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H_∞ tracking control of coupled spatiotemporal chaos based on fuzzy models*

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Due to the interactions among coupled spatiotemporal subsystems, it is difficult to achieve the tracking control of the coupled spatiotemporal chaos. However, every subsystem of the coupled spatiotemporal chaos can be approximated by a set of fuzzy models, of which each represents a linearized model of the subsystem corresponding to the operating point of the controlled system. Based on these fuzzy models, an H_∞ fuzzy tracking control scheme is suggested, where a linear matrix inequalities (LMI) is employed to represent the feedback controller. The parameters of controller are obtained by using convex optimization techniques of LMI. The model reference tracking control of the coupled spatiotemporal chaos is achieved, and the stability of the system is also guaranteed. The tracking performance is tested by simulation as an example.

Keywords: fuzzy model, coupled spatiotemporal chaos, H_∞ fuzzy tracking control, linear matrix inequalities (LMI)

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1. Introduction

In the recent decade, because of large-scale nonlinear chaos systems rapidly emerging and studies of chaos control problems continuously deep-going, more and more people have become interested in more complicated chaotic control problems, and many different approaches have been suggested to stabilize these chaos systems.[1,2] However, there have been few studies concerning the stabilization control for coupled spatiotemporal chaos systems. In general, stabilization and tracking are two typical control problems; the former is more difficult than the latter. For this reason, there has existed no satisfactory tracking control scheme for the coupled spatiotemporal chaos systems so far. In the past few years, there has been a significant discovery that a nonlinear system can be well approximated by a Takagi–Sugeno (T–S) fuzzy linear model. Therefore, interest in fuzzy control for nonlinear chaos is rapidly growing based on the T–S model.[3−5] However there have existed very few studies concerning the fuzzy control for the coupled spatiotemporal chaos systems based on the T–S model. This paper aims to solve this kind of difficult problem in the following steps. First, the coupled spatiotemporal chaos is approximated by T–S fuzzy model. Second, a new H_∞ fuzzy tracking control scheme is designed. Finally, the problem about tracking control of output feedback is characterized by solving a linear matrix inequality (LMI). The convex optimization techniques of LMI are used here to achieve the parameters of controller in this paper.[6−18] In the scheme, the external disturbances can be got rid of and the robust gradual stability of the coupled spatiotemporal chaos systems can be also guaranteed. The tracking performance is tested by simulation as an example.

2. Fuzzy models of the coupled spatiotemporal chaos system

Consider a class of coupled spatiotemporal chaos system with n subsystems, which is composed of

$$\dot{\boldsymbol{x}}_i(t) = f_i(\boldsymbol{X}(t), \boldsymbol{u}_i(t)) + \boldsymbol{\omega}_i(t), \qquad (1)$$

where $i = 1, 2, \cdots, n$; $\boldsymbol{x}_i(t) \in R^{n_i}$, $\boldsymbol{u}_i(t) \in R^{m_i}$, and $\boldsymbol{\omega}_i(t)$ are the state vector, control vector, and external disturbance vector of the ith subsystem respectively,

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$N = \sum_{i=1}^{n} n_i$, $f_i(\cdot)$ is a smooth nonlinear function of the ith subsystem, and

$$\boldsymbol{X}(t) = (\boldsymbol{x}_1^{\mathrm{T}}(t), \boldsymbol{x}_2^{\mathrm{T}}(t), \cdots, \boldsymbol{x}_n^{\mathrm{T}}(t))^{\mathrm{T}} \in R^N.$$

It is difficult to design an overall controller for the coupled spatiotemporal chaos based on Eq.(1). However, the T–S fuzzy models can be employed to represent every subsystem of the coupled spatiotemporal chaos. These models are described by fuzzy If–Then rules in the following form:

R_p^k : If $z_1(t)$ is $F_{k1}, \ldots$, and $z_g(t)$ is F_{kg}, then

$$\dot{\boldsymbol{x}}_i(t) = \boldsymbol{A}_{ik}\boldsymbol{X}(t) + \boldsymbol{B}_{ik}\boldsymbol{u}_i(t) + \boldsymbol{\omega}_i(t), \tag{2}$$

where $k = 1, 2, \cdots, l$ are fuzzy rule numbers, $F_{k1}, \cdots, F_{kg}$ are fuzzy sets, $z_1(t), \cdots, z_g(t)$ are premise variables. $\boldsymbol{A}_{ik}$ and $\boldsymbol{B}_{ik}$ are coefficient matrices.

The overall fuzzy model of the subsystem can be rearranged in the following form:

$$\dot{\boldsymbol{x}}_i(t) = \sum_{k=1}^{l} h_k(z(t))[\boldsymbol{A}_{ik}\boldsymbol{X}(t) + \boldsymbol{B}_{ik}\boldsymbol{u}_i(t) + \boldsymbol{\omega}_i(t)], \tag{3}$$

where $\mu_k(z(t)) = \prod_{j=1}^{g} F_{kj}(z_j(t))$,

$$h_k(z(t)) = \mu_k(z(t)) / \sum_{k=1}^{l} \mu_k(z(t)).$$

Assume $\mu_k(z(t)) \geq 0$, therefore, $h_k(z(t)) \geq 0$ and $\sum_{k=1}^{l} h_k(z(t)) = 1$.

The overall coupled spatiotemporal chaos can be arranged in the following form:

$$\dot{\boldsymbol{X}}(t) = \sum_{k=1}^{l} h_k(z(t))[\boldsymbol{A}_k\boldsymbol{X}(t) + \boldsymbol{B}_k\boldsymbol{u}(t) + \boldsymbol{\omega}(t)],$$

where $\boldsymbol{A}_k = (\boldsymbol{A}_{1k}^{\mathrm{T}}, \cdots, \boldsymbol{A}_{nk}^{\mathrm{T}})^{\mathrm{T}}$,

$$\boldsymbol{B}_k = \mathrm{diag}(\boldsymbol{B}_{ik}), \quad \boldsymbol{u}(t) = [\boldsymbol{u}_1^{\mathrm{T}}(t), \cdots, \boldsymbol{u}_n^{\mathrm{T}}(t)]^{\mathrm{T}},$$

and

$$\boldsymbol{\omega}(t) = [\boldsymbol{\omega}_1^{\mathrm{T}}(t), \cdots, \boldsymbol{\omega}_n^{\mathrm{T}}(t)]^{\mathrm{T}}.$$

3. H_∞ tracking control for the coupled spatiotemporal chaos system

Consider a reference model for the chaos system in the form

$$\dot{\boldsymbol{X}}_r(t) = \boldsymbol{A}_r\boldsymbol{X}_r(t) + \boldsymbol{r}(t), \tag{4}$$

where $\boldsymbol{X}_r(t) \in R^N$ is the reference state, $\boldsymbol{A}_r$ is a specific asymptotically stable matrix, and $\boldsymbol{r}(t) \in R^N$ is the bounded reference input.

The fuzzy controller is designed to be in the following form:

R_p^k: If $z_1(t)$ is $F_{k1}, \ldots$, and $z_g(t)$ is F_{kg}, then

$$\boldsymbol{u}(t) = \boldsymbol{K}_k(\boldsymbol{X}(t) - \boldsymbol{X}_r(t)).$$

And the overall controller has the form

$$\boldsymbol{u}(t) = \sum_{k=1}^{l} h_k(z(t))[\boldsymbol{K}_k(\boldsymbol{X}(t) - \boldsymbol{X}_r(t))]. \tag{5}$$

Substituting Eq.(5) into Eq.(3) yields

$$\dot{\boldsymbol{X}}(t) = \sum_{k=1}^{l}\sum_{m=1}^{l} h_k(z(t))h_m(z(t))[(\boldsymbol{A}_k + \boldsymbol{B}_K\boldsymbol{K}_m) \times \boldsymbol{X}(t) - \boldsymbol{B}_K\boldsymbol{K}_m\boldsymbol{X}_r(t) + \boldsymbol{\omega}(t)]. \tag{6}$$

H_∞ tracking performance is related to the tracking error in the following form:

$$\frac{\int_0^{t_f} [(\boldsymbol{X}(t) - \boldsymbol{X}_r(t))^{\mathrm{T}}\boldsymbol{Q}(\boldsymbol{X}(t) - \boldsymbol{X}_r(t))]\mathrm{d}t}{\int_0^{t_f} \bar{\boldsymbol{\omega}}(t)^{\mathrm{T}}\bar{\boldsymbol{\omega}}(t)\mathrm{d}t} \leq \rho^2,$$

where $\bar{\boldsymbol{\omega}}(t) = [\boldsymbol{\omega}^{\mathrm{T}}(t), \boldsymbol{r}^{\mathrm{T}}(t)]^{\mathrm{T}}$, and $\boldsymbol{Q} = \boldsymbol{Q}^{\mathrm{T}} > 0$.

By use of Eqs.(6) and (4) the tracking system can be represented as follows:

$$\dot{\bar{\boldsymbol{X}}}(t) = \sum_{k=1}^{l}\sum_{m=1}^{l} h_k(z(t))h_m(z(t))\{\boldsymbol{A}_{km}\bar{\boldsymbol{X}}(t) + \bar{\boldsymbol{\omega}}(t)\}, \tag{7}$$

where $\bar{\boldsymbol{X}}(t) = [\boldsymbol{X}^{\mathrm{T}}(t), \boldsymbol{X}_r^{\mathrm{T}}(t)]^{\mathrm{T}}$,

$$\boldsymbol{A}_{km} = \begin{bmatrix} \boldsymbol{A}_k + \boldsymbol{B}_k\boldsymbol{K}_m & -\boldsymbol{B}_k\boldsymbol{K}_m \\ \boldsymbol{0} & \boldsymbol{A}_r \end{bmatrix}.$$

Taking into consideration of the initial condition, the H_∞ tracking performance can be rewritten as follows:

$$\int_0^{t_f} \bar{\boldsymbol{X}}^{\mathrm{T}}(t)\bar{\boldsymbol{Q}}\bar{\boldsymbol{X}}(t)\mathrm{d}t \leq \rho^2 \int_0^{t_f} \bar{\boldsymbol{\omega}}^{\mathrm{T}}(t)\bar{\boldsymbol{\omega}}(t)\mathrm{d}t + \bar{\boldsymbol{X}}^{\mathrm{T}}(0)\boldsymbol{P}\bar{\boldsymbol{X}}(0), \tag{8}$$

where $\bar{\boldsymbol{Q}} = \begin{bmatrix} \boldsymbol{Q} & -\boldsymbol{Q} \\ -\boldsymbol{Q} & \boldsymbol{Q} \end{bmatrix}$, and $\boldsymbol{P} = \boldsymbol{P}^{\mathrm{T}} > 0$.

Theorem In the chaotic tracking system (7), if $\boldsymbol{P} = \boldsymbol{P}^{\mathrm{T}} > 0$ and matrix inequality

$$\begin{bmatrix} \boldsymbol{A}_{km}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A}_{km} + \bar{\boldsymbol{Q}} & \boldsymbol{P} \\ \boldsymbol{P} & -\rho^2\boldsymbol{I} \end{bmatrix} \leq 0 \tag{9}$$

holds, then the H_∞ tracing performance in Eq.(8) of the whole chaos system is guaranteed for a prescribed ρ^2 when $\bar{\boldsymbol{\omega}}(t) \neq 0$.

Proof

$$\begin{aligned}
&\int_0^{t_f} [(\boldsymbol{X}(t) - \boldsymbol{X}_r(t))^{\mathrm{T}} \boldsymbol{Q} (\boldsymbol{X}(t) - \boldsymbol{X}_r(t))] \mathrm{d}t \\
=&\int_0^{t_f} \bar{\boldsymbol{X}}^{\mathrm{T}}(t) \bar{\boldsymbol{Q}} \bar{\boldsymbol{X}}(t) \mathrm{d}t \\
=&\bar{\boldsymbol{X}}^{\mathrm{T}}(0) \boldsymbol{P} \bar{\boldsymbol{X}}(0) - \bar{\boldsymbol{X}}^{\mathrm{T}}(t_f) \boldsymbol{P} \bar{\boldsymbol{X}}(t_f) \\
&+ \int_0^{t_f} \{\bar{\boldsymbol{X}}^{\mathrm{T}}(t) \bar{\boldsymbol{Q}} \bar{\boldsymbol{X}}(t) + \frac{d}{\mathrm{d}t} (\bar{\boldsymbol{X}}^{\mathrm{T}}(t) \boldsymbol{P} \bar{\boldsymbol{X}}(t))\} \mathrm{d}t \\
\leq&\bar{\boldsymbol{X}}^{\mathrm{T}}(0) \boldsymbol{P} \bar{\boldsymbol{X}}(0) + \int_0^{t_f} \{\bar{\boldsymbol{X}}^{\mathrm{T}}(t) \bar{\boldsymbol{Q}} \bar{\boldsymbol{X}}(t) \\
&+ \dot{\bar{\boldsymbol{X}}}^{\mathrm{T}}(t) \boldsymbol{P} \bar{\boldsymbol{X}}(t) + \bar{\boldsymbol{X}}^{\mathrm{T}}(t) \boldsymbol{P} \dot{\bar{\boldsymbol{X}}}(t)\} \mathrm{d}t \\
=&\bar{\boldsymbol{X}}^{\mathrm{T}}(0) \boldsymbol{P} \bar{\boldsymbol{X}}(0) + \int_0^{t_f} \{\bar{\boldsymbol{X}}^{\mathrm{T}}(t) \bar{\boldsymbol{Q}} \bar{\boldsymbol{X}}(t) \\
&+ \Big[\sum_{k=1}^{l} \sum_{m=1}^{l} h_k(z(t)) h_m(z(t)) \\
&\times (\boldsymbol{A}_{km} \bar{\boldsymbol{X}}(t) + \bar{\boldsymbol{\omega}}(t))\Big]^{\mathrm{T}} \boldsymbol{P} \bar{\boldsymbol{X}}(t) \\
&+ \bar{\boldsymbol{X}}^{\mathrm{T}}(t) \boldsymbol{P} \Big[\sum_{k=1}^{l} \sum_{m=1}^{l} h_k(z(t)) h_m(z(t)) \\
&\times (\boldsymbol{A}_{km} \bar{\boldsymbol{X}}(t) + \bar{\boldsymbol{\omega}}(t))\Big] \\
&- \rho^2 \bar{\boldsymbol{\omega}}^{\mathrm{T}}(t) \bar{\boldsymbol{\omega}}(t) + \rho^2 \bar{\boldsymbol{\omega}}^{\mathrm{T}}(t) \bar{\boldsymbol{\omega}}(t)\} \mathrm{d}t \\
=&\bar{\boldsymbol{X}}^{\mathrm{T}}(0) \boldsymbol{P} \bar{\boldsymbol{X}}(0) + \sum_{k=1}^{l} \sum_{m=1}^{l} h_k(z(t)) h_m(z(t)) \\
&\times \int_0^{t_f} \left\{ \begin{bmatrix} \bar{\boldsymbol{X}}^{\mathrm{T}}(t) \\ \bar{\boldsymbol{\omega}}^{\mathrm{T}}(t) \end{bmatrix}^{\mathrm{T}} \right. \\
&\begin{bmatrix} \boldsymbol{A}_{km}^{\mathrm{T}} \boldsymbol{P} + \boldsymbol{P} \boldsymbol{A}_{km} + \bar{\boldsymbol{Q}} & \boldsymbol{P} \\ \boldsymbol{P} & -\rho^2 \boldsymbol{I} \end{bmatrix} \\
&\left. \begin{bmatrix} \bar{\boldsymbol{X}}(t) \\ \bar{\boldsymbol{\omega}}(t) \end{bmatrix} + \rho^2 \bar{\boldsymbol{\omega}}^{\mathrm{T}}(t) \bar{\boldsymbol{\omega}}(t) \right\} \mathrm{d}t.
\end{aligned}$$

By use of the matrix inequality (9), the H_∞ tracing performance in Eq.(8) is achieved with a prescribed ρ^2.

To obtain better robust tracking performance, the robust tracking performance can be treated as a minimization problem: in $\min_P \rho^2$, choosing such a $\boldsymbol{P} = \boldsymbol{P}^{\mathrm{T}} > 0$ that the matrix inequality (9) holds true.

Let $\boldsymbol{W} = \begin{bmatrix} \bar{\boldsymbol{W}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}^{-1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{I} \end{bmatrix}$ and $\boldsymbol{P} = \boldsymbol{P}^{\mathrm{T}} > 0$, therefore $\boldsymbol{W} = \boldsymbol{W}^{\mathrm{T}} > 0$,

$$\boldsymbol{W} \begin{bmatrix} \boldsymbol{A}_{km}^{\mathrm{T}} \boldsymbol{P} + \boldsymbol{P} \boldsymbol{A}_{km} + \bar{\boldsymbol{Q}} & \boldsymbol{P} \\ \boldsymbol{P} & -\rho^2 \boldsymbol{I} \end{bmatrix} \boldsymbol{W} \leq 0 \quad \text{and}$$

$$\begin{bmatrix} \bar{\boldsymbol{W}} \boldsymbol{A}_{km}^{\mathrm{T}} + \boldsymbol{A}_{km} \bar{\boldsymbol{W}} + \bar{\boldsymbol{W}} \bar{\boldsymbol{Q}} \bar{\boldsymbol{W}} & \boldsymbol{I} \\ \boldsymbol{I} & -\rho^2 \boldsymbol{I} \end{bmatrix} \leq 0.$$

Consequently we obtain

$$\begin{bmatrix} \bar{\boldsymbol{W}} \boldsymbol{A}_{km}^{\mathrm{T}} + \boldsymbol{A}_{km} \bar{\boldsymbol{W}} & \bar{\boldsymbol{W}} \bar{\boldsymbol{Q}}^{\frac{1}{2}} & \boldsymbol{I} \\ (\bar{\boldsymbol{Q}}^{\frac{1}{2}})^{\mathrm{T}} \bar{\boldsymbol{W}} & -\boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{I} & \boldsymbol{0} & -\rho^2 \boldsymbol{I} \end{bmatrix} \leq 0.$$

For the convenience of design, assuming

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{P}_{11} \end{bmatrix} \quad \text{and} \quad \boldsymbol{P}_{11} = \boldsymbol{P}_{11}^{\mathrm{T}} > 0 \text{ gives}$$

$$\bar{\boldsymbol{W}} = \begin{bmatrix} \boldsymbol{W}_{11} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{W}_{11} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_{11}^{-1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{P}_{11}^{-1} \end{bmatrix}.$$

And let $\boldsymbol{Y}_m = \boldsymbol{K}_m \boldsymbol{W}_{11}$, $\boldsymbol{Y}_m$ and $\boldsymbol{W}_{11}$ can be achieved by MATLAB tool boxes of convex optimization techniques of LMI.[12,13] Thus parameters of controller $\boldsymbol{K}_m$ are obtained.

4. Simulation as an example

Describing a nonlinear propagating wave (a coupled Duffing system) as

$$\begin{aligned}
\frac{\partial^2 \phi}{\partial t^2} =& -\alpha \frac{\partial \phi}{\partial t} - \delta_1 \phi^3 + \delta_2 \phi + \delta \frac{\partial^2 \phi}{\partial \lambda^2} \\
&+ \eta \sin(\beta t) + d(t),
\end{aligned}$$

where δ_1, δ_2 are the spreading coefficients in infinite extended space, α is the medium damping coefficient, $\phi = \phi(\lambda, t)$ is the local position of medium, δ is a physical quantity related to the wave velocity, η and β are the gain and frequency of extending force respectively, and $d(t)$ is the extending disturbance. Assuming $\eta \sin(\beta t) + d(t) = \hat{d}(t)$, $\phi(\lambda, t) \to x_{i1}(t)$, the number of the subsystems being 2, and $\partial^2 \phi / \partial \lambda^2 = x_{22} - x_{12}$, the Duffing system can be represented by two coupled subsystems as follows:

$$\begin{cases}
\dot{x}_{i1} = x_{i2}, \\
\dot{x}_{i2} = -\alpha x_{i2} - \delta_1 x_{i1}^3 + \delta_2 x_{i1} \\
\qquad +\delta(x_{22} - x_{12}) + \hat{d}(t),
\end{cases}$$

where $\boldsymbol{x}_i = [x_{i1}, x_{i2}]^{\mathrm{T}} \in R^2$ is the state vector of the subsystem, δ is the coupling strength between the two subsystems. Let $\alpha = 1$, $\delta_1 = 100$, $\delta_2 = 10$, $\eta = 1$, $\beta = 3.5$, along with $\delta (0 < \delta < 10)$ strengthening, the

Duffing system will show the characteristics of nonlinear coupled spatiotemporal chaotic system. Here we let $\delta = 8$ and the reference input be

$$\boldsymbol{r}(t) = [-2.5, 2\cos 2\pi t, 5, (3 + 3\sin 3\pi t)]^{\mathrm{T}}.$$

The fuzzy model of the coupled Duffing system is achieved in four fuzzy rules, and using MATLAB tool boxes of convex optimization techniques of LMI gives

$$\boldsymbol{W}_{11} = \begin{bmatrix} 77.2367 & -9.3456 & 4.5986 & 2.4129 \\ -9.3826 & 79.6713 & -5.8237 & 3.3235 \\ 4.5466 & -5.8347 & 88.6624 & -9.6673 \\ 2.4129 & 3.3325 & -9.6223 & 44.7923 \end{bmatrix},$$

and the parameters $\boldsymbol{K}_m$ of the controller being

$$\boldsymbol{K}_1 = \begin{bmatrix} 17.3546 & -88.7925 & -67.4336 & 33.2290 \\ 26.7852 & -63.7728 & -55.4478 & 40.7798 \end{bmatrix},$$

$$\boldsymbol{K}_2 = \begin{bmatrix} 18.3865 & -85.1992 & -63.3586 & 35.8723 \\ 27.5283 & -67.7806 & -52.5673 & 44.7865 \end{bmatrix},$$

$$\boldsymbol{K}_3 = \begin{bmatrix} 19.7583 & -88.8971 & -66.3364 & 34.8972 \\ 26.4351 & -66.7345 & -54.7523 & 42.6568 \end{bmatrix},$$

$$\boldsymbol{K}_4 = \begin{bmatrix} 18.7842 & -86.4470 & -64.7541 & 34.8765 \\ 27.2359 & -65.4529 & -53.2245 & 43.0842 \end{bmatrix}.$$

The initial positions are chosen to be at [–2.5, 2.5, 5.0, 0], and the control is applied at t=1.6s. The tracking performance of the system is shown in Fig.1. From the simulation results, the performance of the suggested H_∞ fuzzy tracking control scheme is obviously efficacious.

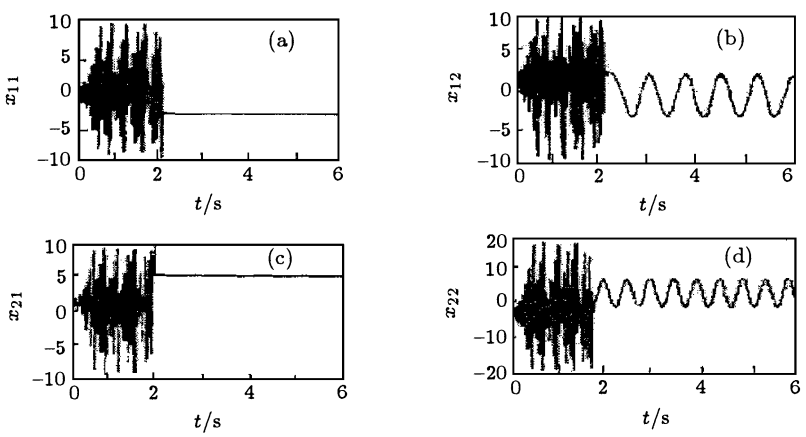


Fig.1. State trajectories of the chaotic system (a) x_{11} state trajectory, (b) x_{12} state trajectory, (c) x_{21} state trajectory, (d) x_{22} state trajectory.

5. Conclusion

In this paper, a kind of T–S fuzzy model is adopted to approximate the coupled spatiotemporal chaos. Based on these fuzzy models, a new H_∞ fuzzy tracking control scheme for the coupled spatiotemporal chaos is suggested and is formulated in the LMI format. A simple and systematic algorithm is developed based on LMI optimization techniques to solve the H_∞ fuzzy tracking control problem. A simulation example is given to test the well tracking performance of the scheme. By use of the scheme, the difficult problem for the tracking control to the coupled spatiotemporal chaos is well solved. The main contribution of this paper are the suggestions for a new H_∞ fuzzy tracking control design scheme and a new sufficient condition in the LMI format of the controller for the coupled spatiotemporal chaos as well as the solution to the robust stabilization problem for the coupled spatiotemporal chaos.

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