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# 基于观测器的非线性互连系统的自适应模糊控制

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**摘 要**: 针对一类不确定非线性MIMO互连系统,提出一种自适应模糊控制算法. 通过设计观测器来估计系统的状态,因此不要求假设系统的状态是可测的. 给出的自适应律只对不确定界进行在线调节,从而大大减轻了在线计算负担. 该算法能够保证闭环系统的所有信号是一致有界的,并且跟踪误差指数收敛到一个小的零邻域内. 仿真结果表明了算法的可行性.

**关键词**: 非线性MIMO系统; 自适应模糊控制; 鲁棒控制; 观测器; 不确定性
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# Observer-based adaptive fuzzy control for a class of nonlinear interconnected systems

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**Abstract**: An adaptive fuzzy control algorithm is proposed for a class of nonlinear multiple-input multiple-output (MIMO) interconnected systems with uncertainty. The system states are estimated by the observer design. Thus it is not required to assume that system states are measurable. The estimations of the unknown bounds are only adjusted in the algorithm, therefore computing burden on-line is alleviated greatly. The proposed control algorithm can guarantee that all the signals of the closed-loop system are consistently bounded and the tracking errors exponentially converge to a small neighborhood of origin. A simulation result shows the effectiveness of the proposed algorithm.

**Key words**: Nonlinear MIMO systems; Adaptive fuzzy control; Robust control; Observer; Uncertainty

## 1 引 言

在实际中,许多系统都存在着复杂的非线性和不确定性,对这类系统的控制人们提出了多种方法,其中比较有效的一种方法是模糊控制. 这种方法可直接利用专家知识和操作人员的经验知识,而且不依赖于精确的数学模型. 近年来,人们对模糊控制进行了大量研究,通过将自适应控制与模糊控制相结合,基于万能逼近特性理论[1],提出了多种自适应模糊控制方法. 文献[2-7]针对SISO或MIMO非线性系统提出了几种自适应模糊控制算法. 然而,上述工作需要假定系统状态是可测的,因此提供的算法很难应用到系统状态不完全可测的情况.

一些研究者针对不确定非线性系统,提出了几种自适应模糊控制方法不需要状态可测的假设条件[8-13]. 在这些方法中,一个共同的缺点是提出的自适应控制算法对最优逼近参数向量的估计进行自适应调节,在线计算负担非常繁重,致使系统执行时间过长,从而影响了系统的控制性能. 另外,在文献[8-13]中需要假设逼近误差满足平方可积条件,或假设是有界的但界限是已知的. 事实上,如果逼近误差大于假设的界限或不满足平方可积条件,系统的稳定性或性能不能被保证,而且逼近误差满足平方可积条件在工程上很难实现.

考虑到已有文献的不足,针对一类不确定非线性MIMO互连系统,本文提出了一种自适应鲁棒模糊控制算法. 该算法利用模糊逻辑系统(FLS)去逼近系统的未知动态,通过鲁棒控制项来补偿函数逼近误差以及外部干扰对跟踪误差的影响. 在该算法中,通过设计观测器来估计系统的状态. 另外,该算法中给出的自适应律只对不确定界的估计进行自适应

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应在线调节,从而解决了 MIMO 系统的在线计算负担繁重的问题. 另外,该算法不需要假设逼近误差的界限已知或逼近误差满足平方可积条件,改善了闭环系统的鲁棒性. 本文提出的算法能够保证闭环系统的所有信号是一致有界的,并且跟踪误差指数收敛到一个小的零邻域内. 仿真结果表明了该算法的有效性.

## 2　问题描述

考虑非线性 MIMO 系统,它的第 $i$ 个子系统可以表示为[8]

$$y_i^{(n_i)} = f_i(\mathrm{x}_i) + g_i(\mathrm{x}_i)u_i + \Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p) + d_i. \quad (1)$$

其中: $u = [u_1 \cdots u_p]^{\mathrm{T}} \in R^p$ 为系统的输入向量, $y = [y_1 \cdots y_p]^{\mathrm{T}} \in R^p$ 为系统的输出向量, $d = [d_1 \cdots d_p]^{\mathrm{T}} \in R^p$ 为系统的外部干扰向量, $y_i^{(n_i)}$ 是 $y_i$ 的 $n_i$ 阶导数, $n_i$ 是正整数, $f_i(\mathrm{x}_i)$ 和 $g_i(\mathrm{x}_i)$ 对于 $i = 1, 2, \cdots, p$ 是未知的连续函数, $\Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p)$ 是子系统之间的互连项. 为了方便, 下文将利用 $\Phi_i$ 表示 $\Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p)$. $\mathrm{x}_i = (y_i \cdots y_i^{(n_i-1)})^{\mathrm{T}} \in R^{n_i}$ 表示子系统的状态是不完全可测的. $\mathrm{x} = (\mathrm{x}_1, \cdots, \mathrm{x}_p)^{\mathrm{T}}$ 是整个系统的状态变量.

假设给定的期望参考输出信号为 $y_r = [y_{r1} \cdots y_{rp}]^{\mathrm{T}} \in R^p$, $\mathrm{y}_{ri} = (y_{ri} \cdots y_{ri}^{(n_i-1)})^{\mathrm{T}} \in R^{n_i}$, 则跟踪误差可以定义为 $e_1 = y_{r1} - y_1, \cdots, e_p = y_{rp} - y_p$, $\mathrm{e}_i = \mathrm{y}_{ri} - \mathrm{x}_i = [e_i \; \dot{e}_i \cdots e_i^{(n_i-1)}]^{\mathrm{T}}$.

控制的目标是设计一个模糊控制器和调整相关参数的自适应律,使得闭环系统的所有信号都是有界的,并且跟踪误差 $e_i (i = 1, 2, \cdots, p)$ 尽可能地收敛到零. 经过简单推导,方程(1) 可被写成

$$\dot{\mathrm{e}}_i = A_i \mathrm{e}_i + B_i[-f_i(\mathrm{x}_i) - g_i(\mathrm{x}_i)u_i - \Phi_i + y_{ri}^{(n_i)} - d_i],$$
$$e_i = C^{\mathrm{T}} \mathrm{e}_i. \quad (2)$$

其中

$$A_i = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{n_i \times n_i},$$

$$B_i = \begin{bmatrix} 0 \\ 0 \\ \cdots \\ 0 \\ 1 \end{bmatrix}_{n_i \times 1}, \quad C_i = \begin{bmatrix} 1 \\ 0 \\ \cdots \\ 0 \\ 0 \end{bmatrix}_{n_i \times 1}.$$

在控制器设计过程中,下面的假设是需要的.

**假设 1**　存在已知常数 $g_{Li}$, 使得 $|g_i(\mathrm{x}_i)| \geq g_{Li} > 0$. 不失一般性, 假设 $g_i(\mathrm{x}_i) \geq g_{Li} > 0$, $\forall \mathrm{x}_i \in R^n$.

**假设 2**[8]　互连项 $\Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p)$ 满足下面的不等式:

$$|\Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p)| \leq \sum_{j=1}^{N} q_{ij} |y_j|^2,$$

其中 $q_{ij}$ 是已知常数.

**假设 3**　干扰 $d_i$ 是有界的, 即

$$|d_i| \leq \kappa_{di}, \quad (3)$$

其中 $\kappa_{di}$ 是未知的.

如果函数 $f_i(\mathrm{x}_i)$, $g_i(\mathrm{x}_i)$ 和 $\Phi_i$ 是已知的以及 $d_i = 0$, 则可以选择如下理想的控制器:

$$u_i^* = \frac{1}{g_i(\mathrm{x}_i)}(-f_i(\mathrm{x}_i) - \Phi_i + y_{ri}^{(n_i)} + K_c^{\mathrm{T}} \mathrm{e}_i), \quad (4)$$

其中 $K_{ci} = [k_{ci}^1, k_{ci}^2, \cdots, k_{ci}^{n_i}]^{\mathrm{T}} \in R^{n_i}$ 是反馈增益向量. 选择 $K_{ci} \in R^{n_i}$, 满足 $A_{ci} = A_i - B_i K_{ci}^{\mathrm{T}}$ 的特征多项式的所有根在复平面的左半平面. 也就是说, 选择方程(4) 所示的控制器 $u_i$, 可使得 $\lim_{t \to \infty} e_i(t) = 0$.

$f_i(\mathrm{x}_i)$, $g_i(\mathrm{x}_i)$ 和 $\Phi_i(t, \mathrm{x}_1, \cdots, \mathrm{x}_p)$ 是未知的, 并且 $d_i \neq 0$, 所以控制器(4) 是不可用的. 另外当系统的状态 $\mathrm{x}_i$ 不可测时, $e_i$ 也是不能用的.

## 3　自适应模糊控制器与自适应律的设计

由于模糊逻辑系统能以任意精度逼近任意非线性连续函数[1], 可通过模糊逻辑系统来逼近 $f_i(\mathrm{x}_i)$, $g_i(\mathrm{x}_i)$. 利用逼近的函数来执行控制器, 而产生的逼近误差通过设计的鲁棒控制器加以补偿.

控制器(4) 中跟踪误差向量 $\mathrm{e}_i$ 因状态不可测而不能被直接利用. 因此, 需要设计观测器来观测跟踪误差向量.

设计观测器

$$\dot{\hat{\mathrm{e}}}_i = A_i \hat{\mathrm{e}}_i - B_i K_{ci}^{\mathrm{T}} \hat{\mathrm{e}}_i + K_{0i}(e_i - \hat{e}_i),$$
$$\hat{e}_i = C_i^{\mathrm{T}} \hat{\mathrm{e}}_i. \quad (5)$$

其中: $\hat{e}_i = y_{ri} - \hat{y}_i$ 是跟踪误差估计, $\hat{\mathrm{e}}_i = \mathrm{y}_{ri} - \hat{\mathrm{x}}_i$ 是跟踪误差估计向量, $\hat{\mathrm{x}}_i$ 是 $\mathrm{x}_i$ 的估计向量, $K_{0i} = [k_{0i}^1, \cdots, k_{0i}^{n_i}]^{\mathrm{T}} \in R^{n_i}$ 是观测增益向量. 选择 $K_{0i} \in R^{n_i}$ 满足 $A_{0i} = A_i - K_{0i} C_i^{\mathrm{T}}$ 的特征多项式的所有根在复平面左半开平面.

观测误差定义为 $\tilde{e}_i = e_i - \hat{e}_i$, 观测误差向量为 $\tilde{\mathrm{e}}_i = \mathrm{e}_i - \hat{\mathrm{e}}_i$, 由式(2) 和(5) 可得到观测误差动态方程

$$\dot{\tilde{\mathrm{e}}}_i = A_{0i} \tilde{\mathrm{e}}_i + B_i K_{ci}^{\mathrm{T}} \hat{\mathrm{e}}_i + B_i[-f_i(\mathrm{x}_i) - g_i(\mathrm{x}_i)u_i - \Phi_i + y_{ri}^{(n_i)} - d_i],$$
$$\tilde{e}_i = C_i^{\mathrm{T}} \tilde{\mathrm{e}}_i. \quad (6)$$

根据模糊逻辑系统的万能逼近特性, 未知的非

线性函数 $f_i(x_i)$, $g_i(x_i)$ 可表示如下:

$$f_i(x_i) = \theta_{fi}^{*T}\xi_{fi}(\hat{x}_i) + \Delta f_i(\hat{x}_i), \tag{7}$$

$$g_i(x_i) = \theta_{gi}^{*T}\xi_{gi}(\hat{x}_i) + \Delta g_i(\hat{x}_i). \tag{8}$$

其中:$\hat{x}_i$ 为状态向量 $x_i$ 的估计, $\theta_{fi}^*$ 和 $\theta_{gi}^*$ 为未知最优逼近参数向量, $\xi_{fi}(\hat{x}_i)$ 和 $\xi_{gi}(\hat{x}_i)$ 为模糊基函数向量, $\Delta f_i(\hat{x}_i)$ 和 $\Delta g_i(\hat{x}_i)$ 为最优逼近误差.

**假设 4** 逼近误差 $\Delta f_i(\hat{x}_i)$ 和 $\Delta g_i(\hat{x}_i)$ 是有界的,即

$$|\Delta f_i(\hat{x}_i)| \leq l_{fi}, \ |\Delta g_i(\hat{x}_i)| \leq b_{gi}, \tag{9}$$

其中 $l_{fi}$ 和 $b_{gi}$ 是未知的.

根据式(3) 和(9),可得

$$\Delta f_i(\hat{x}_i) + d_i \leq$$
$$|\Delta f_i(\hat{x}_i)| + |d_i| \leq l_{fi} + \kappa_{di} = b_{fi},$$

其中 $b_{fi}$ 是未知正的常数.

定义标称参数向量 $\theta_{fi}$ 和 $\theta_{gi}$,相应的标称函数分别为 $f_i^0(\hat{x}_i)$, $g_i^0(\hat{x}_i)$, 其中 $g_i^0(\hat{x}_i) \neq 0$. 已知函数 $f_i^0(\hat{x}_i)$, $g_i^0(\hat{x}_i)$ 可用模糊系统表示为

$$f_i^0(\hat{x}_i) = \theta_{fi}^{T}\xi_{fi}(\hat{x}_i), \tag{10}$$

$$g_i^0(\hat{x}_i) = \theta_{gi}^{T}\xi_{gi}(\hat{x}_i), \tag{11}$$

其中 $\xi_{fi}(\hat{x}_i)$ 和 $\xi_{gi}(\hat{x}_i)$ 可通过模糊隶属度函数求得.

定义 $\tilde{\theta}_{fi} = \theta_{fi}^* - \theta_{fi}$, $\tilde{\theta}_{gi} = \theta_{gi}^* - \theta_{gi}$,作如下假设:

$$\|\tilde{\theta}_{fi}\| \leq p_{fi}, \quad \|\tilde{\theta}_{gi}\| \leq p_{gi}.$$

其中:$p_{fi}$ 和 $p_{gi}$ 是未知的, $\|\cdot\|$ 表示 2 范数.

给出如下控制器:

$$u_i = u_{0i} + u_{ci}, \tag{12}$$

其中 $u_{0i}$ 表示标称控制器,定义如下:

$$u_{0i} = \frac{1}{g_i^0(\hat{x}_i)}\Big[-f_i^0(\hat{x}_i) + y_{ri}^{(n_i)} + K_c^{T}\hat{e}_i - \operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2\Big]. \tag{13}$$

其中 $L_i(s)$ 和 $u_{ci}$ 是为了补偿函数逼近误差和外部干扰的影响,将稍后定义.

将式(12),(13) 代入(6),整理后得

$$\begin{cases}\dot{\tilde{e}}_i = \\ A_{0i}\tilde{e}_i - B_i\Big[(f_i - f_i^0) + (g_i - g_i^0)u_{0i} - \\ \operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2 - \Phi_i + (g_i u_{ci} + d_i)\Big], \\ \tilde{e}_i = C_i^{T}\tilde{e}_i.\end{cases} \tag{14}$$

再将式(7),(8),(10),(11) 代入(14),进一步整理得

$$\dot{\tilde{e}}_i = A_{0i}\tilde{e}_i + B_i\Big[-(\tilde{\theta}_{fi}^{T}\xi_{fi}(\hat{x}_i) + \Delta f_i(\hat{x}_i) + d_i) - \Phi_i - \operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2 - (\tilde{\theta}_{gi}^{T}\xi_{gi}(\hat{x}_i) + \Delta g_i(\hat{x})) u_{0i} - g_i u_{ci}\Big]. \tag{15}$$

式(15) 可重新写成

$$\tilde{e}_i = H_i(s)\Big[-(\tilde{\theta}_{fi}^{T}\xi_{fi}(\hat{x}_i) + \Delta f_i(\hat{x}_i) + d_i) - \Phi_i - \operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2 - (\tilde{\theta}_{gi}^{T}\xi_{gi}(\hat{x}_i) + \Delta g_i(\hat{x}_i)) u_{0i} - g_i u_{ci}\Big], \tag{16}$$

其中 $H_i(s) = C_i^{T}(I - s(A_{0i} - K_{0i}C_i^{T}))^{-1}B_i$ 是传递函数, $s$ 是拉普拉斯变量.

为了利用严格正实(SPR) 李雅普诺夫设计方法,式(16) 进一步可变为

$$\tilde{e}_i = H_i(s)L_i(s)\Big[-L_i^{-1}(s)(\tilde{\theta}_{fi}^{T}\xi_{fi}(\hat{x}_i) + \Delta f_i(\hat{x}_i) + d_i) - \Phi_i - L_i^{-1}(s)g_i u_{ci} - \operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2\Big] - L_i^{-1}(s)(\tilde{\theta}_{gi}^{T}\xi_{gi}(\hat{x}_i) + \Delta g_i(\hat{x}_i))u_{0i}. \tag{17}$$

其中选择 $L_i(s)$ 满足 $L_i^{-1}(s)$ 是一个适当的稳定传递函数和 $H_i(s)L_i(s)$ 是一个适当的严格正实传递函数, $L_i(s) = s^{m_i} + b_1 s^{m_i - 1} + \cdots + b_{m_i}$, $m_i = n_i - 1$. 则式(17) 的状态空间实现为

$$\begin{cases}\dot{\tilde{e}}_i = \\ A_{0i}\tilde{e}_i + B_{ci}\Big[-L_i^{-1}(s)(\tilde{\theta}_{fi}^{T}\xi_{fi}(\hat{x}_i) + \Delta f_i(\hat{x}_i) + d_i) - \\ L_i^{-1}(s)(\tilde{\theta}_{gi}^{T}\xi_{gi}(\hat{x}_i) + \Delta g_i(\hat{x}_i))u_{0i} - \\ L_i^{-1}(s)\operatorname{sgn}(L_i^{-1}(s)\tilde{e}_i)\sum_{j=1}^{N} q_{ij}|y_j|^2 - \\ L_i^{-1}(s)\Phi_i - L_i^{-1}(s)g_i u_{ci}\Big], \\ \tilde{e}_i = C_{ci}^{T}\tilde{e}_i.\end{cases}$$

其中

$$B_{ci} = [1, b_1, b_2, \cdots, b_{m_i}]^{T}, \quad C_{ci} = [1, 0, \cdots, 0]^{T}.$$

假设存在对称正定矩阵 $P_{1i}, P_{2i}, Q_{1i}, Q_{2i}$ 满足

$$A_{ci}^{T}P_{1i} + P_{1i}A_{ci} + P_{1i}K_{0i}K_{0i}^{T}P_{1i} = -Q_{1i}, \tag{18}$$

$$\begin{cases}A_{0i}^{T}P_{2i} + P_{2i}A_{0i} + C_iC_i^{T} = -Q_{2i}, \\ P_{2i}B_{ci} = C_{ci}.\end{cases} \tag{19}$$

控制律(14) 中的 $u_{ci}$ 选择如下:

$$u_{ci} = \theta_{fi}^{T}\xi_{fi}(\hat{x}) + u_{1i} + [\theta_{gi}^{T}\xi_{gi}(\hat{x}_i) + u_{2i}]u_{0i}, \tag{20}$$

$$\theta_{fi}^{T} = \frac{\hat{p}_{fi}^2}{g_{Li}}\frac{\tilde{e}_iL_i^{-1}(s)\xi_{fi}^{T}(\hat{x}_i)}{\hat{p}_{fi}|\tilde{e}_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat{x}_i)\| + \rho_{fi}^0}, \tag{21}$$

$$u_{1i} = \frac{\hat{b}_{fi}^2}{g_{Li}}\frac{\tilde{e}_iL_i^{-1}(s)}{\hat{b}_{fi}|\tilde{e}_i||L_i^{-1}(s)| + \rho_{fi}^1}, \tag{22}$$

$$\theta_{gi}^{T} = \frac{\hat{p}_{gi}^2}{g_{Li}}\frac{\tilde{e}_iL_i^{-1}(s)\xi_{gi}^{T}(\hat{x}_i)u_{0i}}{\hat{p}_{gi}|\tilde{e}_i|\,\|L_i^{-1}(s)\xi_{gi}^{T}(\hat{x}_i)u_{0i}\| + \rho_{gi}^0}, \tag{23}$$

$$u_{2i} = \frac{\hat{b}_{gi}^2}{g_{Li}}\frac{\tilde{e}_iL_i^{-1}(s)u_{0i}}{\hat{b}_{gi}|\tilde{e}_i||L_i^{-1}(s)u_{0i}| + \rho_{gi}^1}. \tag{24}$$

其中: $\rho^0_{fi},\rho^1_{fi},\rho^0_{gi},\rho^1_{gi}>0$ 是设计参数; $\hat p_{fi},\hat p_{gi},\hat b_{fi},\hat b_{gi}$ 分别是 $p_{fi},p_{gi},b_{fi},b_{gi}$ 的估计值, 且 $\hat p_{fi},\hat p_{gi},\hat b_{fi},\hat b_{gi}>0$. 选择如下的自适应律:

$$\dot{\hat p}_{fi} = -\delta^0_{fi}\hat p_{fi} + \gamma^0_{fi}|\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\|, \tag{25}$$

$$\dot{\hat b}_{fi} = -\delta^1_{fi}\hat b_{fi} + \gamma^1_{fi}|\tilde e_i L_i^{-1}(s)|, \tag{26}$$

$$\dot{\hat p}_{gi} = -\delta^0_{gi}\hat p_{gi} + \gamma^0_{gi}|\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)u_{0i}\|, \tag{27}$$

$$\dot{\hat b}_{gi} = -\delta^1_{gi}\hat b_{gi} + \gamma^1_{gi}|\tilde e_i L_i^{-1}(s)u_{0i}|, \tag{28}$$

其中 $\delta^0_{fi},\delta^1_{fi},\delta^0_{gi},\delta^1_{gi}>0$ 和 $\gamma^0_{fi},\gamma^1_{fi},\gamma^0_{gi},\gamma^1_{gi}>0$ 是设计参数.

## 4　稳定性与性能分析

下面的定理给出了稳定性结果.

**定理 1**　针对非线性系统(1), 在适当的假设条件下, 采用式(12), (13) 和(20) 给出的控制律, 以及(25) ～ (28) 所示的参数自适应调节律, 则有:

1) 信号 $\hat e_i,\tilde e_i$ 和估计参数 $\hat p_{fi},\hat b_{fi},\hat p_{gi},\hat b_{gi}$ 都是有界的;

2) 跟踪误差 $e_i$ 指数收敛到一个小的零邻域内.

**证明**　1) 将式(20) 代入(17), 整理后得

$$\begin{cases}\dot{\tilde e}_i = A_{0i}\tilde e_i + B_{ci}\big[-L_i^{-1}(s)(\theta_{fi}^{T}\xi_{fi}(\hat x_i) + \Delta f_i(\hat x_i) + d_i) - L_i^{-1}(s)(\theta_{gi}^{T}\xi_{gi}(\hat x_i) + \Delta g_i(\hat x_i))u_{0i} - L_i^{-1}(s)\Phi_i - \\ \quad L_i^{-1}(s)\,\mathrm{sgn}(L_i^{-1}(s)\tilde e_i)\sum_{j=1}^{N}q_{ij}|y_j|^2 - L_i^{-1}(s)g_i(\theta_{fi}^{T}\xi_{fi}(\hat x_i) + u_{1i} + (\theta_{gi}^{T}\xi_{gi}(\hat x_i) + u_{2i})u_{0i})\big], \\ \tilde e_i = C_{ci}^{T}\tilde e_i.\end{cases} \tag{29}$$

令

$$\tilde p_{fi} = \hat p_{fi} - p_{fi},\ \tilde p_{gi} = \hat p_{gi} - p_{gi},$$
$$\tilde b_{fi} = \hat b_{fi} - b_{fi},\ \tilde b_{gi} = \hat b_{gi} - b_{gi}.$$

选取如下正定的李雅普诺夫函数:

$$V_i = \frac12\hat e_i^{T}P_{1i}\hat e_i + \frac12\tilde e_i^{T}P_{2i}\tilde e_i + \frac{\tilde p_{fi}^2}{2\gamma^0_{fi}} + \frac{\tilde b_{fi}^2}{2\gamma^1_{fi}} + \frac{\tilde p_{gi}^2}{2\gamma^0_{gi}} + \frac{\tilde b_{gi}^2}{2\gamma^1_{gi}}, \tag{30}$$

则

$$\dot V_i = \frac12\dot{\hat e}_i^{T}P_{1i}\hat e_i + \frac12\hat e_i^{T}P_{1i}\dot{\hat e}_i + \frac12\dot{\tilde e}_i^{T}P_{2i}\tilde e_i + \frac12\tilde e_i^{T}P_{2i}\dot{\tilde e}_i + \frac{1}{\gamma^0_{fi}}\tilde p_{fi}\dot{\hat p}_{fi} + \frac{1}{\gamma^1_{fi}}\tilde b_{fi}\dot{\hat b}_{fi} + \frac{1}{\gamma^0_{gi}}\tilde p_{gi}\dot{\hat p}_{gi} + \frac{1}{\gamma^1_{gi}}\tilde b_{gi}\dot{\hat b}_{gi}. \tag{31}$$

将式(5), (29) 代入(31), 整理后得

$$\begin{aligned}\dot V_i = {} & \frac12\hat e_i^{T}(A_{ci}^{T}P_{1i} + P_{1i}A_{ci})\hat e_i + \frac12\tilde e_i^{T}(A_{0i}^{T}P_{2i} + P_{2i}A_{0i})\tilde e_i + \tilde e_i^{T}C_iK_{0i}^{T}P_{1i}\hat e_i - \\ & \tilde e_i[(\theta_{fi}^{T} + g_i\theta_{fi}^{T})L_i^{-1}(s)\xi_{fi}(\hat x_i) + L_i^{-1}(s)(\Delta f_i(\hat x_i) + d_i + g_{ii}u_{1i}) + \\ & (\theta_{gi}^{T} + g_i\theta_{gi}^{T})L_i^{-1}(s)\xi_{gi}(\hat x_i)u_{0i} + L_i^{-1}(s)(\Delta g_i(\hat x_i) + g_iu_{2i})u_{0i}] - \tilde e_iL_i^{-1}(s)\Phi_i - \\ & \tilde e_iL_i^{-1}(s)\,\mathrm{sgn}(L_i^{-1}(s)\tilde e_i)\sum_{j=1}^{N}q_{ij}|y_j|^2 + \\ & \frac{1}{\gamma^0_{fi}}\tilde p_{fi}\dot{\hat p}_{fi} + \frac{1}{\gamma^1_{fi}}\tilde b_{fi}\dot{\hat b}_{fi} + \frac{1}{\gamma^0_{gi}}\tilde p_{gi}\dot{\hat p}_{gi} + \frac{1}{\gamma^1_{gi}}\tilde b_{gi}\dot{\hat b}_{gi}.\end{aligned} \tag{32}$$

根据不等式

$$ab \le ka^2/2 + b^2/2k,\quad \forall k > 0,$$

可知下式成立:

$$\tilde e_i^{T}C_iK_{0i}^{T}P_{1i}\hat e_i \le \frac12\tilde e_i^{T}C_iC_i^{T}\tilde e_i + \frac12\hat e_i^{T}P_{1i}K_{0i}K_{0i}^{T}P_{1i}\hat e_i. \tag{33}$$

利用式(18), (19), (33), 可得下面的不等式成立:

$$\begin{aligned}\dot V_i \le {} & \Big(-\frac12\hat e_i^{T}Q_{1i}\hat e_i - \frac12\tilde e_i^{T}Q_{2i}\tilde e_i\Big) + \\ & \Big[-\tilde e_i(\theta_{fi}^{T} + g_i\theta_{fi}^{T})L_i^{-1}(s)\xi_{fi}(\hat x_i) + \frac{1}{\gamma^0_{fi}}\tilde p_{fi}\dot{\hat p}_{fi}\Big] + \\ & \Big[-\tilde e_iL_i^{-1}(s)(\Delta f_i(\hat x_i) + d_i + g_iu_{1i}) + \frac{1}{\gamma^1_{fi}}\tilde b_{fi}\dot{\hat b}_{fi}\Big] + \\ & \Big[-\tilde e_iL_i^{-1}(s)(\theta_{gi}^{T} + g_i\theta_{gi}^{T})\xi_{gi}(\hat x_i)u_{0i} + \frac{1}{\gamma^0_{gi}}\tilde p_{gi}\dot{\hat p}_{gi}\Big] + \\ & \Big[-\tilde e_iL_i^{-1}(s)(\Delta g_i(\hat x_i) + g_iu_{2i})u_{0i} + \frac{1}{\gamma^1_{gi}}\tilde b_{gi}\dot{\hat b}_{gi}\Big] + \\ & \Big[-\tilde e_iL_i^{-1}(s)\Phi_i - \tilde e_iL_i^{-1}(s)\times \mathrm{sgn}(L_i^{-1}(s)\tilde e_i)\sum_{j=1}^{N}q_{ij}|y_j|^2\Big].\end{aligned} \tag{34}$$

利用式(21) 和(25), 方程式(34) 不等号右端第 2 项满足下面不等式:

$$\begin{aligned} & -\tilde e_i(\theta_{fi}^{T} + g_i\theta_{fi}^{T})L_i^{-1}(s)\xi_{fi}(\hat x_i) + \frac{1}{\gamma^0_{fi}}\tilde p_{fi}\dot{\hat p}_{fi} \le \\ & p_{fi}|\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\| - g_{Li}\tilde e_i\theta_{fi}^{T}L_i^{-1}(s)\xi_{fi}(\hat x_i) + \frac{1}{\gamma^0_{fi}}\tilde p_{fi}\dot{\hat p}_{fi} = \\ & \hat p_{fi}|\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\| - \frac{(\hat p_{fi})^2|\tilde e_i|^2\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\|^2}{\hat p_{fi}|\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\| + \rho^0_{fi}} - \\ & \tilde p_{fi}\Big(\frac{1}{\gamma^0_{fi}}\dot{\hat p}_{fi} - |\tilde e_i|\,\|L_i^{-1}(s)\xi_{fi}(\hat x_i)\|\Big) \le \\ & \rho^0_{fi} - \frac{\delta^0_{fi}}{\gamma^0_{fi}}\tilde p_{fi}\hat p_{fi} = \rho^0_{fi} - \frac{\delta^0_{fi}}{\gamma^0_{fi}}\tilde p_{fi}^2 - \frac{\delta^0_{fi}}{\gamma^0_{fi}}\tilde p_{fi}p_{fi} \le\end{aligned}$$

$$\rho^0_{fi} - \frac{\delta_{fi}}{\gamma^0_{fi}}\tilde{p}^2_{fi} + \frac{\delta_{fi}}{\gamma^0_{fi}}p^2_{fi}. \tag{35}$$

利用式(22)和(26),可得下面不等式:

$$-\tilde{e}_i L_i^{-1}(s)(\Delta f_i(\hat{x}_i) + d_i + g_i u_{1i}) + \frac{1}{\gamma^1_{fi}}\tilde{b}_{fi}\dot{\hat{b}}_{fi} \le$$

$$b_{fi} L_i^{-1}(s)|\tilde{e}_i| - \tilde{e}_i g_{Li} L_i^{-1}(s) u_{1i} + \frac{1}{\gamma^1_{fi}}\tilde{b}_{fi}\dot{\hat{b}}_{fi} \le$$

$$b_{fi}L_i^{-1}(s)|\tilde{e}_i| - (\hat{b}_{fi})^2 \frac{\tilde{e}_i L_i^{-1}(s)}{\hat{b}_{fi}|\tilde{e}_i||L_i^{-1}(s)| + \rho^1_{fi}} +$$

$$\tilde{b}_{fi}\Big(\frac{1}{\gamma^1_{fi}}\dot{\hat{b}}_{fi} - |\tilde{e}_i||L_i^{-1}(s)|\Big) \le$$

$$\rho^1_{fi} - \frac{\delta_{fi}}{\gamma^1_{fi}}\tilde{b}_{fi}\hat{b}_{fi} \le \rho^1_{fi} - \frac{\delta_{fi}}{\gamma^1_{fi}}\tilde{b}^2_{fi} + \frac{\delta_{fi}}{\gamma^1_{fi}}b^2_{fi}. \tag{36}$$

用同样的方法进行推导,方程式(34)不等号右端第4项和第5项满足下面不等式:

$$-\tilde{e}_i L_i^{-1}(s)(\theta^{\mathrm{T}}_{gi} + g_i\theta^{\mathrm{T}}_{gi})\xi_{gi}(\hat{x}_i)u_{0i} + \frac{1}{\gamma^0_{gi}}\tilde{p}_{gi}\dot{\hat{p}}_{gi} \le$$

$$\rho^0_{gi} - \frac{\delta_{gi}}{\gamma^0_{gi}}\tilde{p}^2_{gi} + \frac{\delta_{gi}}{\gamma^0_{gi}}p^2_{gi}, \tag{37}$$

$$-\tilde{e}_i L_i^{-1}(s)(\Delta g_i(\hat{x}_i) + g_i u_{2i})u_{0i} + \frac{1}{\gamma^1_{gi}}\tilde{b}_{gi}\dot{\hat{b}}_{gi} \le$$

$$\rho^1_{gi} - \frac{\delta_{gi}}{\gamma^1_{gi}}\tilde{b}^2_{gi} + \frac{\delta_{gi}}{\gamma^1_{gi}}b^2_{gi}. \tag{38}$$

根据假设2,有

$$-\tilde{e}_i L_i^{-1}(s)\Phi_i \le |\tilde{e}_i L_i^{-1}(s)||\Phi_i| \le$$

$$|\tilde{e}_i L_i^{-1}(s)|\sum_{j=1}^{N} q_{ij}|y_j|^2. \tag{39}$$

综合式(34)～(39)可得

$$\dot{V}_i \le -\frac{1}{2}\hat{e}_i^{\mathrm{T}}Q_{1i}\hat{e}_i - \frac{1}{2}\tilde{e}_i^{\mathrm{T}}Q_{2i}\tilde{e}_i - \frac{\delta_{fi}}{\gamma^0_{fi}}\tilde{p}^2_{fi} - \frac{\delta_{fi}}{\gamma^1_{fi}}\tilde{b}^2_{fi} - \frac{\delta_{gi}}{\gamma^0_{gi}}\tilde{p}^2_{gi} - \frac{\delta_{gi}}{\gamma^1_{gi}}\tilde{b}^2_{gi} + \frac{\delta_{fi}}{\gamma^0_{fi}}p^2_{fi} + \frac{\delta_{fi}}{\gamma^1_{fi}}b^2_{fi} + \frac{\delta_{gi}}{\gamma^0_{gi}}p^2_{gi} + \frac{\delta_{gi}}{\gamma^1_{gi}}b^2_{gi} + \rho^0_{fi} + \rho^1_{fi} + \rho^0_{gi} + \rho^1_{gi}. \tag{40}$$

上式可简化为

$$\dot{V}_i \le -2\alpha_i V_i + \rho_i. \tag{41}$$

其中

$$\alpha_i = \min\Big(\frac{1}{2}\frac{\lambda_{\min}(Q_{1i})}{\lambda_{\max}(P_{1i})}, \frac{1}{2}\frac{\lambda_{\min}(Q_{2i})}{\lambda_{\max}(P_{2i})}, \delta_{fi}, \delta_{fi}, \delta_{gi}, \delta_{gi}\Big),$$

$$\rho_i = \frac{\delta_{fi}}{\gamma^0_{fi}}p^2_{fi} + \frac{\delta_{fi}}{\gamma^1_{fi}}p^2_{fi} + \frac{\delta_{gi}}{\gamma^0_{gi}}p^2_{gi} + \frac{\delta_{gi}}{\gamma^1_{gi}}p^2_{gi} + \rho^0_{fi} + \rho^1_{fi} + \rho^0_{gi} + \rho^1_{gi}.$$

将式(41)两端从0到$t$积分,有

$$V_i(t) \le \Big[V_i(0) - \frac{\rho_i}{2\alpha_i}\Big]\mathrm{e}^{-2\alpha_i t} + \frac{\rho_i}{2\alpha_i}. \tag{42}$$

选择式(21),(22)中的$P_{1i}$, $P_{2i}$,下面的不等式是成立的:

$$\lambda_{\min}(P_{1i})\|\hat{e}_i\|^2 \le \hat{e}_i^{\mathrm{T}}P_{1i}\hat{e}_i,$$

$$\lambda_{\min}(P_{2i})\|\tilde{e}_i\|^2 \le \tilde{e}_i^{\mathrm{T}}P_{2i}\tilde{e}_i. \tag{43}$$

再利用式(30),进一步可得

$$\lambda_{\min}(P_{1i})\|\hat{e}_i\|^2 \le \Big[2V_i(0) - \frac{\rho_i}{\alpha_i}\Big]\mathrm{e}^{-2\alpha_i t} + \frac{\rho_i}{\alpha_i} - \lambda_{\min}(P_{2i})\|\tilde{e}_i\|^2. \tag{44}$$

由上式可知,$\hat{e}_i$是有界的.同理可知,$\tilde{e}_i$是有界的.通过式(43),再利用(30),下面的不等式成立:

$$V_i(t) \ge \frac{1}{2}\lambda_{\min}(P_{1i})\|\hat{e}_i\|^2 + \frac{1}{2}\lambda_{\min}(P_{2i})\|\tilde{e}_i\|^2 + \frac{\tilde{p}^2_{fi}}{2\gamma^0_{fi}}.$$

整理上式,可得

$$\tilde{p}^2_{fi} \le 2\gamma^0_{fi}\Big(V_i(t) - \frac{1}{2}\lambda_{\min}(P_{1i})\|\hat{e}_i\|^2 - \frac{1}{2}\lambda_{\min}(P_{2i})\|\tilde{e}_i\|^2\Big).$$

再结合式(42)可知,$\tilde{p}_{fi}$是有界的.又由于$\tilde{p}_{fi} = \hat{p}_{fi} - p_{fi}$, $p_{fi}$有界,则$\hat{p}_{fi}$有界.同理可知,其他的在线估计参数$\hat{b}_{fi}$, $\hat{p}_{gi}$, $\hat{b}_{gi}$都是有界的.

因$\|\hat{e}_i\| = \sqrt{\hat{e}_i^2 + \dot{\hat{e}}_i^2 + \cdots + (\hat{e}_i^{(n_i-1)})^2}$,所以$|\hat{e}_i| \le \|\hat{e}_i\|$.再结合式(44)可知,跟踪误差$\hat{e}_i$指数收敛到球心在原点,半径为$\Big(\frac{\rho_i}{\alpha_i\lambda_{\min}(P_{1i})} - \frac{\lambda_{\min}(P_{2i})\|\tilde{e}_i\|^2}{\lambda_{\min}(P_{1i})}\Big)^{1/2}$的邻域内. □

## 5 仿真实验

考虑质量-弹簧-阻尼系统,该机械系统的运动方程可表示如下[5]:

$$M_1\ddot{y}_1 = u_1 - f_{K_1}(x) - f_{B_1}(x) + f_{K_2}(x) + f_{B_2}(x) - f_{C_1}(x) + f_{C_2}(x) + d_1, \tag{45}$$

$$M_2\ddot{y}_2 = u_2 - f_{K_2}(x) - f_{B_2}(x) - f_{C_2}(x) + d_2. \tag{46}$$

式中

$$x = (y_1, \dot{y}_1, y_2, \dot{y}_2)^{\mathrm{T}},$$

$$f_{K_1}(x) = K_{10}y_1 + \Delta K_1 y_1^3,$$

$$f_{K_2}(x) = K_{20}(y_2 - y_1) + \Delta K_2(y_2 - y_1)^3,$$

$$M_1 = M_2 = 0.2,\ f_{B_1}(x) = B_{10}\dot{y}_1 + \Delta B_1\dot{y}_{21},$$

$$f_{B_2}(x) = B_{20}(\dot{y}_2 - \dot{y}_1) + \Delta B_2(\dot{y}_2 - \dot{y}_1)^2.$$

其中:$f_{K_1}(x)$, $f_{K_2}(x)$为弹力;$f_{B_1}(x)$, $f_{B_2}(x)$为摩擦力;$K_{10} = 1$, $\Delta K_1 = 0.1$, $K_{20} = 2$, $\Delta K_2 = 0.12$; $B_{10} = 2$, $\Delta B_1 = 0.2$, $B_{20} = 2.2$, $\Delta B_2 = 0.15$;静摩擦力$f_{C_1} = 0.02\mathrm{sgn}(\dot{y}_1)$, $f_{C_2} = 0.02\mathrm{sgn}(\dot{y}_2 - \dot{y}_1)$; $d_1 = 0.2\sin(3t)\exp(-0.2t)$, $d_2 = 0.2\cos(3t)\exp(-0.1t)$.假设期望的输出信号为$y_{r1}(t) = 0.5\sin(2t)$, $y_{r2}(t) = 0.5\cos t$.

对每个 $x_i(i=1,2,3,4)$ 定义 5 个模糊集合 $F_i^r(r=1,2,\cdots,5)$,对应的隶属度函数为

$$\mu_{F_i^1}(x_i)=1/(1+\exp(5(x_i+1))),$$

$$\mu_{F_i^2}(x_i)=\exp(-2(x_i+0.5)^2),$$

$$\mu_{F_i^3}(x_i)=\exp(-2x_i^2),$$

$$\mu_{F_i^4}(x_i)=\exp(-2(x_i-0.5)^2),$$

$$\mu_{F_i^5}(x_i)=1/(1+\exp(-5(x_i-1))).$$

定义如下 10 个模糊规则:

$R^{(l)}$: 如果 $x_1$ 是 $F_1^m$ 且 $x_3$ 是 $F_3^m$,则 $y$ 是 $F^l$, $m, l=1,2,\cdots,5$;

$R^{(l)}$: 如果 $x_2$ 是 $F_2^m$ 且 $x_4$ 是 $F_4^m$,则 $y$ 是 $F^l$, $m=1,2,\cdots,5$, $l=6,7,\cdots,10$; $\xi_{f1}=[\xi_{f11},\xi_{f12},\cdots,\xi_{f110}]^{\mathrm{T}}\in R^{10}$.

其中

$$\xi_{f11}=\mu_{F_1^1}(x_1)\mu_{F_3^1}(x_3)/D_1,\cdots,$$

$$\xi_{f15}=\mu_{F_1^5}(x_1)\mu_{F_3^5}(x_3)/D_1,$$

$$\xi_{f16}=\mu_{F_2^1}(x_2)\mu_{F_4^1}(x_4)/D_2,\cdots,$$

$$\xi_{f110}=\mu_{F_2^5}(x_2)\mu_{F_4^5}(x_4)/D_2,$$

$$D_1=\sum_{m=1}^{5}\mu_{F_1^m}(x_1)\mu_{F_3^m}(x_3),$$

$$D_2=\sum_{m=1}^{5}\mu_{F_2^m}(x_2)\mu_{F_4^m}(x_4),$$

选择 $\xi_{f2}=\xi_{f1}$.

为了逼近函数 $g_i(x)$, $x_1$ 和 $x_3$,分别定义 3 个模糊集 $G_i^r(r=1,2,3)$,相应的隶属度函数为

$$\mu_{G_i^1}(x_i)=1/(1+\exp(5(x_i+0.5))),$$

$$\mu_{F_i^2}(x_i)=\exp(-2x_i^2),$$

$$\mu_{G_i^3}(x_i)=1/(1+\exp(-5(x_i-0.5))).$$

定义 3 个模糊规则如下:

$R^{(l)}$: 如果 $x_1$ 是 $G_1^n$ 且 $x_3$ 是 $G_3^n$,则 $y$ 是 $G^l$, $n,l=1,2,3$, $\xi_{g1}=[\xi_{g11},\xi_{g12},\xi_{g13}]^{\mathrm{T}}\in R^3$,选择 $\xi_{g2}=\xi_{g1}$.

选择反馈增益向量 $K_{c1}=K_{c2}=[1,2]^{\mathrm{T}}$,观测增益向量 $K_{01}=K_{02}=[1,2]^{\mathrm{T}}$,控制律(10),(11)中的标称参数向量 $\theta_{f1}=\theta_{f2}=[0.2,0.2,0.5,0.3,0.1,0.4,0.5,0.6,0.7,0.8]^{\mathrm{T}}$, $\theta_{g1}=\theta_{g2}=[2,3,4]^{\mathrm{T}}$. 选择正定阵 $Q_1=Q_2=\mathrm{diag}(10,10)$, $g_{L1}=g_{L2}=0.1$, $A_1=A_2=[0,1;0,0]$, $B_1=B_2=[0,1]^{\mathrm{T}}$, $C_1=C_2=[1,0]^{\mathrm{T}}$, $K_{c1}=K_{c2}=[1,2]^{\mathrm{T}}$. 控制律(21)～(24)中的设计参数 $\rho_{f1}^0=\rho_{f1}^1=\rho_{g1}^0=\rho_{g1}^1=0.01$, $\rho_{f2}^0=\rho_{f2}^1=\rho_{g2}^0=\rho_{g2}^1=0.01$;自适应律(25)～(28)中的设计参数 $\delta_{f1}^0=\delta_{f1}^1=\delta_{g1}^0=\delta_{g1}^1=10$, $\delta_{f2}^0=10$, $\delta_{f2}^1=20$, $\delta_{g2}^0=30$, $\delta_{g2}^1=40$, $\gamma_{f1}^0=\gamma_{f1}^1=\gamma_{g1}^0=\gamma_{g1}^1=5$, $\gamma_{f2}^0=\gamma_{f2}^1=\gamma_{g2}^0=\gamma_{g2}^1=5$. 自适应调节参数的初始条件选择为 $\hat{p}_{f1}(0)=\hat{b}_{f1}(0)=\hat{p}_{g1}(0)=\hat{b}_{g1}(0)=0.05$, $\hat{p}_{f2}(0)=\hat{b}_{f2}(0)=\hat{p}_{g2}(0)=\hat{b}_{g2}(0)=0.05$, 控制的目标是使系统的输出 $y_1$, $y_2$ 跟踪期望的参考输出 $y_{r1}$, $y_{r2}$.

系统(45)和(46)的初始状态选择为 $y_1(0)=0.5$, $y_2(0)=0$,仿真结果如图 1～图 4 所示. 从图 1 和图 2 可以看出,系统的输出 $y_1$, $y_2$ 分别可以很好地跟踪期望的参考输出 $y_{r1}$, $y_{r2}$;从图 3 和图 4 可以看出,误差估计 $\hat{e}_1$ 和 $\hat{e}_2$ 收敛到小的零邻域内,而且控制律 $u_1$, $u_2$ 都是有界的,说明了提出算法的有效性.

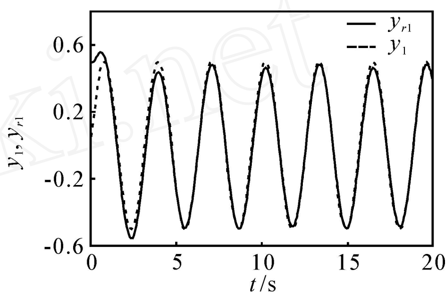


图 1　系统输出 $y_1$ 跟踪参考输出 $y_{r1}$ 曲线

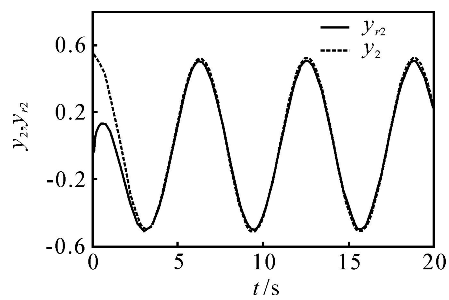


图 2　系统输出 $y_2$ 跟踪参考输出 $y_{r2}$ 曲线

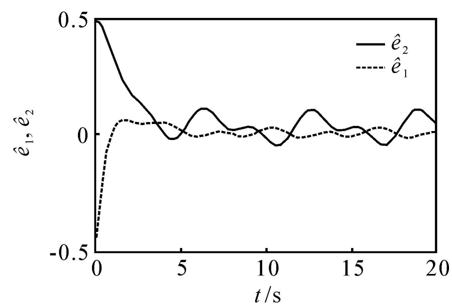


图 3　误差估计 $\hat{e}_1$ 和 $\hat{e}_2$

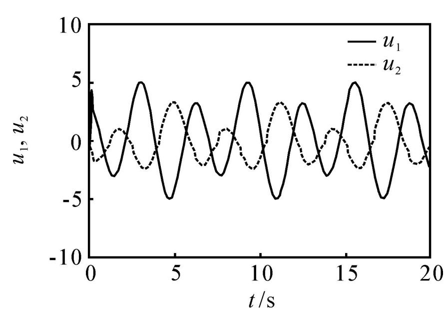


图 4　控制器输出 $u_1$, $u_2$ 曲线

## 6 结 论

针对不确定非线性 MIMO 互连系统,提出一种间接自适应鲁棒模糊控制算法. 该算法通过组合模糊逻辑系统、自适应控制和鲁棒控制的优点设计控制器,可使系统的输出信号很好地跟踪期望的输出. 该算法不需要假设逼近误差的界限已知或逼近误差满足平方可积条件,也不需要假定系统状态是可测的. 给出的自适应律只对逼近误差的不确定界进行在线调节,从而大大减轻了在线计算的负担. 仿真结果表明了该算法的有效性.

### 参考文献(References)


[1] Wang L X. Stable adaptive fuzzy control of nonlinear systems[J]. IEEE Trans on Fuzzy System, 1993, 1(1): 146-155.

[2] Wang M, Chen B, Dai S L. Direct adaptive fuzzy tracking control for a class of perturbed strict-feedback nonlinear systems[J]. Fuzzy Sets and Systems, 2007, 158(24): 2655-2670.

[3] 刘国荣,万百五. 一类非线性 MIMO 系统的间接自适应模糊鲁棒控制[J]. 控制与决策, 2002, 17(增): 676-680.
(Liu G R, Wan B W. Indirect adaptive fuzzy robust control for a class of nonlinear MIMO systems[J]. Control and Decision, 2002, 17(S): 676-680.)

[4] Liu Y J, Wang W. Adaptive fuzzy control for a class of uncertain non-affine nonlinear systems[J]. Information Sciences, 2007, 177(18): 3901-3917.

[5] Chang Y C. Robust tracking control of nonlinear MIMO systems via fuzzy approaches[J]. Automatica, 2000, 36(10): 1535-1545.

[6] Labiod S, Boucherit M S, Guerra T M. Adaptive fuzzy control of a class of MIMO nonlinear systems[J]. Fuzzy Sets and Systems, 2005, 151(1): 59-77.

[7] Daniel V D, Tang Y. Adaptive robust fuzzy control of nonlinear system[J]. IEEE Trans on Systems, Man, and Cybernetics — Part B: Cybernetics, 2004, 34(3): 1596-1601.

[8] Tong S C, Tang J T, Wang T. Fuzzy adaptive control of multivariable nonlinear systems[J]. Fuzzy Sets and Systems, 2000, 111(2): 153-167.

[9] Tong S C, Chen B, Wang Y F. Fuzzy adaptive output feedback control for MIMO nonlinear systems[J]. Fuzzy Sets and Systems, 2005, 156: 285-299.

[10] Tong S C, Li H X, Chen G R. Adaptive fuzzy decentralized control for a class of large-scale nonlinear systems[J]. IEEE Trans on Systems, Man, and Cybernetics — Part B, 2004, 34(1): 770-775.

[11] Li H X, Tong S C. A hybrid adaptive fuzzy control for a class of nonlinear MIMO systems[J]. IEEE Trans on Fuzzy Systems, 2003, 11(1): 24-34.

[12] Golea N, Golea A, Barra K, et al. Observer-based adaptive control of robot manipulators: Fuzzy systems approach[J]. Applied Soft Computing, 2008, 8(1): 778-787.

[13] Hanmzaoui A, Essounbouli N, Benmahammed K, et al. State observer based robust adaptive fuzzy controller for nonlinear uncertain and perturbed systems[J]. IEEE Trans on Systems, Man, and Cybernetics — Part B: Cybernetics, 2004, 34(2): 942-950.


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[12] Bhardwaj P. Delegating pricing decisions [J]. Marketing Science, 2001, 20(2): 143-169.

[13] 侯光明,甘仞初. 隐蔽行为的约束机制研究[J]. 北京理工大学学报, 1999, 19(1): 122-126.
(Hou G M, Gan R C. On restriction mechanism for hidden actions[J]. J of Beijing Institute of Technology, 1999, 19(1): 122-126.)

[14] 蒋洪浪,沈思玮,戴国强. 对企业高级管理人员的监督机制[J]. 上海交通大学学报, 2001, 35(12): 1889-1891.
(Jiang H L, Shen S W, Dai G Q. Research on CEO supervise system [J]. J of Shanghai Jiaotong University, 2001, 35(12): 1889-1891.)

[15] 王艳梅,赵希男. 软件企业研发人员的激励与监督问题[J]. 东北大学学报, 2008, 29(5): 750-756.
(Wang Y M, Zhao X N. Incentive and monitoring for R&D staff in software enterprises [J]. J of Northeastern University, 2008, 29(5): 750-756.)

[16] 郭焱,张世英,郭彬,等. 企业家选择的最优机制设计[J]. 西南交通大学学报, 2004, 39(4): 498-502.
(Guo Y, Zhang S Y, Guo B, et al. Design of optimal incentive payment scheme for enterpriser [J]. J of Southwest Jiaotong University, 2004, 39(4): 498-502.)

[17] Baiman S, Fischer P E, Rajan M V. Information, contracting and quality costs[J]. Management Science, 2000, 46(6): 776-789.

[18] 曹柬,杨春节. 考虑质量失误的供应链博弈模型研究[J]. 中国管理科学, 2006, 14(1): 25-29.
(Cao J, Yang C J. A game analysis on quality failure of supply chain[J]. Chinese J of Management Science, 2006, 14(1): 25-29.)

[19] Kos, Hart, Gustav Stickley. The economics of contracts[M]. Beijng: Economic Science Press, 2001.