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基于LMI的不确定离散模糊时滞系统鲁棒控制

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摘 要: 利用T-S模糊模型, 讨论了一类具有状态时滞和控制输入时滞的不确定离散非线性系统鲁棒控制问题. 基于Lyapunov稳定性理论, 导出了系统采用线性矩阵不等式表示的时滞相关型鲁棒镇定充分条件, 并设计了相应的状态反馈模糊控制器. 仿真结果证明了所提出方法的有效性和可行性.

关键词: 离散时滞系统; T-S模糊模型; 时滞相关; 鲁棒控制; 线性矩阵不等式
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Robust Control for Uncertain Discrete Time-delay Fuzzy Systems via LMI Approach

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Abstract: By using T-S fuzzy model, the robust control problem for a class of uncertain discrete-time nonlinear systems with delays in state and control input is studied. Based on Lyapunov stability theory, sufficient conditions of delay-dependent robust stabilization for the nonlinear delay systems are obtained. Design method for the state feedback fuzzy controller is derived in terms of linear matrix inequality. A simulation example shows the practical applicability of the proposed method.

Key words: Discrete time-delay systems; T-S fuzzy model; Delay-dependent; Robust control; LMI

1 引 言

时滞和不确定性普遍存在于各种控制系统中. 近年来, 利用T-S模糊模型对不确定非线性时滞系统进行建模和控制, 已成为当前控制理论研究的一个热点[1~5]. 但是, 以往的研究主要针对连续时滞系统, 而且所获得的稳定性和稳定化条件是时滞无关的[1~3], 当系统时滞较小时具有较强的保守性. 与连续系统相比, 对离散T-S模糊时滞系统的研究较少, 而关于不确定离散模糊时滞系统的时滞相关型鲁棒稳定性分析与综合问题, 迄今尚未见有相关报道.

本文基于Lyapunov稳定性理论, 采用LMI方法, 研究了一类具有状态时滞和控制输入时滞的不确定离散T-S模糊系统的时滞相关鲁棒控制问题, 并给出了仿真实例.

2 问题描述

考虑一类不确定离散T-S模糊多时滞系统, 它的第i条模糊规则可描述为

R_i: If $z_1(k)$ is m_{i1} $\cdots$ and $z_r(k)$ is m_{ir},

Then

$$\begin{cases} x(k+1) = \\ (A_i + \Delta A_i(k))x(k) + \\ (A_{di} + \Delta A_{di}(k))x(k-d) + \\ (B_i + \Delta B_i(k))u(k) + B_{hi}u(k-h), \\ x(k) = \varphi(k),\ -\max\{d,h\} \leq k \leq 0, \\ \qquad i = 1 \sim q. \end{cases} \tag{1}$$

式中: q为模糊规则数; $z_1(k), \cdots, z_r(k)$为规则前件

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变量; m_{ij} 为模糊语言值; $x(k)\in R^{n}$, $u(k)\in R^{m}$ 分别为系统的状态和控制向量; A_i, A_{di}, B_i, B_{hi} 为适当维数的常数矩阵; $\Delta A_i(k)$, $\Delta A_{di}(k)$, $\Delta B_i(k)$ 表示系统的参数不确定性; $d, h>0$ 分别为系统的状态和控制滞后; $\phi(k)$ 为系统状态的初始向量 假设系统(1) 中的参数不确定性满足如下范数有界条件:

$$[\Delta A_i(k), \Delta A_{di}(k), \Delta B_i(k)] = DF(k)[E_i, E_{di}, E_{bi}]. \tag{2}$$

式中: D, E_i, E_{di}, E_{bi} 为已知的适当维数的常数矩阵; $F(k)$ 为具有 Lebesgue 可测元的时变不确定矩阵, 且满足 $F^{\mathrm{T}}(k)F(k)\le I, \forall k$.

系统(1) 的全局模糊模型表达式为

$$x(k+1) = \sum_{i=1}^{q}\lambda_i(z(k))[(A_i+\Delta A_i(k))x(k) + (A_{di}+\Delta A_{di}(k))x(k-d) + (B_i+\Delta B_i(k))u(k)+B_{ki}u(k-h)]. \tag{3}$$

式中

$$z(k) = [z_1(k), \cdots, z_r(k)],$$

$$\lambda_i(z(k)) = \omega(z(k))\Big/\sum_{i=1}^{q}\omega(z(k)),$$

$$\omega(z(k)) = \prod_{j=1}^{r}m_{ij}(z_j(k)).$$

$m_{ij}(z_j(k))$ 表示 $z_j(k)$ 对应于 m_{ij} 的隶属度, $\omega(z(k))$ 为第 i 条模糊规则的权值 这里

$$\omega(z(k))\ge 0,\ \sum_{i=1}^{q}\omega(z(k))>0,$$

$$\lambda_i(z(k))\ge 0,\ \sum_{i=1}^{q}\lambda_i(z(k))=1.$$

为便于描述, 以下将 $\lambda_i(z(k))$ 简记为 λ_i.

本文研究的问题是, 对于给定的离散模糊时滞系统(1), 设计并行分布补偿(PDC)[2] 模糊控制器

R_i: If $z_1(k)$ is m_{i1} $\cdots$ and $z_r(k)$ is m_{ir},

Then $u(k) = K_i x(k)$, $i = 1\sim q$.　　(4)

式中 K_i 为各模糊子系统的控制器增益, 使得由系统(1) 和控制器(4) 构成的闭环系统

$$x(k+1) = \sum_{i=1}^{q}\sum_{j=1}^{q}\lambda_i\lambda_j[(G_{ij}+\Delta G_{ij})x(k) + (G_{dij}+\Delta G_{dij})x(k-d)+G_{hij}x(k-h)] \tag{5}$$

是时滞相关鲁棒镇定的 这里

$$G_{ij} = (A_{ij}+A_{ji})/2,\ \Delta G_{ij} = DF(k)E_{ij},$$

$$A_{ij} = A_i + B_iK_j,\ G_{dij} = (A_{di}+A_{dj})/2,$$

$$G_{hij} = (B_{hi}K_j + B_{hj}K_i)/2,$$

$$\Delta G_{dij} = DF(k)F_{dij},\ E_{dij} = (E_{di}+E_{dj})/2,$$

$$E_{ij} = [(E_i+E_j)+(E_{bi}K_j+E_{bj}K_i)]/2$$

引理 1[6,7]　对于具有适当维数的矩阵 X, Y 和正定矩阵 R, 总有 $X^{\mathrm{T}}Y + Y^{\mathrm{T}}X\le X^{\mathrm{T}}RX + Y^{\mathrm{T}}R^{-1}Y$.

引理 2[8]　给定适当维数的矩阵 $Q = Q^{\mathrm{T}}$, $R = R^{\mathrm{T}}>0$, D 和 E, 则对于所有满足 $F^{\mathrm{T}}F\le R$ 的 F 有 $Q + DFE + E^{\mathrm{T}}F^{\mathrm{T}}D^{\mathrm{T}}<0$ 成立, 当且仅当存在 $\epsilon>0$, 使得 $Q + \epsilon^{-1}DD^{\mathrm{T}} + \epsilon E^{\mathrm{T}}RE<0$.

3　主要结果

记 $y(k) = x(k+1) - x(k)$, 则由式(5) 有

$$E(\tilde{M}) = \sum_{i=1}^{q}\sum_{j=1}^{q}\lambda_i\lambda_j\{2\eta\tilde{M}\cdot[y(k) - (G_{ij}+\Delta G_{ij}-I)x(k) - (G_{dij}+\Delta G_{dij})x(k-d) - G_{hij}x(k-h)]\} = 0, \tag{6}$$

$$H(\tilde{N}) = 2\eta\tilde{N}\cdot\Big[2x(k) - x(k-d) - x(k-h) - \sum_{l=k-d}^{k-1}y(l) - \sum_{l=k-h}^{k-1}y(l)\Big] = 0. \tag{7}$$

式中

$$\eta = [x^{\mathrm{T}}(k), x^{\mathrm{T}}(k-d), x^{\mathrm{T}}(k-h), y^{\mathrm{T}}(k)],$$

$$\tilde{M}^{\mathrm{T}} = [M^{\mathrm{T}}, \rho_1M^{\mathrm{T}}, \rho_2M^{\mathrm{T}}, \rho_3M^{\mathrm{T}}],$$

$$\tilde{N}^{\mathrm{T}} = [N_1^{\mathrm{T}}, N_2^{\mathrm{T}}, N_3^{\mathrm{T}}, N_4^{\mathrm{T}}].$$

这里: ρ_1, ρ_2, ρ_3 为给定的常数; $M, N_i(i=1\sim 4)$ 为具有适当维数的待定权矩阵.

定理 1　对于不确定离散模糊时滞系统(1), 给定常数 $d, h>0$, ρ_1, ρ_2, ρ_3, 如果存在具有适当维数的矩阵 $\hat{P}>0, \hat{Q}_1>0, \hat{Q}_2>0, \hat{S}_1>0, \hat{S}_2>0$ 和矩阵 $\hat{N}_1, \hat{N}_2, \hat{N}_3, \hat{N}_4, Y_i$, $i=1\sim q$, 以及非奇异矩阵 X, 使得如下一组LMI成立:

$$\begin{bmatrix}
\hat{\Phi}_{11} & \hat{\Phi}_{12} & \hat{\Phi}_{13} & \hat{\Phi}_{14} & d\hat{N}_1 & h\hat{N}_1 & D & \hat{E}_{ij}^{\mathrm{T}} \\
* & \hat{\Phi}_{22} & \hat{\Phi}_{23} & \hat{\Phi}_{24} & d\hat{N}_2 & h\hat{N}_2 & \rho_1D & \hat{E}_{dij}^{\mathrm{T}} \\
* & * & \hat{\Phi}_{33} & \hat{\Phi}_{34} & d\hat{N}_3 & h\hat{N}_3 & \rho_2D & 0 \\
* & * & * & \hat{\Phi}_{44} & d\hat{N}_4 & h\hat{N}_4 & \rho_3D & 0 \\
* & * & * & * & -d\hat{S}_1 & 0 & 0 & 0 \\
* & * & * & * & * & -h\hat{S}_2 & 0 & 0 \\
* & * & * & * & * & * & -I & 0 \\
* & * & * & * & * & * & * & -I
\end{bmatrix} < 0,$$

$$1\le i\le j\le q. \tag{8}$$

式中: * 表示矩阵对称位置元素的转置, 而

$$\hat{\Phi}_{11} = 2(\hat{N}_1 + \hat{N}_1^{\mathrm{T}}) - (\hat{G}_{ij} - X^{\mathrm{T}}) - (\hat{G}_{ij}^{\mathrm{T}} - X) + \hat{Q}_1 + \hat{Q}_2,$$

$$\hat{\Phi}_{12} = -\hat{N}_1 + 2\hat{N}_2^{\mathrm{T}} - \hat{G}_{dij} - \rho_1(\hat{G}_{ij}^{\mathrm{T}} - X),$$

$$\hat{\Phi}_{13} = -\hat{N}_1 + 2\hat{N}_3^{\mathrm{T}} - \hat{G}_{hij} - \rho_2(\hat{G}_{ij}^{\mathrm{T}} - X),$$

$$\hat{\Phi}_{14} = \hat{P} + X^{\mathrm{T}} + 2\hat{N}_4^{\mathrm{T}} - \rho_3(\hat{G}_{ij}^{\mathrm{T}} - X),$$

$$\hat{\Phi}_{22} = -\hat{Q}_1 - \hat{N}_2 - \hat{N}_2^{\mathrm{T}} - \rho_1\hat{G}_{dij} - \rho_1\hat{G}_{dij}^{\mathrm{T}},$$

$$\hat\Phi_{23} = -\hat N_2 - \hat N_3^{\mathrm T} - \rho_1 \hat G_{hij} - \rho_2 \hat G_{dij}^{\mathrm T},$$
$$\hat\Phi_{24} = -\hat N_4^{\mathrm T} + \rho_1 X^{\mathrm T} - \rho_3 \hat G_{dij}^{\mathrm T},$$
$$\hat\Phi_{33} = -\hat Q_2 - \hat N_3 - \hat N_3^{\mathrm T} - \rho_2 \hat G_{hij} - \rho_2 \hat G_{hij}^{\mathrm T},$$
$$\hat\Phi_{34} = -\hat N_4^{\mathrm T} + \rho_2 X^{\mathrm T} - \rho_3 \hat G_{hij}^{\mathrm T},$$
$$\hat\Phi_{44} = \hat P + d\hat S_1 + h\hat S_2 + \rho_3 X^{\mathrm T} + \rho_3 X,$$
$$\hat G_{ij} = (A_i X^{\mathrm T} + B_i Y_j + A_j X^{\mathrm T} + B_j Y_i)/2,$$
$$\hat G_{dij} = (A_{di} X^{\mathrm T} + A_{dj} X^{\mathrm T})/2,$$
$$\hat G_{hij} = (B_{hi} Y_j + B_{hj} Y_i)/2,$$
$$\hat E_{dij}^{\mathrm T} = (X E_{di}^{\mathrm T} + X E_{dj}^{\mathrm T})/2,$$
$$\hat E_{ij}^{\mathrm T} = [(X E_i^{\mathrm T} + X E_j^{\mathrm T}) + (Y_j^{\mathrm T} E_{bi}^{\mathrm T} + Y_i^{\mathrm T} E_{bj}^{\mathrm T})]/2$$

则对于任意允许的参数不确定性(2), 闭环模糊系统(5)是鲁棒渐近稳定的, 且相应的时滞相关型模糊控制器 $u(k) = \sum_{i=1}^{q} \lambda_i Y_i X^{-\mathrm T} x(k)$.

证明 选取Lyapunov函数

$$\begin{cases} V(k) = V_1(k) + V_2(k) + V_3(k), \\ V_1(k) = x^{\mathrm T}(k) P x(k), \\ V_2(k) = \\ \sum_{l=k-d}^{k-1} x^{\mathrm T}(l) Q_1 x(l) + \sum_{l=k-h}^{k-1} x^{\mathrm T}(l) Q_2 x(l), \\ V_3(k) = \sum_{\theta=-d+1}^{0} \sum_{l=k+\theta-1}^{k-1} y^{\mathrm T}(l) S_1 y(l) + \\ \qquad \sum_{\theta=-h+1}^{0} \sum_{l=k+\theta-1}^{k-1} y^{\mathrm T}(l) S_2 y(l). \end{cases}$$

其中: P, Q_1, Q_2, S_1, S_2 为待定的对称正定权矩阵. 定义 $\Delta V = V(k+1) - V(k)$, 则由闭环系统(5), 并结合式(6)和(7), 有

$$\begin{aligned} &\Delta V = \\ &\Big[x^{\mathrm T}(k)(Q_1 + Q_2)x(k) - \\ &x^{\mathrm T}(k-d) Q_1 x(k-d) - \\ &x^{\mathrm T}(k-h) Q_2 x(k-h) + \\ &y^{\mathrm T}(k)(P + dS_1 + hS_2) y(k) + \\ &2x^{\mathrm T}(k) P y(k) - \sum_{l=k-d}^{k-1} y^{\mathrm T}(l) S_1 y(l) - \\ &\sum_{l=k-h}^{k-1} y^{\mathrm T}(l) S_2 y(l)\Big] + E(\tilde M) + H(\tilde N). \end{aligned}$$

根据引理1, 有

$$\begin{aligned} &2\eta^{\mathrm T} \tilde N \cdot \Big(-\sum_{l=k-d}^{k-1} y(l)\Big) \le \\ &d\eta^{\mathrm T} \tilde N S_1^{-1} \tilde N^{\mathrm T} \eta + \sum_{l=k-d}^{k-1} y^{\mathrm T}(l) S_1 y(l), \\ &2\eta^{\mathrm T} \tilde N \cdot \Big(-\sum_{l=k-h}^{k-1} y(l)\Big) \le \\ &h\eta^{\mathrm T} \tilde N S_2^{-1} \tilde N^{\mathrm T} \eta + \sum_{l=k-h}^{k-1} y^{\mathrm T}(l) S_2 y(l). \end{aligned}$$

令: $M = X^{-1}$, $P = X^{-1}\hat P X^{-\mathrm T}$, $Q_1 = X^{-1}\hat Q_1 X^{-\mathrm T}$, $Q_2 = X^{-1}\hat Q_2 X^{-\mathrm T}$, $S_1 = X^{-1}\hat S_1 X^{-\mathrm T}$, $S_2 = X^{-1}\hat S_2 X^{-\mathrm T}$, $K_i = Y_i X^{-\mathrm T}(i = 1\sim q)$, $N_l = X^{-1}\hat N_l X^{-\mathrm T}(l = 1\sim 4)$, $\Gamma = \mathrm{diag}\{M, M, M, M\}$. 经整理可得

$$\Delta V \le \sum_{i=1}^{q}\sum_{j=1}^{q} \lambda_i \lambda_j \eta^{\mathrm T} \Xi_{ij} \eta =$$
$$\eta^{\mathrm T}\Big(\sum_{i=1}^{q} \lambda_i^2 \Xi_{ii} + 2\sum_{i=1}^{q}\sum_{i<j}^{q} \lambda_i \lambda_j \Xi_{ij}\Big)\eta$$

式中

$$\Xi_{ij} = \Gamma \begin{bmatrix} \hat\Phi_{11} & \hat\Phi_{12} & \hat\Phi_{13} & \hat\Phi_{14} \\ * & \hat\Phi_{22} & \hat\Phi_{23} & \hat\Phi_{24} \\ * & * & \hat\Phi_{33} & \hat\Phi_{34} \\ * & * & * & \hat\Phi_{44} \end{bmatrix} \Gamma^{\mathrm T} +$$
$$d\tilde N S_1^{-1} \tilde N^{\mathrm T} + h\tilde N S_2^{-1} \tilde N^{\mathrm T} -$$
$$\tilde M D F(k) \tilde E - \tilde E^{\mathrm T} F^{\mathrm T}(k) D^{\mathrm T} \tilde M^{\mathrm T},$$
$$\tilde E = [E_{ij} \quad E_{dij} \quad 0 \quad 0].$$

由引理2和系统的参数不确定性定义(2)可知

$$-\tilde M D F(k) \tilde E - \tilde E^{\mathrm T} F^{\mathrm T}(k) D^{\mathrm T} \tilde M^{\mathrm T} \le$$
$$\tilde M D D^{\mathrm T} \tilde M^{\mathrm T} + \tilde E^{\mathrm T} \tilde E.$$

根据Schur补引理[9], 不难证明LMI(8)等价于不等式 $\Xi_{ij} < 0$, $1 \le i \le j \le q$. 由此可导出 $\Delta V < 0$, 闭环模糊系统(5)在Lyapunov意义下全局渐近稳定. □

注1 从定理1可知, 利用权矩阵 M 和 $N_i(i = 1\sim 4)$ 表示系统(1)状态方程各项间的相互关系, 可以很好地分离系统矩阵与Lyapunov矩阵 P, 从而有效地解决了系统(1)基于LMI的时滞相关鲁棒镇定问题. 另外, 在定理1中, 系数 ρ_1, ρ_2, ρ_3 的合理选择可以提高LMI(8)的可解性; 合适的 ρ_1, ρ_2, ρ_3 一般根据经验预先给出, 也可通过多次试验获得.

4 仿真实例

考虑多时滞不确定离散非线性系统

$$\begin{cases} x_1(k+1) = \\ (1 + 0.02\sin(0.01k))x_1(k) + \\ 0.06x_1(k)x_1(k-5) + \\ (-0.1 + 0.05\sin(0.01k))x_2(k-5) + \\ u(k) + 0.1u(k-2), \\ x_2(k+1) = \\ -x_1^2(k) + (-0.4 + 0.03\cos(0.01k))x_2(k) + \\ (0.45 + 0.02\cos(0.01k))x_2(k-5) + \\ (1 + 0.015\cos(0.01k))u(k) + 0.25u(k-2). \end{cases}$$

设 $x_1(k)$ 可测, 且 $x_1(k) \in [-1, 1]$. 当 $u(k) = 0, \forall k$ 时, (0, 0) 是该系统的一个稳定平衡点. 因此, 可将上述非线性系统用 T-S 模糊模型表示为

R_1: If $x_1(k)$ is about 1,
Then
$x(k+1) = (A_1 + \Delta A_1)x(k) + (A_{d1} + \Delta A_{d1})x(k-d) + (B_1 + \Delta B_1)u(k) + B_{h1}u(k-h)$,

R_2: If $x_1(k)$ is about 0,
Then
$x(k+1) = (A_2 + \Delta A_2)x(k) + (A_{d2} + \Delta A_{d2})x(k-d) + (B_2 + \Delta B_2)u(k) + B_{h2}u(k-h)$,

R_3: If $x_1(k)$ is about -1,
Then
$x(k+1) = (A_3 + \Delta A_3)x(k) + (A_{d3} + \Delta A_{d3})x(k-d) + (B_3 + \Delta B_3)u(k) + B_{h3}u(k-h)$.

式中

$$x(k) = [x_1^{\mathrm{T}}(k), x_2^{\mathrm{T}}(k)]^{\mathrm{T}},$$

$$A_1 = \begin{bmatrix} 1 & 0 \\ -1 & -0.4 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} 1 & 0 \\ 0 & -0.4 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} 1 & 0 \\ 1 & -0.4 \end{bmatrix},$$

$$A_{d1} = \begin{bmatrix} 0.06 & -0.1 \\ 0 & 0.45 \end{bmatrix},$$

$$A_{d2} = \begin{bmatrix} 0 & -0.1 \\ 0 & 0.45 \end{bmatrix},$$

$$A_{d3} = \begin{bmatrix} -0.06 & -0.1 \\ 0 & 0.45 \end{bmatrix},$$

$$B_1 = B_2 = B_3 = \begin{bmatrix} 1 \\ 1 \end{bmatrix},$$

$$B_{h1} = B_{h2} = B_{h3} = \begin{bmatrix} 0.1 \\ 0.25 \end{bmatrix},$$

$$D = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix},$$

$$F(k) = \begin{bmatrix} \sin(0.01k) & 0 \\ 0 & \cos(0.01k) \end{bmatrix},$$

$$E_1 = E_2 = E_3 = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.3 \end{bmatrix},$$

$$E_{d1} = E_{d2} = E_{d3} = \begin{bmatrix} 0 & 0.5 \\ 0 & 0.2 \end{bmatrix},$$

$$E_{b1} = E_{b2} = E_{b3} = \begin{bmatrix} 0 \\ 0.15 \end{bmatrix},$$

$$d = 5, h = 2.$$

该模糊模型的隶属度函数如图 1 所示.

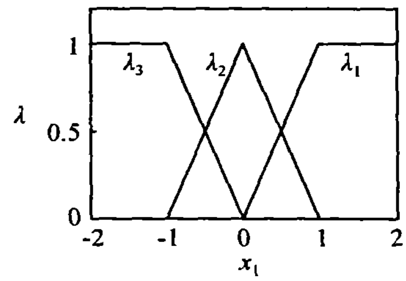

图 1　模糊模型的隶属度函数

取 $\rho_1 = \rho_2 = 0.1, \rho_3 = 1.5$, 根据定理 2 获得模糊控制器(4) 的增益矩阵

$$K_1 = [-0.6801 \quad 0.2069],$$

$$K_2 = [-0.8112 \quad 0.2247],$$

$$K_3 = [-1.224 \quad 0.239].$$

设系统初始状态为 $x(k) = 0, \forall -5 \leq k < 0$, $x(0) = [0.5 \quad -1]^{\mathrm{T}}$. 当系统采样周期取 $T_0 = 0.02$ s, 控制输入 $u(k) = 0$ 时, 开环系统的状态响应如图 2 所示, 显然系统是不稳定的. 而闭环控制系统则能快速地镇定于稳定平衡点(0, 0), 如图 3 所示.

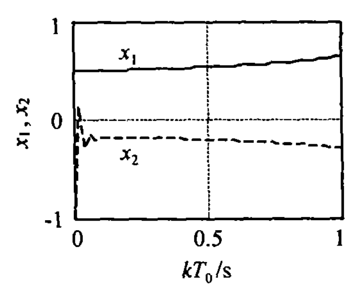

图 2　u = 0 时开环系统的状态响应曲线

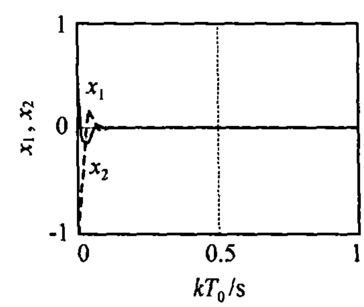

图 3　闭环控制系统的状态响应曲线

5　结　论

本文针对一类具有参数不确定性的离散 T-S 模糊时滞系统, 提出了一种新型鲁棒稳定性分析与综合方法. 状态反馈模糊控制器参数设计方法以线性矩阵不等式的形式给出, 求解十分方便. 如何进一步减少控制器设计的保守性和复杂性, 同时考虑系统在状态不可测情况下的控制问题尚有待进一步研究.

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扰动是有界的, 满足匹配条件. 设计了非线性无记忆控制器和改进的带有 σ-修正项自适应律, 保证了闭环组合系统的解一致有界, 且系统状态是一致渐近稳定的. 仿真结果表明, 该设计方案是可行而有效的, 它可以解决实际系统中存在的含有不确定性和外部扰动的不确定时滞组合系统的分散控制问题.

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