \sum_{i=1}^{r} h_i^2(z(t))\Big\{\xi^T(t)[\bar{A}_{ii}^T P + P\bar{A}_{ii} + P\bar{A}_{d1i}S^{-1}\bar{A}_{d1i}^T P + P\bar{A}_{d2i}S^{-1}\bar{A}_{d2i}^T P + 2(1-\beta)^{-1}S]\xi(t)\Big\}$$
$$+2\sum_{i<j\le r} h_i(z(t))h_j(z(t))\Big\{\xi^T(t)[(\frac{\bar{A}_{ij}+\bar{A}_{ji}}{2})^T P + P(\frac{\bar{A}_{ij}+\bar{A}_{ji}}{2}) + P(\frac{\bar{A}_{d1i}+\bar{A}_{d1j}}{2})S^{-1}(\frac{\bar{A}_{d1i}+\bar{A}_{d1j}}{2})^T P$$
$$+ P(\frac{\bar{A}_{d2i}+\bar{A}_{d2j}}{2})S^{-1}(\frac{\bar{A}_{d2i}+\bar{A}_{d2j}}{2})^T P + \frac{2}{1-\beta}S]\xi(t)\Big\} \quad (21)$$

If there exist symmetric and positive-definite matrices P and S such that the following (22) and (23) holds for $\forall i, j \in \{1,2,\ldots,r\}$, then $\dot{V}$ is negative definite.

$$\bar{A}_{ii}^T P + P\bar{A}_{ii} + P\bar{A}_{d1i}S^{-1}\bar{A}_{d1i}^T P + P\bar{A}_{d2i}S^{-1}\bar{A}_{d2i}^T P + \frac{2}{1-\beta}S < 0 \quad (22)$$

$$(\frac{\bar{A}_{ij}+\bar{A}_{ji}}{2})^T P + P(\frac{\bar{A}_{ij}+\bar{A}_{ji}}{2}) + P(\frac{\bar{A}_{d1i}+\bar{A}_{d1j}}{2})S^{-1}(\frac{\bar{A}_{d1i}+\bar{A}_{d1j}}{2})^T P$$
$$+ P(\frac{\bar{A}_{d2i}+\bar{A}_{d2j}}{2})S^{-1}(\frac{\bar{A}_{d2i}+\bar{A}_{d2j}}{2})^T P + \frac{2}{1-\beta}S < 0, \quad i<j \quad (23)$$

From this fact and the Lyapunov-Krasovskii theorem, the equilibrium point of the whole closed-loop system is asymptotically stable in the large.

Letting $Q = P^{-1}$, we get the following matrix inequalities from (22) and (23)

$$\bar{A}_{ii}Q + Q\bar{A}_{ii}^T + \bar{A}_{d1i}S^{-1}\bar{A}_{d1i}^T + \bar{A}_{d2i}S^{-1}\bar{A}_{d2i}^T + \frac{2}{1-\beta}QSQ < 0 \quad (24)$$

$$\frac{(\bar{A}_{ij}+\bar{A}_{ji})}{2}Q + Q\frac{(\bar{A}_{ij}+\bar{A}_{ji})^T}{2} + \frac{(\bar{A}_{d1i}+\bar{A}_{d1j})}{2}S^{-1}\frac{(\bar{A}_{d1i}+\bar{A}_{d1j})^T}{2}$$
$$+\frac{(\bar{A}_{d2i}+\bar{A}_{d2j})}{2}S^{-1}\frac{(\bar{A}_{d2i}+\bar{A}_{d2j})^T}{2} + \frac{2}{1-\beta}QSQ < 0, \quad i<j \quad (25)$$

Notice that (24) and (25) is not an LMI problem. There is no efficient way to solve this problem. Several methods can be found in [1], [14]. In this paper, the pole-placement strategy together with LMI is used to solve (24) and (25). With the pole-placement method, the feedback gains K_i and the observer gains L_i are determined for each local plant modeling rule. Surely, the observer poles must be located far from the imaginary axis for the accurate observing performance. After the gains are determined, the matrix inequalities turn into LMI problem involving the only common matrix Q (therefore, P) and S. Finally, the conditions (24) and (25) that the system is asymptotically stable can be converted into (15) and (16) by Schur complement. ■

4. Example and simulation

In this section, an illustrative computer simulation examples are provided to demonstrate the validity of the proposed method. For the comparison purpose, the plant used in [2] is employed.

Plant Rule i:

If $x_2(t)$ is M_{i1}

Then $\dot{x}(t) = A_i x(t) + A_{di}x(t-\tau) + B_i u(t)$

$y(t) = C_i x(t)$

where

$$A_1 = \begin{bmatrix} -0.1125 & -0.02 \\ 1 & 0 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -0.1125 & -1.527 \\ 1 & 0 \end{bmatrix},$$

$$A_{d1} = \begin{bmatrix} -0.0125 & -0.005 \\ 0 & 0 \end{bmatrix}, \quad A_{d2} = \begin{bmatrix} -0.0125 & -0.23 \\ 0 & 0 \end{bmatrix},$$

$$B_1 = B_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad C_1 = C_2 = [0 \quad 1].$$

The membership functions of the fuzzy sets are defined as

$$M_{11}(x_2(t)) = \begin{cases} 1 - \dfrac{x_2^2(t)}{2.25} & \text{if } |x_2(t)| \le 1.5 \\ 0 & \text{otherwise} \end{cases}$$

$$M_{21}(x_2(2)) = 1 - M_{11}(x_2(t))$$

Notice that we increase the elements of the coefficient matrices of delayed states by ten times in order to amplify the effect of the time-delay. It is assume that the unknown time-varying delay is

$$\tau(t) = 2 + 0.5\cos(0.9t) \quad (26)$$

By the proposed design procedure, the controller gains of (8) and the observer gains of (7) are determined by the pole-placement method. The desired poles of the controller and the observer are chosen as (−4, −4.1) and (−8, −8.1), respectively.

According to the design procedures, we obtain the following gains and Lyapunov matrices

$K_1 = [7.9875 \quad 16.3800]$, $K_2 = [7.9875 \quad 14.8730]$,

$L_1 = [62.9814 \quad 15.9875]$, $L_2 = [61.4744 \quad 15.9875]$

and

$$Q=\begin{bmatrix} 3.5209 & -0.7199 & 1.1440 & 0.0779 \\ -0.7199 & 0.4921 & 0.1280 & 0.0183 \\ 1.1440 & 0.1280 & 1.3471 & 0.0829 \\ 0.0779 & 0.0183 & 0.0829 & 0.0156 \end{bmatrix}$$

$$S=\begin{bmatrix} 0.0905 & 0.2152 & -0.0527 & -0.6977 \\ 0.2152 & 2.1640 & -0.2539 & -3.5230 \\ -0.0527 & -0.2539 & 0.1121 & 0.8623 \\ -0.6977 & -3.5230 & 0.8623 & 22.1278 \end{bmatrix}.$$

The initial values of the states are set to (1, 1) for all cases.

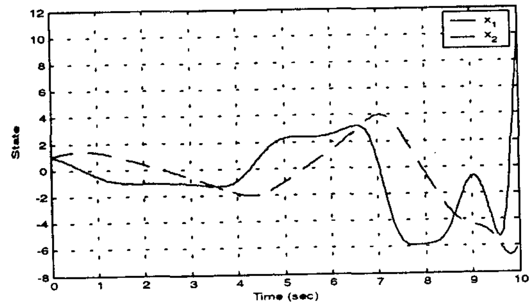

Fig. 1 unforced system

Fig.1 shows the response of the unforced system. Without the delayed states, the response of the unforced system is stable. However, the delayed states destabilize the plant as can be seen.

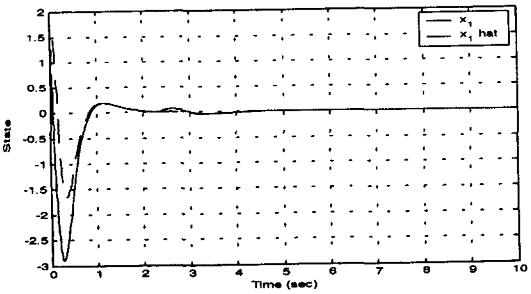

Fig. 2 x_1 and $\hat{x}_1$ ($\hat{\tau}=0$)

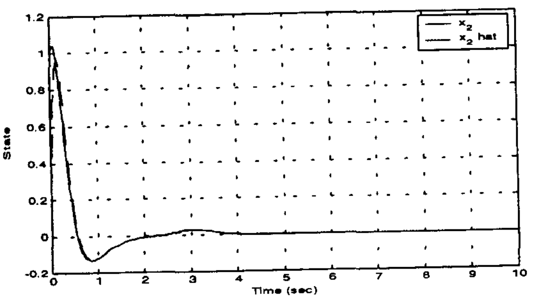

Fig. 3 x_2 and $\hat{x}_2$ ($\hat{\tau}=0$)

Fig. 2 and 3 show the response of the plant when the proposed controller and observer are applied. Assume that no information about the time-delay is available, and $\hat{\tau}$ is just set to zero. In spite of the effect of the time-delay at about 2 second, the proposed method show good performance at all.

5. Discussions

In this paper, new fuzzy controller and observer for the nonlinear systems with unknown time-delay have been proposed. By the Lyapunov-Krasovskii theorem, the sufficient condition for the equilibrium point of the closed-loop system being asymptotically stable is derived and solved in the formulation of LMI. It is shown that the design of controller and observer gains of fuzzy rules satisfying this condition can be converted into the LMI problem. In contrast with the previous method [1], the suggested method does not require the exact information on the time-delay which is usually not available.

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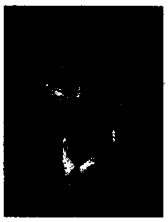

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