含非匹配互联项的一类大型互联非线性系统的鲁棒分散控制

傅 勤 [1, 2] 杨成梧 [1]

摘 要 本文对带有界扰动的一类含非匹配互联项的大型互联非线性系统进行了分散状态反馈控制设计, 通过子系统状态的线性变换, 得到分散状态反馈控制律. 当状态反馈控制律作用于该系统时, 无扰动的闭环系统是全局渐近稳定的, 当扰动有界时, 系统的状态能够收敛到原点的一个与扰动的界相关的邻域内, 并给出仿真算例说明该结论的可行性和有效性.

关键词 大型互联系统, 状态反馈, 分散控制, 非匹配互联项
中图分类号 TP13

Robust Decentralized Control for a Class of Large-scale Interconnected Nonlinear Systems with Mismatched Interconnections

FU Qin[1, 2] YANG Cheng-Wu[1]

Abstract In this paper, decentralized state feedback control design for a class of large-scale interconnected nonlinear systems with mismatched interconnections and bounded disturbances is given. The decentralized state feedback controllers are obtained by using the linear transformation of the states of each subsystem. When the state feedback control laws are applied to the systems, the closed-loop systems without disturbances are globally asymptotic and the states of the systems can converge to a region of the origin which depends on the bounds of the disturbances when disturbances are bounded. A simulation example shows the feasibility and effectiveness of the conclusion.

Key words Large-scale interconnected systems, state feedback, decentralized control, mismatched interconnections

大型互联系统的分散控制设计是近年来控制理论研究的热点问题, 对于互联系统, 不确定互联项具有怎样的形式是研究和考虑的重点, 线性或非线性形式、匹配或非匹配形式等. 文献 [1−2] 对具有线性形式互联项的系统进行了控制设计, 而对于具有非线性形式互联项的系统, 通常的假设约束条件是, 互联项的范数小于等于状态范数的某个多项式[3−7], 文献 [3−4] 所研究的系统的互联项满足匹配条件, 文献 [5−7] 则对互联项不满足匹配条件的系统进行了控制设计, 然此类系统有一定的特殊性, 为适用于反步法的严反馈系统. 对于互联项不满足匹配条件的非严反馈形式的互联系统, 如何进行控制设计, 尚鲜有相关的研究论文.

本文研究带有界扰动的一类大型互联非线性系统的鲁棒分散状态反馈控制问题, 该系统的互联项不满足匹配条件, 我们提出了一种新的控制设计方法. 当状态反馈控制律作用于该系统, 扰动为零时, 原点是闭环系统的全局渐近稳定平衡点; 扰动不为零时, 系统的解有界, 且收敛到原点的一个邻域内, 该邻域与扰动的界有关, 扰动的界越小, 该邻域越小. 该结论是全局成立的, 且状态反馈控制律与扰动的界无关, 因此, 扰动的界是可以未知的.

收稿日期 2006-12-04 收修改稿日期 2007-08-23
Received December 4, 2006; in revised form August 23, 2007
江苏省高校自然科学研究项目 (04KJD110168, 06KJB110107) 和苏州科技学院重点学科基金资助
Supported by Science Foundation from the Ministry of Education of Jiangsu Province (04KJD110168, 06KJB110107) and Key Academic Foundation of University of Science and Technology of Suzhou
1. 南京理工大学动力工程学院 南京 210094 2. 苏州科技学院应用数学系 苏州 215009
1. School of Power Engineering, Nanjing University of Science and Technology, Nanjing 210094 2. Department of Applied Mathematics, University of Science and Technology of Suzhou, Suzhou 215009
DOI: 10.3724/SP.J.1004.2008.00488

1 问题描述

考虑如下形式的大型互联非线性系统

$$\dot{\boldsymbol{z}}_i = A\boldsymbol{z}_i + \boldsymbol{B}u_i + \boldsymbol{f}_i(\boldsymbol{z}) + \boldsymbol{d}_i(\boldsymbol{z}, t) \tag{1}$$

这里 $i = 1, \cdots, N$ 表示各个子系统, $\boldsymbol{z}_i \in \mathbf{R}^n$, $u_i \in \mathbf{R}$ 分别是第 i 个子系统的状态和输入, $\boldsymbol{z} = [\boldsymbol{z}_1^{\mathrm{T}}\ \boldsymbol{z}_2^{\mathrm{T}} \cdots \boldsymbol{z}_N^{\mathrm{T}}]^{\mathrm{T}}$, $\boldsymbol{f}_i(\boldsymbol{z}) \in \mathbf{R}^n$ 是光滑互联项, $\boldsymbol{d}_i(\boldsymbol{z}, t) \in \mathbf{R}^n$ 是有界扰动, 而

$$A = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ddots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix}_{n\times n}$$

$$\boldsymbol{B} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{pmatrix}_{n\times 1}$$

定义范数 $\|\cdot\|$ 为通常的 2-范数, 即 $\|\boldsymbol{x}\| = \sqrt{\sum_{i=1}^{n} x_i^2}$, $\|A\| = \sqrt{\rho(A^{\mathrm{T}}A)}$. 记 I 为 n 阶单位阵. 对系统 (1) 作如下假设:

假设 1. $\|\boldsymbol{d}_i(\boldsymbol{z}, t)\| \le d_i$, d_i 是常数 (可能未知).

假设 2. $\boldsymbol{f}_i(\boldsymbol{z}) = \sum_{j=1}^{N} \boldsymbol{z}_j g_{ij}(\boldsymbol{z})$, $g_{ij}(\boldsymbol{z}) \in \mathbf{R}$ 且未知, 并有 $|g_{ij}(\boldsymbol{z})| \le c_{ij}$, c_{ij} 是已知的正常数.

注 1. 对比文献 [3−4] 中相应的假设条件 ($\|\boldsymbol{f}_i(\boldsymbol{z})\| \le \sum_{j=1}^{N}\sum_{k=1}^{p_{ij}} \beta_{ij}^k \|\boldsymbol{z}_j\|^k$), 假设 2 符合 $p_{ij} = 1$ 的情形.

引理 1[8]**.** $(A, \boldsymbol{B})$ 可控, 存在 n 阶对称正定阵 P 和 n 维行向量 $\boldsymbol{K}$, 使得

$$P(A - \boldsymbol{B}\boldsymbol{K}) + (A - \boldsymbol{B}\boldsymbol{K})^{\mathrm{T}}P = -I \tag{2}$$

成立.

系统 (1) 的鲁棒分散状态反馈控制问题为: 设计一个分散反馈控制律

$$u_i = \alpha_i(\boldsymbol{z}_i), \quad \alpha_i(\boldsymbol{0}) = 0$$

使得

1) 当 $\boldsymbol{d}_i(\boldsymbol{z}, t) = \boldsymbol{0}$ 时, 原点 $\boldsymbol{z} = \boldsymbol{0}$ 是闭环系统

$$\dot{\boldsymbol{z}}_i = A\boldsymbol{z}_i + \boldsymbol{B}\alpha_i(\boldsymbol{z}_i) + \boldsymbol{f}_i(\boldsymbol{z})$$

的全局渐近稳定平衡点 ($i = 1, \cdots, N$).

2) 当 $\boldsymbol{d}_i(\boldsymbol{z}, t) \ne \boldsymbol{0}$, 且 $\|\boldsymbol{d}_i(\boldsymbol{z}, t)\| \le d_i$ 时, 系统

$$\dot{\boldsymbol{z}}_i = A\boldsymbol{z}_i + \boldsymbol{B}\alpha_i(\boldsymbol{z}_i) + \boldsymbol{f}_i(\boldsymbol{z}) + \boldsymbol{d}_i(\boldsymbol{z}, t)$$

的解 $\boldsymbol{z}(t)$ 有界, 且收敛到原点的一个邻域内, 该邻域与扰动的界有关, 扰动的界越小, 该邻域越小 ($i = 1, \cdots, N$).

2　主要结论

利用文献 [9] 的思想方法, 我们对系统 (1) 的每个子系统的状态进行线性变换, 记 $E_l = \mathrm{diag}(l^{n-1}, l^{n-2}, \cdots, l, 1), l$ 为待定正常数, 作状态的线性变换

$$\bar{\boldsymbol{z}}_i = E_l \boldsymbol{z}_i$$

注意到

$$E_l \boldsymbol{B} = \boldsymbol{B},\ E_l A E_l^{-1} = lA$$

由此系统 (1) 可化为

$$\dot{\bar{\boldsymbol{z}}}_i = lA\bar{\boldsymbol{z}}_i + \boldsymbol{B}u_i + E_l \boldsymbol{f}_i(\boldsymbol{z}) + E_l \boldsymbol{d}_i(\boldsymbol{z}, t) \tag{3}$$

我们有下面的主要结论:

定理 1. 假设 1 和 2 成立, 则系统 (1) 的分散状态反馈控制律为

$$u_i = \alpha_i(\boldsymbol{z}_i) = -l\boldsymbol{K}E_l\boldsymbol{z}_i = -l\boldsymbol{K}\bar{\boldsymbol{z}}_i \tag{4}$$

证明. 由变换的等价性, 只需对系统 (3) 进行控制设计.

构造 Lyapunov 函数

$$V(\bar{\boldsymbol{z}}) = \sum_{i=1}^{N} \bar{\boldsymbol{z}}_i^{\mathrm{T}} P \bar{\boldsymbol{z}}_i$$

其中 $\bar{\boldsymbol{z}} = [\bar{\boldsymbol{z}}_1^{\mathrm{T}}\ \bar{\boldsymbol{z}}_2^{\mathrm{T}} \cdots \bar{\boldsymbol{z}}_N^{\mathrm{T}}]^{\mathrm{T}}$.

1) 当 $\boldsymbol{d}_i(\boldsymbol{z}, t) = \boldsymbol{0}$ 时, 将式 (4) 代入式 (3), 利用式 (2) 得

$$\dot{V} = \sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + 2\bar{\boldsymbol{z}}_i^{\mathrm{T}} P E_l \boldsymbol{f}_i(\boldsymbol{z}))$$

由假设 2 得

$$\dot{V} = \sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + 2\bar{\boldsymbol{z}}_i^{\mathrm{T}} P E_l \sum_{j=1}^{N} \boldsymbol{z}_j g_{ij}(\boldsymbol{z})) =$$

$$\sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + 2\bar{\boldsymbol{z}}_i^{\mathrm{T}} P \sum_{j=1}^{N} \bar{\boldsymbol{z}}_j g_{ij}(\boldsymbol{z})) \le$$

$$\sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + 2\|P\| \sum_{j=1}^{N} \|\bar{\boldsymbol{z}}_i\| \|\bar{\boldsymbol{z}}_j\| c_{ij})$$

由基本不等式性质得

$$\dot{V} \le \sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + \|P\| \sum_{j=1}^{N} c_{ij} (\|\bar{\boldsymbol{z}}_i\|^2 + \|\bar{\boldsymbol{z}}_j\|^2)) =$$

$$\sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} c_{ij}) \|\bar{\boldsymbol{z}}_i\|^2 + \|P\| \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ij} \|\bar{\boldsymbol{z}}_j\|^2 =$$

$$\sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} c_{ij}) \|\bar{\boldsymbol{z}}_i\|^2 + \|P\| \sum_{i=1}^{N} \sum_{j=1}^{N} c_{ji} \|\bar{\boldsymbol{z}}_i\|^2 =$$

$$\sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji})) \|\bar{\boldsymbol{z}}_i\|^2 \tag{5}$$

取

$$l = \max_{1 \le i \le N} \{1 + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji})\} \tag{6}$$

则

$$\dot{V} \le -\sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i\|^2$$

记 λ_1, λ_2 分别是 P 的最小和最大特征值,

$$2\lambda_3 = \frac{1}{\lambda_2}$$

则有

$$\dot{V} \le -2\lambda_3 V$$

由系统变换的等价性, 原闭环系统是全局渐近稳定的.

2) 当 $\boldsymbol{d}_i(\boldsymbol{z}, t) \ne \boldsymbol{0}$, 且 $\|\boldsymbol{d}_i(\boldsymbol{z}, t)\| \le d_i$ 时, 将式 (4) 代入式 (3), 利用式 (2) 得

$$\dot{V} = \sum_{i=1}^{N} (-l\|\bar{\boldsymbol{z}}_i\|^2 + 2\bar{\boldsymbol{z}}_i^{\mathrm{T}} P E_l \boldsymbol{f}_i(\boldsymbol{z}) + 2\bar{\boldsymbol{z}}_i^{\mathrm{T}} P E_l \boldsymbol{d}_i(\boldsymbol{z}, t))$$

用同样的推导方法, 假设 1 及式 (5) 可得

$$\dot{V} \le \sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji})) \|\bar{\boldsymbol{z}}_i\|^2 +$$

$$\sum_{i=1}^{N} 2\|P\| \|\bar{\boldsymbol{z}}_i\| \|E_l\| d_i$$

我们要求 $l \ge 1$, 则 $\|E_l\| = l^{n-1}$, 由基本不等式性质可得

$$\dot{V} \le \sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji})) \|\bar{\boldsymbol{z}}_i\|^2 +$$

$$\sum_{i=1}^{N} (\|P\|^2 \|\bar{\boldsymbol{z}}_i\|^2 + l^{2n-2} d_i^2) =$$

$$\sum_{i=1}^{N} (-l + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji}) + \|P\|^2) \|\bar{\boldsymbol{z}}_i\|^2 +$$

$$\sum_{i=1}^{N} l^{2n-2} d_i^2$$

取

$$l = \max_{1 \le i \le N} \{1 + \|P\| \sum_{j=1}^{N} (c_{ij} + c_{ji}) + \|P\|^2\} \ge 1 \tag{7}$$

则

$$\dot{V} \le -\sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i\|^2 + \sum_{i=1}^{N} l^{2n-2} d_i^2$$

所以

$$\dot{V} \le -2\lambda_3 V + \sum_{i=1}^{N} l^{2n-2} d_i^2$$

再由文献 [10] 中引理 1 得

$$V(t) \le V(0)\exp(-2\lambda_3 t) + \frac{\sum\limits_{i=1}^{N} l^{2n-2} d_i^2}{2\lambda_3}$$

由

$$2\lambda_3 = \frac{1}{\lambda_2}$$

记

$$\frac{l^{2n-2}}{2\lambda_1\lambda_3} = \frac{\lambda_2 l^{2n-2}}{\lambda_1} = \lambda_4$$

则

$$\sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i\|^2 \le \frac{\lambda_2}{\lambda_1} \sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2$$

由式 (7), $l \ge 1$, 所以 $\|E_l\| = l^{n-1}$, $\|E_l^{-1}\| = 1$, 由此可得

$$\begin{aligned}
&\sum_{i=1}^{N} \|\boldsymbol{z}_i\|^2 = \sum_{i=1}^{N} \|E_l^{-1}\bar{\boldsymbol{z}}_i\|^2 \le \sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i\|^2 \le \\
&\frac{\lambda_2}{\lambda_1} \sum_{i=1}^{N} \|\bar{\boldsymbol{z}}_i(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2 = \\
&\frac{\lambda_2}{\lambda_1} \sum_{i=1}^{N} \|E_l\boldsymbol{z}_i(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2 \le \\
&\lambda_4 \sum_{i=1}^{N} \|\boldsymbol{z}_i(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2
\end{aligned}$$

所以

$$\begin{aligned}
&\|\boldsymbol{z}\|^2 = \sum_{i=1}^{N} \|\boldsymbol{z}_i\|^2 \le \\
&\lambda_4 \sum_{i=1}^{N} \|\boldsymbol{z}_i(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2 = \\
&\lambda_4 \|\boldsymbol{z}(0)\|^2 \exp(-2\lambda_3 t) + \lambda_4 \sum_{i=1}^{N} d_i^2
\end{aligned}$$

由此解 $\boldsymbol{z}(t)$ 有界, 且收敛到原点的一个邻域内, 该邻域与扰动的界 d_i 有关, 扰动的界越小, 该邻域越小. □

注 2. 因为互联项不满足匹配条件, 在证明过程中, 采用的方法是将变换矩阵 E_l 吸收到互联项的每一项中, 即 $E_l\boldsymbol{z}_j = \bar{\boldsymbol{z}}_j (j = 1, \cdots, N)$, 所以, 与文献 [3−4] 相对比, 本文研究的系统的每个子系统只能具有相同的维数.

注 3. 由定理 1 的证明过程可知, 扰动的界 d_i 允许是任意大的.

3 仿真算例

取 $N = 2$, $n = 2$, 考虑如下的互联系统

$$\begin{aligned}
\dot{z}_{11} &= z_{12} + z_{11}\cos(z_{21} + z_{22}) + z_{21}\cos(z_{11}z_{12}) + \cos t \\
\dot{z}_{12} &= u_1 + z_{12}\cos(z_{21} + z_{22}) + z_{22}\cos(z_{11}z_{12}) + \sin t \\
\dot{z}_{21} &= z_{22} + z_{11}\cos(z_{21}z_{22}) + z_{21}\cos(z_{11} + z_{12}) + \cos t \\
\dot{z}_{22} &= u_2 + z_{12}\cos(z_{21}z_{22}) + z_{22}\cos(z_{11} + z_{12}) + \sin t
\end{aligned} \tag{8}$$

即

$$A = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad \boldsymbol{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$g_{11}(\boldsymbol{z}) = \cos(z_{21} + z_{22}),\ g_{12}(\boldsymbol{z}) = \cos(z_{11}z_{12})$$

$$g_{21}(\boldsymbol{z}) = \cos(z_{21}z_{22}),\ g_{22}(\boldsymbol{z}) = \cos(z_{11} + z_{12})$$

$$\boldsymbol{d}_1(\boldsymbol{z}, t) = \boldsymbol{d}_2(\boldsymbol{z}, t) = \begin{pmatrix} \cos t \\ \sin t \end{pmatrix}$$

所以 $c_{11} = c_{12} = c_{21} = c_{22} = 1$, 取 $\boldsymbol{K} = [2\ \ 3]$, 则

$$P = \begin{pmatrix} \frac{5}{4} & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{4} \end{pmatrix}, \quad \|P\| = \frac{3+\sqrt{5}}{4}$$

当扰动为零时, 由式 (6), 取

$$l = 1 + (3 + \sqrt{5}) = 4 + \sqrt{5}$$

由式 (4) 得分散反馈控制律

$$u_1 = -2(4+\sqrt{5})^2 z_{11} - 3(4+\sqrt{5})z_{12}$$

$$u_2 = -2(4+\sqrt{5})^2 z_{21} - 3(4+\sqrt{5})z_{22}$$

所以系统 (8) 化为

$$\begin{aligned}
\dot{z}_{11} &= z_{12} + z_{11}\cos(z_{21} + z_{22}) + z_{21}\cos(z_{11}z_{12}) \\
\dot{z}_{12} &= -2(4+\sqrt{5})^2 z_{11} - 3(4+\sqrt{5})z_{12} + \\
&\quad z_{12}\cos(z_{21} + z_{22}) + z_{22}\cos(z_{11}z_{12}) \\
\dot{z}_{21} &= z_{22} + z_{11}\cos(z_{21}z_{22}) + z_{21}\cos(z_{11} + z_{12}) \\
\dot{z}_{22} &= -2(4+\sqrt{5})^2 z_{21} - 3(4+\sqrt{5})z_{22} + \\
&\quad z_{12}\cos(z_{21}z_{22}) + z_{22}\cos(z_{11} + z_{12})
\end{aligned} \tag{9}$$

取初值

$$z_{11}(0)=z_{12}(0)=z_{21}(0)=z_{22}(0)=1$$

则系统 (9) 的仿真结果为图 $1\sim4$.

当扰动不为零时, 由式 (7), 取

$$l=\frac{39}{8}+\frac{11}{8}\sqrt{5}$$

由式 (4) 得分散反馈控制律

$$u_1=-2(\frac{39}{8}+\frac{11}{8}\sqrt{5})^2z_{11}-3(\frac{39}{8}+\frac{11}{8}\sqrt{5})z_{12}$$

$$u_2=-2(\frac{39}{8}+\frac{11}{8}\sqrt{5})^2z_{21}-3(\frac{39}{8}+\frac{11}{8}\sqrt{5})z_{22}$$

所以系统 (8) 化为

$$\begin{aligned}\dot{z}_{11}=&z_{12}+z_{11}\cos(z_{21}+z_{22})+z_{21}\cos(z_{11}z_{12})+\cos t\\ \dot{z}_{12}=&-2(\frac{39}{8}+\frac{11}{8}\sqrt{5})^2z_{11}-3(\frac{39}{8}+\frac{11}{8}\sqrt{5})z_{12}+\\ &z_{12}\cos(z_{21}+z_{22})+z_{22}\cos(z_{11}z_{12})+\sin t\\ \dot{z}_{21}=&z_{22}+z_{11}\cos(z_{21}z_{22})+z_{21}\cos(z_{11}+z_{12})+\cos t\\ \dot{z}_{22}=&-2(\frac{39}{8}+\frac{11}{8}\sqrt{5})^2z_{21}-3(\frac{39}{8}+\frac{11}{8}\sqrt{5})z_{22}+\\ &z_{12}\cos(z_{21}z_{22})+z_{22}\cos(z_{11}+z_{12})+\sin t\end{aligned}\qquad(10)$$

取初值

$$z_{11}(0)=z_{12}(0)=z_{21}(0)=z_{22}(0)=1$$

则系统 (10) 的仿真结果为图 $5\sim8$.

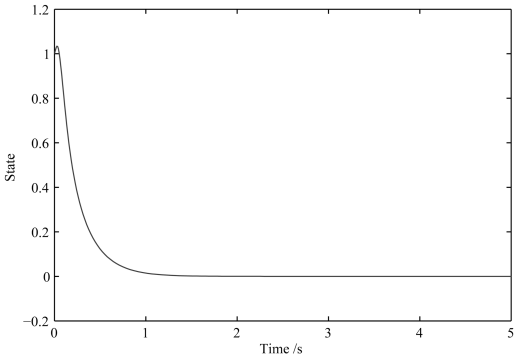

图 1　z_{11} 的轨迹

Fig. 1　The trajectory of z_{11}

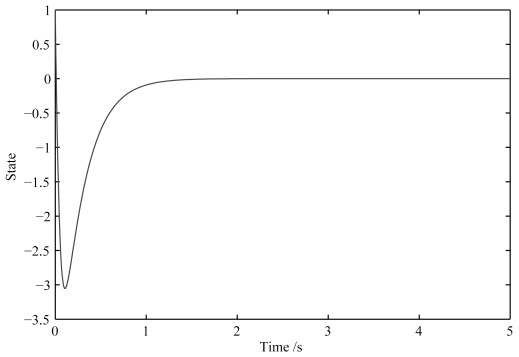

图 2　z_{12} 的轨迹

Fig. 2　The trajectory of z_{12}

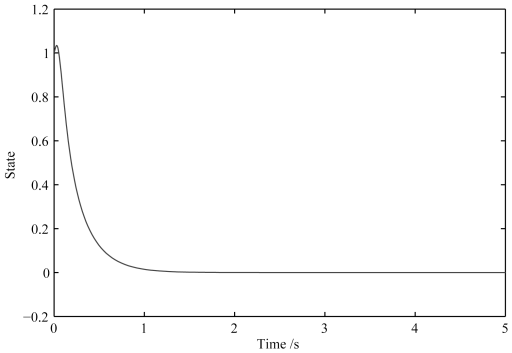

图 3　z_{21} 的轨迹

Fig. 3　The trajectory of z_{21}

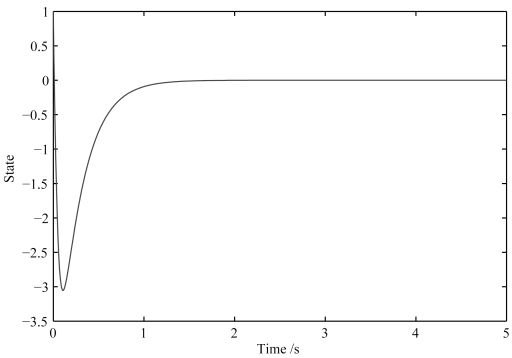

图 4　z_{22} 的轨迹

Fig. 4　The trajectory of z_{22}

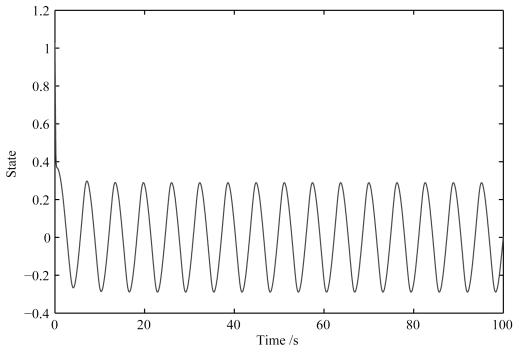

图 5　z_{11} 的轨迹

Fig. 5　The trajectory of z_{11}

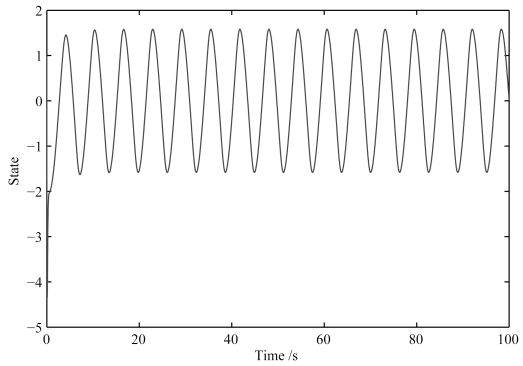

图 6 z_{12} 的轨迹

Fig. 6 The trajectory of z_{12}

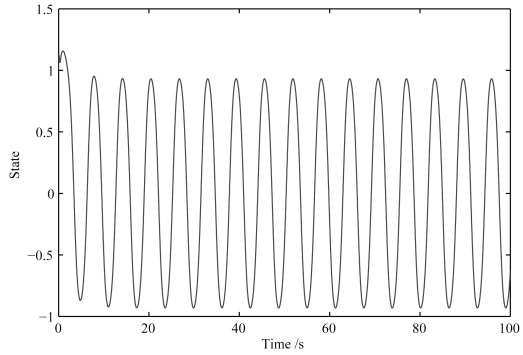

图 7 z_{21} 的轨迹

Fig. 7 The trajectory of z_{21}

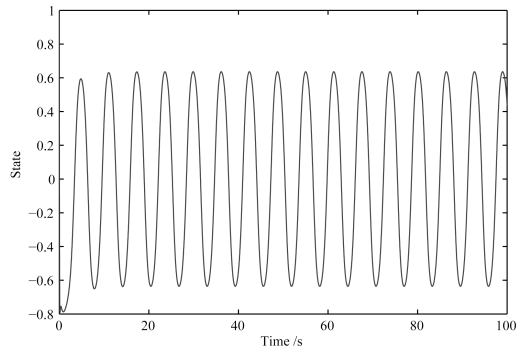

图 8 z_{22} 的轨迹

Fig. 8 The trajectory of z_{22}

4 结论

本文考虑了一类不满足匹配条件的大型互联非线性系统的鲁棒分散状态反馈控制问题. 与文献 [3−4] 相比, 本文的主要贡献是将匹配条件换成了非匹配条件, 并且系统增加了可以是大扰动的有界扰动项. 通过子系统状态的线性变换对系统进行了控制设计, 最终得到了全局成立的结论 (文献 [4] 的结论是半全局的), 仿真算例证明了此结论.

References

1 Liu Hui-Ming, Jing Yuan-Wei, Zhang Si-Ying. Model reference adaptive decentralized control for a class of large-scale composite systems. *Control and Decision*, 2005, **20**(2): 191−194
(刘慧明, 井元伟, 张嗣瀛. 一类组合系统的模型参考自适应分散控制. 控制与决策, 2005, **20**(2): 191−194)

2 Xie Yong-Fang, Jiang Zhao-Hui, Gui Wei-Hua. Decentralized robust H_∞ control for value-bounded uncertain large-scale interconnected systems. *Control Theory and Applications*, 2006, **23**(3): 329−335
(谢永芳, 蒋朝辉, 桂卫华. 数值界不确定性关联大系统分散鲁棒 H_∞ 控制. 控制理论与应用, 2006, **23**(3): 329−335)

3 Pagilla P R. Robust decentralized control of large-scale interconnected systems: general interconnections. In: Proceedings of American Control Conference. San Diego, California, USA: IEEE, 1999. 4527−4531

4 Pagilla P R, Zhong H W. Semi-globally stable decentralized control of a class of large-scale interconnected nonlinear systems. In: Proceedings of American Control Conference. Denver, Colorado, USA: IEEE, 2003. 5017−5022

5 Xie S L, Xie L H. Decentralized global robust stabilization of a class of large-scale interconnected minimum-phase nonlinear systems. In: Proceedings of the 37th IEEE Conference on Decision and Control. Tampa, Florida, USA: IEEE, 1998. 1482−1487

6 Xie S L, Xie L H. Decentralized global robust stabilization of a class of interconnected minimum-phase nonlinear systems. *Systems and Control Letters*, 2000, **41**(4): 251−263

7 Jain S, Khorrami F. Decentralized adaptive control of a class of large-scale interconnected nonlinear systems. *IEEE Transactions on Automatic Control*, 1997, **42**(2): 136−154

8 Khalil H. *Nonlinear Systems*. New Jersey: Prentice Hall, 1996

9 Liu Yi-Jun, Qin Hua-Shu. Stability of nonlinear systems with mismatched uncertainties via linear dynamic output feedback. *Acta Automatica Sinica*, 1998, **24**(2): 145−153
(刘一军, 秦化淑. 带有非匹配不确定性非线性系统的线性动态输出反馈镇定. 自动化学报, 1998, **24**(2): 145−153)

10 Zhou Shao-Sheng, Fei Shu-Min, Feng Chun-Bo. Control of muli-input cascade nonlinear systems with bounded disturbance. *Journal of Southeast University*, 1999, **29**(6): 1−4
(周绍生, 费树岷, 冯纯伯. 带有界扰动的多输入非线性串级系统的控制. 东南大学学报, 1999, **29**(6): 1−4)

傅 勤 南京理工大学动力工程学院博士研究生, 苏州科技学院应用数学系讲师. 主要研究方向为分散控制与非线性系统鲁棒控制. 本文通信作者. E-mail: fuqin925@sina.com
(**FU Qin** Ph. D. candidate in School of Power Engineering at Nanjing University of Science and Technology, lecturer in Department of Applied Mathematics at University of Science and Technology of Suzhou. His research interest covers decentralized control and robust control of nonlinear systems. Corresponding author of this paper.)

杨成梧 教授. 主要研究方向为 2D 系统, 广义系统, 采样系统和离散事件系统.
(**YANG Cheng-Wu** Professor. His research interest covers 2D systems, descriptor systems, sampled-data systems, and discrete event dynamic systems.)