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一类非线性时滞互联系统模糊分散输出反馈控制

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摘 要: 对于一类状态不可测非线性互联时滞系统,给出一种基于观测器的模糊分散输出反馈控制方法. 首先采用模糊 T-S 模型对非线性互联时滞系统进行模糊建模,在此基础上给出了模糊分散观测器和基于观测器的模糊分散输出控制器的设计. 应用李亚普诺夫函数法和线性矩阵不等式方法给出了模糊分散控制系统稳定的充分条件. 仿真结果进一步验证了所提出的模糊分散控制方法的有效性.

关键词: 非线性时滞互联系统; 模糊分散控制; 线性矩阵不等式; 稳定性分析
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Fuzzy decentralized output feedback control for a class of nonlinear interconnected systems with time-delay

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Abstract: An observer based on fuzzy decentralized control method for a class of nonlinear interconnected systems with time-delay is proposed. An equivalent T-S fuzzy model is applied to the fuzzy modeling of the nonlinear interconnected system with time-delay , then the fuzzy decentralized observer and fuzzy decentralized controller are designed. The sufficient conditions for the stability of the fuzzy decentralized system with time-delay are proposed by using Lyapunov function combined with linear matrix inequalities (LMIs). Finally, the simulation results show the effectiveness of the proposed methods.

Key words: Nonlinear interconnected systems with time-delay; Decentralized fuzzy control; Linear matrix inequalities; Stability analysis

1 引 言

近年来,基于模糊 T-S 模型的非线性系统的控制器设计及其理论研究取得了很大进展[1,2]. 例如模糊控制系统的状态反馈和基于观测器的输出反馈设计[3],模糊控制系统的稳定性和鲁棒性分析[4]等,初步建立了与现代控制理论相平行的设计和理论体系. 由于工业过程的日趋复杂化和大型化,互联系统理论已成为控制界的研究热点之一. 因此,利用模糊 T-S 模型和模糊控制来研究非线性互联系统的控制问题具有重要意义.

文献[5]提出了一类模糊互联系统的状态反馈和基于观测器的模糊分散控制方法;文献[6]针对一类模糊时滞互联系统提出了模糊分散控制方法. 然而,以上方法要么是针对模糊非时滞互联系统,要么要求模糊互联系统的状态是完全可测的,这便限制了它们的应用范围.

本文针对一类状态不完全可测的非线性互联时滞系统,利用模糊 T-S 模型对其进行建模;然后提出一种模糊分散观测器和基于观测器的模糊分散输出反馈控制器的设计方法;最后结合李亚普诺夫函数方法和线性矩阵不等式理论,证明了模糊分散控制系统的稳定性.

2 模糊分散观测器和输出反馈控制器的设计

考虑由 N 个子系统 $F_k(k = 1,2,\cdots,N)$ 组成的一类连续非线性时滞互联系统 F,其第 k 个子系统由下述方程表示:

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$$F_k:\begin{cases}\dot{x}_k(t)=f_{1k}(x_k(t))+f_{2k}(x_k(t-h_k))+\\ \qquad g_k(x_k(t))u_k(t)+\sum_{h=1,h\neq k}^{N}f_{hk}x_h(t),\\ y_k=h_k(x_k(t)),x_k(t)=\phi_k(t).\end{cases}\tag{1}$$

其中:$x_k(t)\in R^{n_k}$ 为第 k 个非线性子系统的状态向量;$u_k(t)\in R^{m_k}$ 为第 k 个非线性子系统的控制向量;$f_{1k}(x_k(t))$,$f_{2k}(x_k(t-h_k))$,$g_k(x_k(t))$,$f_{hk}(x_h(t))$,$h_k(x_h(t))$ 均为非线性函数;$h_k>0$ 为第 k 个非线性子系统的时滞常数;$f_{hk}(x_h(t))$ 为第 h 个非线性子系统与第 k 个非线性子系统的关联项;$t\in[-\tau,0]$;$0\le h_k\le\tau$;$k=1,2,\cdots,N$.

采用 Takagi 和 Sugeno 提出的模糊模型,在合适的工作点对式(1)进行局部线性化.线性化后的模型由模糊 If-Then 规则来描述,其第 $i(i=1,2,\cdots,r_k)$ 条模糊规则如下:

R_i: If $z_1(t)$ is F_{i1k}, $z_2(t)$ is F_{i2k}, $\cdots$, $z_l(t)$ is F_{ilk}, Then

$$\begin{cases}\dot{x}_k(t)=A_{1ik}x_k(t)+A_{2ik}x_k(t-h_k)+\\ \qquad B_{ik}u_k(t)+\sum_{h=1,h\neq k}^{N}R_{ihk}x_h(t),\\ y_k(t)=C_{1ik}x_k(t)+C_{2ik}x_k(t-h_k).\end{cases}\tag{2}$$

其中:$F_{igk}(g=1,2,\cdots,l)$ 为模糊集合;$z(t)=[z_1(t),z_2(t),\cdots,z_l(t)]^{\mathrm T}$ 是可测的系统变量,即前件变量;A_{1ik},C_{1ik},A_{2ik},C_{2ik} 是局部可观测的.

采用单点模糊化、乘积推理和平均加权反模糊化,则第 k 个子模糊系统的模型为

$$\begin{cases}\dot{x}_k(t)=\\ \sum_{i=1}^{r_k}\mu_{ik}\Big[A_{1ik}x_k(t)+A_{2ik}x_k(t-h_k)+\\ B_{ik}u_k(t)+\sum_{h=1,h\neq k}^{N}R_{ihk}x_h(t)\Big],\\ y_k(t)=\sum_{i=1}^{r_k}\mu_{ik}[C_{1ik}x_k(t)+C_{2ik}x_k(t-h_k)].\end{cases}\tag{3}$$

设计第 k 个子模糊系统的观测器如下:

R_i: If $z_1(t)$ is F_{i1k}, $z_2(t)$ is F_{i2k}, $\cdots$, $z_l(t)$ is F_{ilk}, Then

$$\begin{cases}\dot{\hat{x}}_k(t)=\\ A_{1ik}\hat{x}_k(t)+A_{2ik}\hat{x}_k(t-h_k)+B_{ik}u_k(t)+\\ \sum_{h=1,h\neq k}^{N}R_{ihk}\hat{x}_h(t)+L_{ik}(y_k(t)-\hat{y}_k(t)),\\ \hat{y}_k(t)=C_{1ik}\hat{x}_k(t)+C_{2ik}\hat{x}_k(t-h_k).\end{cases}\tag{4}$$

则第 k 个子模糊系统的观测器为

$$\begin{cases}\dot{\hat{x}}_k(t)=\\ \sum_{i=1}^{r_k}\mu_{ik}\Big[A_{1ik}\hat{x}_k(t)+A_{2ik}\hat{x}_k(t)+B_{ik}u_k(t)+\\ \sum_{h=1,h\neq k}^{N}R_{ikh}\hat{x}_h(t)+L_{ik}(y_k(t)-\hat{y}_k(t))\Big],\\ \hat{y}_k(t)=\sum_{i=1}^{r_k}\mu_{ik}[C_{1ik}\hat{x}_k(t)+C_{2ik}\hat{x}_k(t-h_k)].\end{cases}\tag{5}$$

基于观测器的模糊分散输出反馈控制器为

$$u_k(t)=-\sum_{i=1}^{r_k}\mu_{ik}K_{ik}\hat{x}_k(t).\tag{6}$$

本文的控制目标是:利用线性矩阵不等式理论,分别给出反馈增益矩阵 K_i 和观测增益矩阵 L_i 的设计,使得模糊分散控制系统在李亚普诺夫函数意义下渐近稳定.

3　模糊分散控制系统的稳定性分析[7-10]

定义观测器误差 $e_k(t)=x_k(t)-\hat{x}_k(t)$,由式(3)～(6),得第 k 个闭环模糊子系统的状态和误差方程

$$\dot{x}_k(t)=\sum_{i=1}^{r_k}\sum_{j=1}^{r_k}\mu_{ik}\mu_{jk}\Big[(A_{1ik}-B_{ik}K_{jk})x_k(t)+A_{2ik}x_k(t-h_k)+B_{ik}K_{jk}e_k(t)+\sum_{h=1,h\neq k}^{N}R_{ihk}x_h(t)\Big],\tag{7}$$

$$\dot{e}_k(t)=\sum_{i=1}^{r_k}\sum_{j=1}^{r_k}\mu_{ik}\mu_{jk}\Big[(A_{1ik}-L_{ik}C_{1jk})e_k(t)+(A_{2ik}-L_{ik}C_{2jk})e_k(t-h_k)+\sum_{h=1,h\neq k}^{N}R_{ihk}e_h(t)\Big].\tag{8}$$

定义第 k 个辅助闭环时滞系统

$$\dot{\tilde{x}}_k(t)=\sum_{i=1}^{r_k}\sum_{j=1}^{r_k}\mu_{ik}\mu_{jk}\Big[G_{1ijk}\tilde{x}_k(t)+G_{2ijk}\tilde{x}_k(t-h_k)+\sum_{h=1,h\neq k}^{N}\tilde{R}_{ihk}\tilde{x}_h(t)\Big].\tag{9}$$

其中

$$\tilde{x}_k(t)=\begin{bmatrix}x_k(t)\\ e_k(t)\end{bmatrix},\ \tilde{R}_{ihk}=\begin{bmatrix}R_{ihk}&0\\ 0&R_{ihk}\end{bmatrix},$$

$$G_{1ijk}=\begin{bmatrix}A_{1ik}-B_{ik}K_{jk}&B_{ik}K_{jk}\\ 0&A_{1ik}-L_{ik}C_{1jk}\end{bmatrix},$$

$$G_{2ijk}=\begin{bmatrix}A_{2ik}&0\\ 0&A_{2ik}-L_{ik}C_{2jk}\end{bmatrix}.$$

定理 1　如果存在 N 个正定对称矩阵 X_{1k} 和 X_{2k},$\sum_{k=1}^{N}r_k$ 个正定对称矩阵 S_{1ik} 和 S_{2ik},$\sum_{k=1}^{N}r_k$ 个矩阵

Y_{ik}, $\sum_{k=1}^{N} r_k$ 个矩阵 $L_{ik}(k=1,2,\cdots,N, i=1,2,\cdots,r_k)$,满足 $S_{1ik} \geq X_{1k}$, $X_{2k} \geq S_{2ik}$,以及如下线性矩阵不等式:

$$\begin{bmatrix} \frac{1}{2}M_{1iik} & X_{1k}R_{ik}^{\mathrm{T}} \\ R_{ik}X_{1k} & -I \end{bmatrix} < 0, \tag{10}$$

$$\begin{bmatrix} \frac{1}{2}M_{2iik} & \sqrt{N-1}X_{2k} & X_{2k}A_{2ik}-F_{ik}C_{2ik} \\ \sqrt{N-1}X_{2k} & -I & 0 \\ (X_{2k}A_{2ik}-F_{ik}C_{2ik})^{\mathrm{T}} & 0 & -S_{2ik} \end{bmatrix} < 0, \tag{11}$$

$$\begin{bmatrix} M_{1ijk} & X_{1k}R_{ik}^{\mathrm{T}} & X_{1k}R_{jk}^{\mathrm{T}} \\ R_{ik}X_{1k} & -I & 0 \\ R_{jk}X_{1k} & 0 & -I \end{bmatrix} < 0, \tag{12}$$

$$\begin{bmatrix} M_{2ijk} & \sqrt{2(N-1)}X_{2k} & X_{2k}A_{2ik}-F_{ik}C_{2jk} & X_{2k}A_{2jk}-F_{jk}C_{2ik} \\ \sqrt{2(N-1)}X_{2k} & -I & 0 & 0 \\ (X_{2k}A_{2ik}-F_{ik}C_{2jk})^{\mathrm{T}} & 0 & -S_{2ik} & 0 \\ (X_{2k}A_{2jk}-F_{jk}C_{2ik})^{\mathrm{T}} & 0 & 0 & -S_{2jk} \end{bmatrix} < 0. \tag{13}$$

其中

$$M_{1ijk} = X_{1k}(A_{1ik}+A_{1jk})^{\mathrm{T}} + (A_{1ik}+A_{1jk})X_{1k} - B_{ik}Y_{jk} - Y_{jk}^{\mathrm{T}}B_{ik}^{\mathrm{T}} - B_{jk}Y_{ik} - Y_{ik}^{\mathrm{T}}B_{jk}^{\mathrm{T}} + 2X_{1k} + 2(N-1)I + A_{2ik}S_{1ik}A_{2ik}^{\mathrm{T}} + A_{2jk}S_{1jk}A_{2jk}^{\mathrm{T}},$$

$$M_{2ijk} = (A_{1ik}+A_{1jk})^{\mathrm{T}}X_{2k} + X_{2k}(A_{1ik}+A_{1jk}) - F_{ik}C_{1jk} - C_{1jk}^{\mathrm{T}}F_{ik}^{\mathrm{T}} - F_{jk}C_{1ik} - C_{1ik}^{\mathrm{T}}F_{jk}^{\mathrm{T}} + 2X_{2k} + \sum_{h=1,h\neq k}^{N}(R_{ihk}^{\mathrm{T}}R_{ihk} + R_{jhk}^{\mathrm{T}}R_{jhk}),$$

$$R_{ik}^{\mathrm{T}} = [R_{i1k}^{\mathrm{T}}, \cdots, R_{i(k-1)k}^{\mathrm{T}}, R_{i(k+1)k}^{\mathrm{T}}, \cdots, R_{iNk}^{\mathrm{T}}],$$

$$F_{ik} = X_{2k}L_{ik}, \quad Y_{ik} = K_{ik}X_{1k}.$$

则模糊分散输出反馈控制器(6)使得模糊时滞互联系统(9)在李亚普诺夫函数意义下渐近稳定.

证明 令

$$P_k^{-1} = X_k = \begin{bmatrix} X_{1k} & 0 \\ 0 & X_{2k}^{-1} \end{bmatrix},$$

$$S_{ik} = \begin{bmatrix} S_{1ik} & 0 \\ 0 & S_{2ik}^{-1} \end{bmatrix}.$$

取李亚普诺夫函数

$$V(t) = \sum_{k=1}^{N} \tilde{x}_k^{\mathrm{T}}(t)P_k\tilde{x}_k(t). \tag{14}$$

对 $V(t)$ 求时间的导数,得

$$\dot{V}(t) = \sum_{k=1}^{N}[\dot{\tilde{x}}_k^{\mathrm{T}}(t)P_k\tilde{x}_k(t) + \tilde{x}_k^{\mathrm{T}}(t)P_k\dot{\tilde{x}}_k(t)]. \tag{15}$$

式(9)代入式(15),得

$$\dot{V}(t) \leq \sum_{k=1}^{N}\sum_{i=1}^{r_k}\sum_{j=1}^{r_k}\mu_{ik}\mu_{jk}\Big\{\tilde{x}_k^{\mathrm{T}}(t)\Big[G_{1ijk}^{\mathrm{T}}P_k + P_kG_{1ijk} + P_kG_{2ijk}S_{ik}G_{2ijk}^{\mathrm{T}}P_k + \sum_{h=1,h\neq k}^{N}\tilde{R}_{ikh}^{\mathrm{T}}\tilde{R}_{ikh} + (N-1)P_k^2\Big]\tilde{x}_k(t) + \tilde{x}_k^{\mathrm{T}}(t-h_k)S_{ik}^{-1}\tilde{x}_k(t-h_k)\Big\}. \tag{16}$$

由文献[3]知,假设存在 $v>1$,对于所有的 $\theta \in [0,\tau]$,有

$$V(t-\theta) < vV(t). \tag{17}$$

则式(16)变为

$$\dot{V}(t) \leq \sum_{k=1}^{N}\sum_{i=1}^{r_k}\mu_{ik}^2\tilde{x}_k^{\mathrm{T}}(t)\Big[G_{1iik}^{\mathrm{T}}P_k + P_kG_{1iik} + P_kG_{2iik}S_{ik}G_{2iik}^{\mathrm{T}}P_k + (N-1)P_k^2 + vP_k + \sum_{h=1,h\neq k}^{N}\tilde{R}_{ikh}^{\mathrm{T}}\tilde{R}_{ikh}\Big]\tilde{x}_k(t) + \sum_{k=1}^{N}\sum_{i,j=1,i<j}^{r_k}\mu_{ik}\mu_{jk}\tilde{x}_k^{\mathrm{T}}(t) \times \Big[(G_{1ijk}+G_{1jik})^{\mathrm{T}}P_k + P_k(G_{1ijk}+G_{1jik}) + 2(N-1)P_k^2 + 2vP_k + P_kG_{2ijk}S_{ik}G_{2ijk}^{\mathrm{T}}P_k + P_kG_{2jik}S_{jk}G_{2jik}^{\mathrm{T}}P_k + \sum_{h=1,h\neq k}^{N}(\tilde{R}_{ikh}^{\mathrm{T}}\tilde{R}_{ikh} + \tilde{R}_{jkh}^{\mathrm{T}}\tilde{R}_{jkh})\Big]\tilde{x}_k(t). \tag{18}$$

显然,在式(18)中,如果下面的矩阵不等式成立:

$$X_kG_{1iik}^{\mathrm{T}} + G_{1iik}X_k + G_{2iik}S_{ik}G_{2iik}^{\mathrm{T}} + (N-1)I + vX_k + \sum_{h=1,h\neq k}^{N}X_k\tilde{R}_{ikh}^{\mathrm{T}}\tilde{R}_{ikh}X_k \leq 0, \tag{19}$$

$$X_k(G_{1ijk}+G_{1jik})^{\mathrm{T}} + (G_{1ijk}+G_{1jik})X_k + G_{2ijk}S_{ik}G_{2ijk}^{\mathrm{T}} + G_{2jik}S_{jk}G_{2jik}^{\mathrm{T}} + 2(N-1)I + 2vX_k + \sum_{h=1,h\neq k}^{N}X_k(\tilde{R}_{ikh}^{\mathrm{T}}\tilde{R}_{ikh} + \tilde{R}_{jkh}^{\mathrm{T}}\tilde{R}_{jkh})X_k \leq 0. \tag{20}$$

则 $\dot{V}(t) < 0$. 如果矩阵不等式(19)和(20)成立,则一定存在 $v>1$ 满足上面的不等式. 将 G_{1ijk}, G_{2ijk}, X_k, S_{ik} 的表达式代入不等式(19)和(20),整理得

$$X_{1k}A_{1ik}^{\mathrm{T}} + A_{1ik}X_{1k} - B_{ik}K_{ik}X_{1k} - X_{1k}K_{ik}^{\mathrm{T}}B_{ik}^{\mathrm{T}} + A_{2ik}S_{1ik}A_{2ik}^{\mathrm{T}} + X_{1k} + (N-1)I + \sum_{h=1,h\neq k}^{N}X_{1k}R_{ihk}^{\mathrm{T}}R_{ihk}X_{1k} < 0, \tag{21}$$

$$X_{2k}^{-1}A_{1ik}^{\mathrm{T}} + A_{1ik}X_{2k}^{-1} - L_{ik}C_{1ik}X_{2k}^{-1} - X_{2k}^{-1}C_{1ik}^{\mathrm{T}}L_{ik}^{\mathrm{T}} + (A_{2ik} - L_{ik}C_{2ik})S_{2ik}^{-1}(A_{2ik} - L_{ik}C_{2ik})^{\mathrm{T}} + X_{2k}^{-1} + (N-1)I + \sum_{h=1,h\neq k}^{N} X_{2k}^{-1}R_{ihk}^{\mathrm{T}}R_{ihk}X_{2k}^{-1} < 0, \tag{22}$$

$$X_{1k}(A_{1ik} + A_{1jk})^{\mathrm{T}} + (A_{1ik} + A_{1jk})X_{1k} - B_{ik}K_{jk}X_{1k} - X_{1k}K_{jk}^{\mathrm{T}}B_{ik}^{\mathrm{T}} - B_{jk}K_{ik}X_{1k} - X_{1k}K_{ik}^{\mathrm{T}}B_{ik}^{\mathrm{T}} + A_{2ik}S_{1ik}A_{2ik}^{\mathrm{T}} + A_{2jk}S_{1jk}A_{2jk}^{\mathrm{T}} + 2X_{1k} + 2(N-1)I + \sum_{h=1,h\neq k}^{N}(X_{1k}R_{ihk}^{\mathrm{T}}R_{ihk}X_{1k} + X_{1k}R_{jhk}^{\mathrm{T}}R_{jhk}X_{1k}) < 0, \tag{23}$$

$$X_{2k}^{-1}(A_{1ik} + A_{1jk})^{\mathrm{T}} + (A_{1ik} + A_{1jk})X_{2k}^{-1} - L_{ik}C_{1jk}X_{2k}^{-1} - X_{2k}^{-1}C_{1jk}^{\mathrm{T}}L_{ik}^{\mathrm{T}} - L_{jk}C_{1ik}X_{2k}^{-1} - X_{2k}^{-1}C_{1ik}^{\mathrm{T}}L_{jk}^{\mathrm{T}} + 2X_{2k}^{-1} + 2(N-1)I + (A_{2ik} - L_{ik}C_{2jk})S_{2ik}^{-1}(A_{2ik} - L_{ik}C_{2jk})^{\mathrm{T}} + (A_{2jk} - L_{jk}C_{2ik})S_{2jk}^{-1}(A_{2jk} - L_{jk}C_{2ik})^{\mathrm{T}} + \sum_{h=1,h\neq k}^{N} X_{2k}^{-1}(R_{ihk}^{\mathrm{T}}R_{ihk} + R_{jhk}^{\mathrm{T}}R_{jhk})X_{2k}^{-1} < 0. \tag{24}$$

令 $Y_{ik} = K_{ik}X_{1k}$, $F_{ik} = X_{2k}L_{ik}$,则由 Schur 分解方法知,式(21) ~ (24) 分别等价于线性矩阵不等式(9) ~ (12). □

4　仿真结果

考虑如下双机互联时滞系统,它由两个子系统组成.

$$F_k:\begin{cases}\dot{x}_{1k}(t) = x_{2k}(t) + x_{1k}(t-h_k),\\ \dot{x}_{2k}(t) = \\ -\dfrac{D_k}{M_k}x_{2k}(t) + x_{2k}(t-h_k) + \\ \dfrac{1}{M_k}u_k(t) + \sum_{h=1,h\neq k}^{2}\dfrac{E_kE_hY_{kh}}{M_k} + \\ [\cos(\delta_{kh} - \theta_{kh}) - \cos(x_{1k}(t) - \\ x_{1h}(t) + \delta_{kh} - \theta_{kh})],\\ y_k(t) = x_{1k}(t) + x_{1k}(t-h_k).\end{cases} \tag{25}$$

其中:$x_{1k}(t)$ 和 $x_{2k}(t)$ 分别为每个子系统的转角和转速,M_k 为惯性系数,E_k 为内部电压,Y_{kh} 为第 h 和第 k 个机器之间导纳的模,θ_{kh} 为第 h 和第 k 个机器之间导纳的相角.有关参数选取与文献[8]相同.

在非线性时滞互联系统(25)中,假设状态变量 x_{11} 和 x_{12} 是可测的,分别对两个子系统在工作点 $\pi/2, 0, -\pi/2$ 处局部线性化,利用模糊 T-S 模型对式(25)进行模糊建模.定义模糊规则如下:

R_1: If $x_{11}(t)$ about $-\pi/2$ and $x_{12}(t)$ about $-\pi/2$, Then

$$\dot{x}_k(t) = A_{11k}x_k(t) + A_{21k}x_k(t-h_k) + B_{1k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{1hk}x_h(t),$$
$$y_k(t) = C_{11k}x_k(t) + C_{21k}x_k(t-h_k);$$

R_2: If $x_{11}(t)$ about $-\pi/2$ and $x_{12}(t)$ about 0, Then

$$\dot{x}_k(t) = A_{12k}x_k(t) + A_{22k}x_k(t-h_k) + B_{2k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{2hk}x_h(t),$$
$$y_k(t) = C_{12k}x_k(t) + C_{22k}x_k(t-h_k);$$

R_3: If $x_{11}(t)$ about $-\pi/2$ and $x_{12}(t)$ about $\pi/2$, Then

$$\dot{x}_k(t) = A_{13k}x_k(t) + A_{23k}x_k(t-h_k) + B_{3k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{3hk}x_h(t),$$
$$y_k(t) = C_{13k}x_k(t) + C_{23k}x_k(t-h_k);$$

R_4: If $x_{11}(t)$ about 0 and $x_{12}(t)$ about $-\pi/2$, Then

$$\dot{x}_k(t) = A_{14k}x_k(t) + A_{24k}x_k(t-h_k) + B_{4k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{4hk}x_h(t),$$
$$y_k(t) = C_{14k}x_k(t) + C_{24k}x_k(t-h_k);$$

R_5: If $x_{11}(t)$ about 0 and $x_{12}(t)$ about 0, Then

$$\dot{x}_k(t) = A_{15k}x_k(t) + A_{25k}x_k(t-h_k) + B_{5k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{5hk}x_h(t),$$
$$y_k(t) = C_{15k}x_k(t) + C_{25k}x_k(t-h_k);$$

R_6: If $x_{11}(t)$ about 0 and $x_{12}(t)$ about $\pi/2$, Then

$$\dot{x}_k(t) = A_{16k}x_k(t) + A_{26k}x_k(t-h_k) + B_{6k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{6hk}x_h(t),$$
$$y_k(t) = C_{16k}x_k(t) + C_{26k}x_k(t-h_k);$$

R_7: If $x_{11}(t)$ about $\pi/2$ and $x_{12}(t)$ about $-\pi/2$, Then

$$\dot{x}_k(t) = A_{17k}x_k(t) + A_{27k}x_k(t-h_k) + B_{7k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{7hk}x_h(t),$$
$$y_k(t) = C_{17k}x_k(t) + C_{27k}x_k(t-h_k);$$

R_8: If $x_{11}(t)$ about $\pi/2$ and $x_{12}(t)$ about 0, Then

$$\dot{x}_k(t) = A_{18k}x_k(t) + A_{21k}x_k(t-h_k) + B_{1k}u_k(t) + \sum_{h=1,h\neq k}^{2}R_{1hk}x_h(t),$$
$$y_k(t) = C_{11k}x_k(t) + C_{21k}x_k(t-h_k);$$

R_9: If $x_{11}(t)$ about $-\pi/2$ and $x_{12}(t)$ about $\pi/2$, Then

$$\dot{x}_k(t) = A_{19k}x_k(t) + A_{29k}x_k(t-h_k) +$$

$$B_{9k}u_k(t) + \sum_{h=1,h\neq k}^{2} R_{9hk}x_h(t),$$
$$y_k(t) = C_{19k}x_k(t) + C_{29k}x_k(t-h_k).$$

在上面的模糊推理规则中,模糊隶属函数 A_{1ik}, B_{ik}, R_{ihk} 和 C_{1ik} 的选取与文献[5]相同,且

$$A_{211} = \begin{bmatrix} 0 & 1 \\ -0.5 & 0 \end{bmatrix}, A_{221} = \begin{bmatrix} 0 & 1 \\ -1.5 & 0 \end{bmatrix},$$
$$A_{231} = \begin{bmatrix} 0 & 0 \\ -1.4 & -0.5 \end{bmatrix}, A_{241} = \begin{bmatrix} 0 & 0 \\ 0 & -0.7 \end{bmatrix},$$
$$A_{242} = \begin{bmatrix} 0 & 0 \\ -1.5 & 0 \end{bmatrix}, A_{252} = \begin{bmatrix} 0 & -1.5 \\ -0.5 & 0 \end{bmatrix},$$
$$A_{262} = \begin{bmatrix} 0 & 0 \\ 0.5 & 0 \end{bmatrix}, A_{272} = \begin{bmatrix} 0 & 0 \\ 1.5 & 0.8 \end{bmatrix},$$
$$A_{282} = \begin{bmatrix} 0 & 0 \\ 2.5 & 1 \end{bmatrix}, A_{292} = \begin{bmatrix} 0 & 0 \\ -0.5 & 0.8 \end{bmatrix},$$
$$C_{2ik} = [1 \quad 0]; i = 1,2,\cdots,9, k = 1,2,$$
$$h = 1,2, h \neq k.$$

通过求解式(9)～(12),解得控制和观测增益矩阵

$$K_{11} = [96.32 \quad 12.487], K_{21} = [94.56 \quad 12.362],$$
$$K_{31} = [94.36 \quad 12.368], K_{41} = [93.94 \quad 12.256],$$
$$K_{51} = [96.51 \quad 12.506], K_{61} = [95.34 \quad 12.447],$$
$$K_{71} = [93.69 \quad 12.196], K_{81} = [92.94 \quad 12.198],$$
$$K_{91} = [96.9 \quad 12.469], K_{12} = [67 \quad 28.082],$$
$$K_{22} = [61.64 \quad 27.779], K_{32} = [62.09 \quad 27.806],$$
$$K_{42} = [66.53 \quad 28.033], K_{52} = [67.38 \quad 28.086],$$
$$K_{62} = [61.9 \quad 27.794], K_{72} = [64.8 \quad 27.871],$$
$$K_{82} = [64.4 \quad 27.915], K_{92} = [66.4 \quad 28.018],$$
$$L_{11} = \begin{bmatrix} 7.1032 \\ 2.4246 \end{bmatrix}, L_{21} = \begin{bmatrix} 7.1045 \\ 1.4253 \end{bmatrix},$$
$$L_{31} = \begin{bmatrix} 7.1044 \\ 1.5252 \end{bmatrix}, L_{41} = \begin{bmatrix} 7.1053 \\ 2.9622 \end{bmatrix},$$
$$L_{51} = \begin{bmatrix} 7.1032 \\ 2.9244 \end{bmatrix}, L_{61} = \begin{bmatrix} 7.1035 \\ 1.4248 \end{bmatrix},$$
$$L_{71} = \begin{bmatrix} 7.1053 \\ 2.9262 \end{bmatrix}, L_{81} = \begin{bmatrix} 7.1057 \\ 3.6258 \end{bmatrix},$$
$$L_{91} = \begin{bmatrix} 7.1032 \\ 2.9245 \end{bmatrix}, L_{12} = \begin{bmatrix} 6.9303 \\ -3.2195 \end{bmatrix},$$
$$L_{22} = \begin{bmatrix} 6.9137 \\ -3.5178 \end{bmatrix}, L_{32} = \begin{bmatrix} 6.9345 \\ -2.2230 \end{bmatrix},$$
$$L_{42} = \begin{bmatrix} 6.9632 \\ -3.2507 \end{bmatrix}, L_{52} = \begin{bmatrix} 6.9714 \\ -3.7587 \end{bmatrix},$$
$$L_{62} = \begin{bmatrix} 6.9244 \\ -4.1140 \end{bmatrix}, L_{72} = \begin{bmatrix} 6.9322 \\ -1.7206 \end{bmatrix},$$
$$L_{82} = \begin{bmatrix} 6.9317 \\ -0.7210 \end{bmatrix}, L_{92} = \begin{bmatrix} 6.9307 \\ -3.7190 \end{bmatrix}.$$

初始条件为

$$x_1(0) = [-4 \quad -4]^{\mathrm{T}}, x_2(0) = [3 \quad 2]^{\mathrm{T}},$$
$$\hat{x}_1(0) = [-4 \quad -3]^{\mathrm{T}}, \hat{x}_2(0) = [2.5 \quad 2]^{\mathrm{T}}.$$

各子系统的闭环状态响应曲线如图1～图4所示.

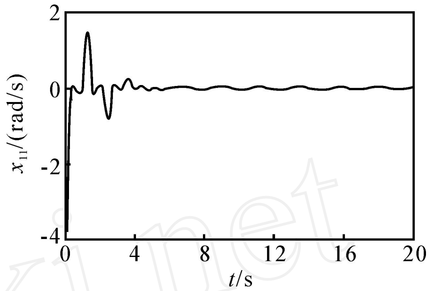

图1 子系统1的 $x_{11}(t)$ 状态响应

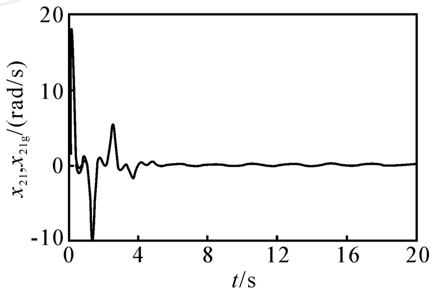

图2 子系统1的 $x_{21}(t)$ 状态响应

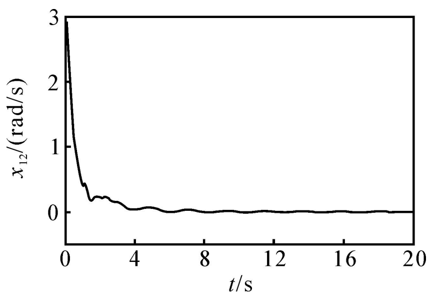

图3 子系统2的 $x_{12}(t)$ 状态响应

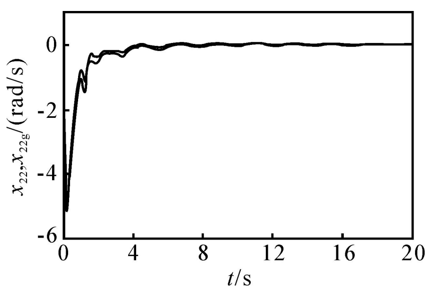

图4 子系统2的 $x_{22}(t)$ 状态响应

5 结 语

本文针对一类非线性互联时滞系统,基于模糊T-S模型和分布补偿算法,给出了一种基于模糊观测器的分散模糊控制设计方法,并结合李亚普诺夫稳定性和线性矩阵不等式理论,给出了闭环系统的稳定性条件.仿真结果验证了所提出的模糊分散控制方法的有效性. (下转第1118页)

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