第 21 卷 第 8 期 控 制 与 决 策 2006 年 8 月
Vol 21 No. 8 Control and Decision Aug. 2006

文章编号: 1001-0920(2006)08-0929-04

一类复杂系统的自适应控制

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摘 要: 对于具有相似性的一类不确定复杂系统, 应用高阶神经网络逼近各个子系统的互联项, 设计了控制器, 即提出了难以解决的互联项问题的高阶神经网络表示方法 该方法通过在线调节神经网络的权值来确保闭环系统的稳定性 由于复杂系统的结构相似性, 降低了控制器设计过程中的计算量, 使得工程上较易实现 仿真算例表明了所提出方法的有效性

关键词: 高阶神经网络; 相似复杂系统; 鲁棒自适应控制
中图分类号: TP13 **文献标识码**: A

Adaptive Control for a Class of Complex Systems

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Abstract: A novel robust adaptive controller is designed for a class of uncertain complex systems with similarity. This approach uses high-order neural networks to deal with interconnections of subsystems It assures the stability of closed-loop systems by updating the weights of NN on line. It needs less calculation and is easy to realize in engineering because of the similarities of complex systems The simulation example shows the effectiveness of proposed method.

Key words: High-order neural networks; Complex systems with similarity; Robust adaptive control

1 引 言

复杂系统的镇定问题是控制理论中的重要问题之一[1]. 复杂系统是由几十乃至上千个子系统互联而成[2], 系统维数高和结构复杂等特点使得各个子系统之间的信息传递受到一定限制[3], 即使信息传递不受影响, 也可能由于计算量过大而无法采用集中控制方式 本文研究的复杂系统是具有相似性的一类复杂系统 由于复杂系统的相似性, 降低了控制器设计过程中的计算量, 因而工程上较易实现

互联性、不确定性和非线性的存在增加了复杂系统控制的难度 文献[4]所研究的一类复杂系统的互联项是有界的; 文献[5]所研究的复杂系统的各个子系统是线性的; 文献[2, 3]研究了一类复杂系统的控制问题, 对互联项的处理方法是将互联项当作干扰抵消掉 本文所研究的一类复杂系统, 不仅具有匹配的不确定项, 而且具有非匹配的不确定项 本文对互联项采取了新的处理方法, 即应用高阶神经网络逼近子系统间的互联项, 所设计的控制器通过在线调节神经网络的权值来确保闭环系统的稳定性

2 问题描述

考虑如下不确定复杂系统:

$$\dot{x}_i = f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i + \Delta g_i(x_i)] + H_i(x),\ i = 1, 2, \cdots, N. \quad (1)$$

其中: $x_i \in R^n$, $u_i \in R^m$ 为第 i 个子系统的状态和输入, 且 $G(x_i) = (g_1(x_i), g_2(x_i), \cdots, g_m(x_i))^{\mathrm{T}}$; $g_l(x_i)$, $l = 1, 2, \cdots, m$; $f(x_i)$ 为光滑向量函数; $\Delta f_i(x_i)$ 为非匹配的不确定项; $\Delta g_i(x_i)$ 为匹配的不确定项; $H_i(x)$ 为互联项, 且 $x = (x_1^{\mathrm{T}}, x_2^{\mathrm{T}}, \cdots, x_N^{\mathrm{T}})^{\mathrm{T}}$, $H(x) = (H_1(x), H_2(x), \cdots, H_N(x))^{\mathrm{T}}$.

收稿日期: 2005-06-14; **修回日期**: 2006-01-14
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定义 1　如下系统:

$\mathring{x}_i =$

$f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i +$

$\Delta g_i(x_i)], i = 1, 2, \cdots, N,$ (2)

称为第 i 个名义子系统.

本文作如下假设:

假设 1　对于系统(1), 有

$$\|\Delta g_i(x_i)\| \leq \xi(x_i), i = 1, 2, \cdots, N, \quad (3)$$

其中 $\xi(\cdot)$ 为已知连续函数.

假设 2　存在 $u_i = u_i^a(x_i)$ 和 $\bar{V}(x_i) \subset C^1$, 使得

$$k_1\|x_i\|^2 \leq \bar{V}(x_i) \leq k_2\|x_i\|^2, \quad (4)$$

$$\frac{\partial \bar{V}(x_i)}{\partial x_i}(f(x_i) + G(x_i)u_i^a(x_i)) \leq$$

$$-k_3|\partial \bar{V}(x_i)/\partial x_i|^2 \leq -k_4\bar{V}(x_i). \quad (5)$$

其中: $i = 1, 2, \cdots, N$; k_1, k_2, k_3, k_4 为正常数.

假设 3　不匹配的不确定项 $\Delta f_i(x_i)$ 满足

$$\left\|\left(\frac{\partial \bar{V}(x_i)}{\partial x_i}\right)^{\mathrm{T}}\Delta f_i(x_i)\right\| \leq \rho(x_i),$$

$$i = 1, 2, \cdots, N, \quad (6)$$

和 $\rho(x_i)\Big/\left\|\left(\frac{\partial \bar{V}(x_i)}{\partial x_i}\right)^{\mathrm{T}}G(x_i)\right\|$ 是连续的. 其中: $\rho(\cdot)$ 为已知函数, $\bar{V}(\cdot)$ 由假设 2 给出.

注 1　因为 $\rho(x_i)\Big/\left\|\left(\frac{\partial \bar{V}(x_i)}{\partial x_i}\right)^{\mathrm{T}}G(x_i)\right\|$ 是连续的, 从而可知, 如果 $\left\|\left(\frac{\partial \bar{V}(x_i)}{\partial x_i}\right)^{\mathrm{T}}\right\|G(x_i)|_{x_i^0} = 0$, 那么 $\rho(x_i^0) = 0$.

注 2　对于系统(1) 的不确定项, 由不等式(3) 和(6) 可知, 由于子系统受到的干扰是相似的, 各名义子系统的不确定项具有相同结构的界定函数.

3　主要结果

非线性互联项 $H_i(x)$ 的特点是具有高维性, 从而高阶神经网络对其具有良好的逼近能力. 本文首先应用高阶神经网络建模非线性互联项 $H_i(x)$, $i = 1, 2, \cdots, N$. 假设 x 为高阶神经网络的输入, y_i 为输出, 那么 $y_i = \hat{W}_i S(x)$. 其中: $\hat{W}_i \in R^{n \times L}$ 为权矩阵; $S_i(x)$ $(i = 1, 2, \cdots, L)$ 为 $S(x) \in R^{L \times 1}$ 的元素, 且 $S_i(x) = \prod_{k=1}^{N}\prod_{j \in I_i}[S(x_{kj})]^{d_j(i)}$. $\{I_i | i = 1, 2, \cdots, L\}$ 为 $\{1, 2, \cdots, n\}$ 的 L 个子集, $d_j(i)$ 为非负整数, 且

$$S(x_{kj}) = \frac{\mu_0}{1 + e^{-l_0 x_{kj}}} + \lambda_0,$$

$$j = 1, 2, \cdots, n, \; k = 1, 2, \cdots, N.$$

由上述高阶神经网络可以看出, 存在整数 L, $d_j(i)$ 和最优权矩阵 W_i^*, 使得对于任意 $\epsilon > 0$, $|H_i(x) - W_i^* S(x)| \leq \epsilon$, 即存在权矩阵使得 $W_i^* S(x)$ 能够以任意精度逼近 $H_i(x)$, 且 W_i^* 和 $S(x)$ 是有界的. 那么存在正整数 s, M_W 和 k_s 使得 $\|W_i^*\| \leq M_W$, $|S(x)| \leq k_s\|x_i\| \leq s$. 因此, 系统(1) 可以写成

$\mathring{x}_i =$

$f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i + \Delta g_i(x_i)] +$

$W_i^* S(x) + \epsilon_i(x), i = 1, 2, \cdots, N,$ (7)

其中 $\epsilon_i(x) = H_i(x) - W_i^* S(x)$ 为函数估计误差. 另外, 存在 $\epsilon \geq 0$, 使得 $|\epsilon_i(x)| \leq \epsilon$, $i = 1, 2, \cdots, N$. 如果记 W_i 为权矩阵 W_i^* 的估计, 那么

$\mathring{x}_i =$

$f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i + \Delta g_i(x_i)] -$

$\tilde{W}_i S(x) + W_i S(x) + \epsilon_i(x), i = 1, 2, \cdots, N,$

(8)

其中误差 $\tilde{W}_i$ 满足 $\tilde{W}_i = W_i - W_i^*$.

定理 1　假如系统(1) 满足假设 1～假设 3, 设计控制器如下:

$$u_i = u_i^a + u_i^b + u_i^c + u_i^d, \quad (9)$$

其中 u_i^a 由假设 2 给出. 令

$$E_i = \left(x_i \,\Big|\, G^{\mathrm{T}}(x_i)\frac{\partial \bar{V}(x_i)}{\partial x_i}\right) = 0,$$

有

$$u_i^b = \begin{cases} -\dfrac{G^{\mathrm{T}}(x_i)\dfrac{\partial \bar{V}(x_i)}{\partial x_i}}{\left\|G^{\mathrm{T}}(x_i)\dfrac{\partial \bar{V}(x_i)}{\partial x_i}\right\|}\xi(x_i), & x_i \notin E_i; \\ 0, & x_i \in E_i. \end{cases} \quad (10)$$

$$u_i^c = \begin{cases} -\dfrac{G^{\mathrm{T}}(x_i)\dfrac{\partial \bar{V}(x_i)}{\partial x_i}}{\left\|G^{\mathrm{T}}(x_i)\dfrac{\partial \bar{V}(x_i)}{\partial x_i}\right\|}\rho(x_i), & x_i \notin E_i; \\ 0, & x_i \in E_i. \end{cases} \quad (11)$$

$$u_i^d = \frac{k_s G_i^{\mathrm{T}} W_i x_i}{\lambda_i[1 + \|G_i\|^2]} + \frac{G_i^{\mathrm{T}}\Theta_i}{\lambda_{1,i}[1 + \|G_i\|^2]}. \quad (12)$$

其中: $\Theta_i \in R^{n \times L}$, $\Theta_i = [\theta_i, 0, \cdots, 0]^{\mathrm{T}}$, $i = 1, 2, \cdots, N$. 那么状态 x_i 在集合

$D_i =$

$$\left\{x_i \in R^n: v_{0i}(x_i) \leq \frac{\mu_i}{k_{0,i}\alpha_i}, \frac{\bar{k}_2^i}{\bar{k}_1^i} \leq k_{0,i} \leq 1\right\},$$

$$i = 1, 2, \cdots, N \quad (13)$$

是一致有界的. 自适应律为

$$\dot{W}_i = \begin{cases} 2k_{0,i}k_s\dfrac{\partial v_{0i}}{\partial x_i}x_i^{\mathrm{T}}, & \|W_i\| < M_W; \\ -\beta W_i + 2k_{0,i}k_s\dfrac{\partial v_{0i}}{\partial x_i}x_i^{\mathrm{T}}, & \|W_i\| \geq M_W. \end{cases} \quad (14)$$

$$\dot{\theta}_i = -\gamma_{1,i}\theta_i + 2k_{0,i}\left|\frac{\partial v_{0i}}{\partial x_i}\right| \quad (15)$$

式(14) 和(15) 分别为权 W_i 和 θ_i 的调节律.

证明　定理的证明过程分为以下两步:

1) 首先证明对于名义子系统 $\dot{x}_i = f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i + \Delta g_i(x_i)]$, 存在控制器 $u_i = u_i^a + u_i^b + u_i^c: R^n \to R^m$ 和 Lyapunov 函数 $v_{0i}(x_i)$, 使得名义子系统是稳定的.

将控制器(9)～(12) 代入系统(1), 得

$$\dot{x}_i = f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i^a + u_i^b + u_i^c + \Delta g_i(x_i)],\ i = 1, 2, \cdots, N.$$

定义正定函数

$$v_{0i}(x_i) = \sum_{i=1}^{N} \bar{V}(x_i),$$

那么

$$\dot{v}_{0i}(x_i) = \sum_{i=1}^{N}\Big\{\Big(\frac{\partial \bar{V}(x_i)}{\partial x_i}\Big)^{\mathrm{T}}(f(x_i) + G(x_i)u_i^a) + \Big(\frac{\partial \bar{V}(x_i)}{\partial x_i}\Big)^{\mathrm{T}}(\Delta f_i(x_i) + G(x_i)u_i^c) + \Big(\frac{\partial \bar{V}(x_i)}{\partial x_i}\Big)^{\mathrm{T}} G(x_i)(u_i^b + \Delta g_i(x_i))\Big\}.$$

由假设 1, 假设 2, $u_i^b(x)$ 和 $u_i^c(x)$ 的结构, 得

$$\dot{v}_{0i}(x_i) \le -\sum_{i=1}^{N} k_3 \Big|\frac{\partial \bar{V}(x_i)}{\partial x_i}\Big|^2, \tag{16}$$

其中 k_3 由式(5) 确定. 这样, 由不等式(16) 和定义 1, 可知名义子系统是稳定的.

2) 将 1) 的结果作为已知假设, 然后证明定理 1. 对于系统(1), 定义如下 Lyapunov 函数:

$$V(x, \tilde{W}_1, \cdots, \tilde{W}_N, \tilde{\theta}_1, \cdots, \tilde{\theta}_N) = \sum_{i=1}^{N} V_i(x, \tilde{W}_i, \tilde{\theta}_i), \tag{17}$$

$$V_i(x, \tilde{W}_i, \tilde{\theta}_i) = k_{0,i}v_{0i}(x_i) + \frac{1}{2}\mathrm{tr}\{\tilde{W}_i^{\mathrm{T}}\tilde{W}_i\} + \frac{1}{2}\tilde{\theta}_i^2, \tag{18}$$

其中 $\tilde{\theta}_i = \theta_i - \epsilon$. 那么 V_i 的导数为

$$\dot{V}_i = k_{0,i}\frac{\partial v_{0i}}{\partial x_i}\{f(x_i) + \Delta f_i(x_i) + G(x_i)[u_i^a + u_i^b + u_i^c + \Delta g_i(x_i)]\} + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}G_i u_i^d - k_{0,i}\frac{\partial v_{0i}}{\partial x_i}\tilde{W}_i S(x) + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}W_i S(x) + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}\epsilon(x) + \mathrm{tr}\{\dot{W}_i^{\mathrm{T}}\tilde{W}_i\} + \dot{\theta}_i\tilde{\theta}_i. \tag{19}$$

应用式(14), 得

$$\dot{V}_i = k_{0,i}\dot{v}_{0i} + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}G_i u_i^d + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}W_i S(x) + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}\epsilon_i(x) - \beta_i I_W \mathrm{tr}\{W_i^{\mathrm{T}}\tilde{W}_i\} + \dot{\theta}_i\tilde{\theta}_i,$$

其中 I_W 为 W_i 的指示函数, 且满足

$$I_W = \begin{cases} 1, & \|W_i\| \ge M_W; \\ 0, & \|W_i\| < M_W. \end{cases} \tag{20}$$

由于

$$\mathrm{tr}\{W_i^{\mathrm{T}}\tilde{W}_i\} = \frac{1}{2}\|W_i\|^2 + \frac{1}{2}\|\tilde{W}_i\|^2 - \frac{1}{2}\|W_i^*\|^2,$$

有

$$\dot{V}_i = k_{0,i}\dot{V}_{0i} + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}G_i u_i^d + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}W_i S(x) + k_{0,i}\frac{\partial v_{0i}}{\partial x_i}\epsilon(x)_i - \frac{\beta_i}{2}\mathrm{tr}\{\tilde{W}_i^{\mathrm{T}}\tilde{W}_i\} + \frac{\beta_i}{2}(1 - I_W)\mathrm{tr}\{\tilde{W}_i^{\mathrm{T}}\tilde{W}_i\} - \frac{\beta_i}{2}I_W\|W_i\|^2 + \frac{\beta_i}{2}I_W\|W_i^*\|^2 + \dot{\theta}_i\tilde{\theta}_i. \tag{21}$$

由假设 1, 将 $u_i^d(\lambda_i, \lambda_{1,i})$ 代入式(21), 则 V_i 的导数满足

$$\dot{V}_i \le -k_{0,i}k_3\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|^2 + k_{0,i}k_s\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\frac{\|G_i\|^2\|W_i\|\,\|x_i\|}{\lambda_i[1 + \|G_i\|^2]} + k_{0,i}k_s\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\|W_i\|\,\|x_i\| + k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\frac{\|G_i\|^2|\theta_i|}{\lambda_{1,i}[1 + \|G_u\|^2]} + k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big||\epsilon_i(x)| + \dot{\theta}_i\tilde{\theta}_i - \frac{\beta_i}{2}\mathrm{tr}\{\tilde{W}_i^{\mathrm{T}}\tilde{W}_i\} + \frac{\beta_i}{2}(1 - I_W)\mathrm{tr}\{\tilde{W}_i^{\mathrm{T}}\tilde{W}_i\} - \frac{\beta_i}{2}I_W\|W_i\|^2 + \frac{\beta_i}{2}I_W\|W_i^*\|^2. \tag{22}$$

由于 $\dfrac{\|G_i\|^2}{1 + \|G_i\|^2} \le 1$, 式(22) 变成

$$\dot{V}_i \le k_{0,i}k_3\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|^2 + k_{0,i}k_s\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\|W_i\|\,\|x_i\|\Big(1 + \frac{1}{\lambda_i}\Big) + k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\frac{|\theta_i|}{\lambda_{1,i}} + k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\theta_i - k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\theta_i + k_{0,i}\Big|\frac{\partial v_{0i}}{\partial x_i}\Big|\epsilon_i +$$

$$\theta_i\dot\theta_i - \frac{\beta_i}{2}\mathrm{tr}\{\tilde W_i^{\mathrm T}\tilde W_i\} + \frac{\beta_i}{2}(1 - I_W)\mathrm{tr}\{\tilde W_i^{\mathrm T}\tilde W_i\} - \frac{\beta_i}{2}I_W\|W_i\|^2 + \frac{\beta_i}{2}I_W\|W_i^*\|^2. \quad (23)$$

应用式(16), 得

$$\dot V_i \le -\frac{k_{0,i}\bar k_3 k_4}{k_3}v_{0i}(x_i) - \frac{\beta_i}{2}\|\tilde W_i\|^2 - \frac{\gamma_{1,i}}{2}\theta_i^2 + 2\beta M_W^2 + \frac{\gamma_{1,i}}{2}\epsilon^2. \quad (24)$$

所以 $\dot V_i \le -\alpha_i V_i + \mu_i, \dot V = \sum_{i=1}^{N}\dot V_i$. 其中

$$\alpha_i = \min\{\frac{\bar k_3 k_4}{k_3}, \beta_i, \gamma_{1,i}\},$$

$$\mu_i = 2\beta M_W^2 + \frac{\gamma_{1,i}}{2}\epsilon^2. \quad (25)$$

由此, 定理 1 得证. □

注3 β_i 为 W_i 权调节律线性部分的增益, $\gamma_{1,i}$ 为 θ_i 权调节律线性部分的增益.

对比式(25) 的两边, 得

$$V_i(t) \le \frac{\mu_i}{\alpha_i} + [V_i(0) - \frac{\mu_i}{\alpha_i}]e^{-\alpha_i t}, \forall t \ge 0. \quad (26)$$

由式(18), 可得

$$k_{0,i}v_{0i}(x_i) \le V_i. \quad (27)$$

所以

$$v_{0i}(x_i) \le \frac{\mu_i}{k_{0,i}\alpha_i} + \frac{1}{k_{0,i}}[V_i(0) - \frac{\mu_i}{\alpha_i}]e^{-\alpha_i t},$$
$$\forall t \ge 0, i = 1, 2, \cdots, N. \quad (28)$$

由不等式(28), 可得到 x_i 在集合 D_i 上是一致有界的, 即系统(1) 在集合

$$D_i = \{x_i \in R^n: v_{0i}(x_i) \le \frac{\mu_i}{k_{0,i}\alpha_i}\},$$
$$i = 1, 2, \cdots, N \quad (29)$$

是有界的.

4 仿真算例

考虑如下系统:

$$\dot x_1 = \begin{bmatrix}x_{11}\\ x_{12}\end{bmatrix} + \begin{bmatrix}\theta_1 x_{11}e^{x_{12}}\\ 2x_{12}^2 e^{x_{12}}\sin\theta_2\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}[u_1 + x_{12}^2\sin\theta_2] + 4\begin{bmatrix}(x_{11}^2 + x_{12}^2 + x_{22}^2)^{\frac12}\\ 0\end{bmatrix}x_1 + 4\begin{bmatrix}\cos x_{21}\\ \cos x_{22}\end{bmatrix},$$

$$\dot x_2 = \begin{bmatrix}x_{21}\\ x_{22}\end{bmatrix}x_1 + \begin{bmatrix}\theta_2^2 x_{21}e^{x_{22}}\\ x_{22}^2 e^{x_{22}}\cos\theta_1\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}[u_2 + \frac12 x_{22}^2\theta_1] + 4\begin{bmatrix}(x_{11}^2 + x_{12}^2 + x_{22}^2)^{\frac12}\\ 0\end{bmatrix}x_1 + 4\begin{bmatrix}\cos x_{21}\\ \cos x_{22}\end{bmatrix}.$$

其中: $x_i = \mathrm{col}(x_{i1}, x_{i2})$ $(i = 1, 2)$, $\theta_1 \in (-2, 2)$, $\theta_2 \in (-1, 1)$ 是不确定参数. 令 $Q = I, K = (0\ \ 1)$. 控制输入为

$$u_i^a = -(0\ \ 0.5)x_i,$$

$$u_i^b = \begin{cases}\frac{x_{i2}}{|x_{i2}|}\|x_i\|e^{\|x_i\|}, x_{i2} \ne 0;\\ 0, x_{i2} = 0;\\ i = 1, 2\end{cases}$$

$$u_i^c = \begin{cases}\frac14\frac{x_{i2}^2}{x_{i2}}\|x_i\|e^{\|x_i\|}, x_{i2} \ne 0;\\ 0, x_{i2} = 0;\\ i = 1, 2\end{cases}$$

选取 V_{0i} 如下:

$$V_{0i} = x_i^{\mathrm T}x_i = |x_i|^2,$$

$$u_i^d = \frac{40[0\ \ 1]W_i x_i}{0.5} + \frac{[0\ \ 0.5]\begin{bmatrix}\theta_i\\ 0\end{bmatrix}}{0.5}.$$

权自适应律为

$$\dot W_i = 70k_{0,i}x_i x_i^{\mathrm T},$$

$$\dot\theta_i = -0.04\theta_i + k_{0,i}\|x_i\|.$$

选取初始值为(1, 3) 和(1.5, -2), 仿真如图 1 所示.

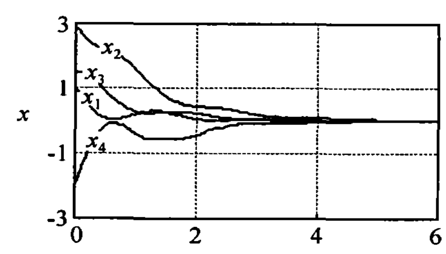

图 1 系统的状态响应曲线

从图 1 可以看出, 系统的状态收敛于零, 即系统是稳定的.

5 结 语

本文针对具有相似结构的复杂系统, 提出了一种自适应的控制器设计方法. 仿真结果表明, 所提出的方法是可行而有效的.

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