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一类非线性时滞系统的鲁棒间接自适应控制

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摘要:针对一类不确定非线性时滞系统,基于变结构控制原理,利用多层神经网络逼近的能力,提出具有投影算法的间接自适应控制方案。该方案通过监督控制器保证闭环系统所有信号有界,并引入综合误差的自适应补偿项来消除建模误差的影响。理论分析证明跟踪误差收敛到零,仿真结果表明该方法的有效性。

关键词:时滞系统;积分变结构;自适应控制;神经网络;全局稳定性

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Robust indirect adaptive control for a class of nonlinear time-delay systems

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Abstract: A new indirect adaptive neural network control scheme with projection algorithm was developed for a class of uncertain nonlinear time-delay systems in this paper. The design was based on the principle of variable structure. Multi-layer Neural Networks (MNNs) were utilized to approximate for unknown plant functions. With the help of a supervisory controller, the resulted closed-loop system was globally stable in the sense that all signals involved were uniformly bounded. Furthermore, the adaptive compensation term of the optimal approximation error was introduced to minimize the effects of modeling error. By theoretical analysis, it is shown that the tracking error converges to zero. Simulation results demonstrate the effectiveness of the approach.

Key words: time-delay systems; integral variable structure; adaptive control; neural work; global stability

0 引言

近年来,利用神经网络或模糊系统研究不确定非线性系统的自适应控制受到国内外学者的广泛关注,取得了一些研究成果。文献[1-2]利用模糊系统的逼近性质,提出了4种保证闭环稳定性的自适应模糊控制方案,但其跟踪误差的收敛性依赖于逼近误差平方可积这一假设。针对这一缺点,文献[3-5]分别提出不同的修正方案,但闭环系统的渐近稳定性分析中假设最优逼近误差的上确界已知。文献[6]根据目标的不同,利用多模型神经网络,提出一种间接神经网络控制策略,但跟踪误差的收敛性仍依赖于逼近误差平方可积。此外,假设了逼近误差存在有界上界。由于模糊系统和神经网络的通用逼近性质只在给定的有界闭区域上有效,因此,在未证明状态有界的条件下假定逼近误差的上确界存在且有界是不合理的。另外,实际控制中此条件无法验证。文献[7-8]分别利用多层神经网络系统和第Ⅱ类模糊逻辑系统的逼近能力,提出间接鲁棒自适应神经网络控制器的设计方案。

在各类工业系统中,时滞现象是普遍存在的。时滞的存在使得系统的分析与综合变得更加复杂和困难,同时也往往是导致系统不稳定和系统性能变差的根源,因而时滞系统的稳定性问题一直是人们感兴趣的课题之一。非线性系统时滞(或时间延迟)对各类工程系统的控制性能产生重要影响,在这一领域已经取得了一些重要的成果^[9-12]。文献[9]针对一类未知的非线性时滞系统,提出了一种自适应神经网络控制

方案。但神经网络只用来逼近未知无时滞非线性函数,要求未知非线性时滞函数被已知的上界函数所界定。文献[10]将Nussbaum增益设计技术,神经网络以及后推设计技术综合起来,给出了一种神经网络自适应控制策略。文献[11]给出了具有未知时延的非线性系统神经网络控制策略。文献[12]针对一类下三角结构的非线性时滞系统,采用后推设计方法,研究了鲁棒控制器设计问题。

本文在文献[8]基础上,考虑了具有未知函数增益的一类非线性时滞系统,利用多层神经网络的逼近能力,并基于变结构控制原理,引入积分型切换函数,提出了稳定的神经网络自适应控制器设计的新方案。该方案通过监督控制项保证闭环系统的稳定性,由此确定出用于建模的有界闭区域,保证跟踪误差收敛到零。该方案无须求解李亚普诺夫方程,控制结构简单。

1 问题的描述及基本假设

考虑下面一类SISO非线性系统:

$$\begin{cases} \dot{x}_i = x_{i+1} \\ x^{(n)} = f(x) + g_\tau(x_\tau) + g(x)u(t) + d(x, t) \\ y = x_1 \end{cases} \quad (1)$$

其中: $i = 1, \dots, n-1$; $x = [x_1, x_2, \dots, x_n]^T = [x, \dot{x}, \dots, x^{(n-1)}]^T$ 是 n 维状态向量; u 是控制输入; y 是系统输出。 $x_\tau = [x_1(t - \tau_1(t)), x_2(t - \tau_2(t)), \dots, x_n(t - \tau_n(t))]^T \in R^n$, $\tau_1(t), \dots, \tau_m(t)$ 是未知时变时滞,且 $0 < \tau_i(t) \leq \tau_{\max}$, τ_{\max} 是设计正常

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数 $f(x)$, $g_r(x_r)$ 是未知连续函数, $g(x)$ 是未知光滑控制增益函数, $d(x, t)$ 代表外来干扰或未建模动态。控制目标要求系统输出 y 尽可能好地去跟踪一个指定的期望轨迹 y_d 。因此, 问题是设计一个控制律 u , 使得 $y_d - y$ 收敛到零。定义跟踪误差向量 e 如下:

$$e = [e_1, e_2, \dots, e_n]^T = [y_d - x_1, \dots, y_d^{(n-1)} - x_n]^T \quad (2)$$

为了设计稳定的自适应神经网络控制, 对未知函数 $f(x)$, $g(x)$, $g_r(x_r)$, $d(x, t)$ 作出如下假设:

① $f(x) \in F(x)$, $\forall x \in R^n$; ② $0 < g_0(x) \leq g(x) \leq g_1(x)$, $\forall x \in R^n$; ③ $|d(x, t)| \leq D(x)$, $\forall x \in R^n, \forall t \geq 0$; ④ $x_d \in \Omega_d \subset R^{n+1}$ 且 $\|x_d\| \leq M_d$; ⑤ 时滞不确定项满足 $|g_r(x_r)| \leq B(x) + \sum_{i=1}^n h_i |x_i(t - \tau_i)|$ 。其中 $F(x)$, $g_1(x)$, $g_0(x)$, $D(x)$, $B(x)$ 均是已知正的连续函数, h_i 是未知正常数, $x_d = [y_d, \dot{y}_d, \dots, y_d^{(n-1)}]^T$, Ω_d 是一个已知的有界闭集, M_d 是一个已知的正常数。

选取常数 k_1, k_2, \dots, k_n , 使得 $H(s) = s^n + k_1 s^{n-1} + \dots + k_{n-1} s + k_n = (s + \lambda)^n$, $\lambda > 0$, 即 $k_i = C_n^{n-i} \lambda^i$, $i = 1, \dots, n$ 。若 $f(x)$, $g(x)$ 已知, $g_r(x_r)$, $d(x, t) = 0$, 则取:

$$u^* = [-f(x) + y_d^{(n)} + \sum_{i=1}^n k_i e_{n-i+1}] / g(x) \quad (3)$$

将式(3)代入式(1)中不难推出 $e_1^{(n)} + k_1 e_1^{(n-1)} + k_2 e_1^{(n-2)} + \dots + k_n e_1 = 0$, 从而可得 $\lim_{t \rightarrow \infty} e_1(t) = 0$ 。由于 $f(x)$, $g(x)$ 未知且 $g_r(x_r)$, $d(x, t) \neq 0$, 故控制律式(3)不可实现。

下面将采用神经网络分别对 u^* 中的未知函数 $f(x)$, $g(x)$ 进行逼近。定义具有积分的切换函数

$$\sigma = k_n e_0 + \sum_{i=1}^{n-1} k_{n-i} e_i + e_n = (d/dt + \lambda)^n e_0 \quad (4)$$

其中: $\dot{e}_0 = y_d - x_1 = e_1$ 或 $e_0 = \int e_1 dt$, 将式(4)两边对时间 t 求导并利用式(1)得:

$$\dot{\sigma} = \sum_{i=1}^n k_i e_{n-i+1} + y_d^{(n)} - f(x) - g(x)u - d(x, t) \quad (5)$$

引理 1^[13] 若 σ 由式(4)确定, 则:

① 当 $\sigma = 0$ 时, $\lim_{t \rightarrow \infty} e_0 = 0$ 。

② 当 $|\sigma| \leq c$, $E(0) \in \Omega_c$ 时, $E(t) \in \Omega_c$, $\forall t \geq 0$ 。

③ 当 $|\sigma| \leq c$, $E(0) \notin \Omega_c$ 时, $\exists T = n/\lambda$, 推得 $\forall t \geq T$, 有 $E(t) \in \Omega_c$, 其中 $E(t) = [e_0, e^T]^T$, $c > 0$, $\Omega_c = \{E(t) \mid |e_j| \leq 2^j \lambda^{j-n} c, j = 0, 1, \dots, n\}$ 。

定义有界闭区域 $\Omega_x = \{x \mid \|x\| \leq M_x\}$, 其中 $M_x > M_d$ 是设计常数。设 $h(x, W, V)$ 是一个三层神经网络在区域 Ω_x 上对 $h(x)$ 的逼近, 即:

$$h(x, W, V) = W^T S(V^T \bar{x}) \quad (6)$$

其中: $x = [x_1, \dots, x_n]^T$, $\bar{x} = [x^T, 1]^T$, $V = [v_1, \dots, v_l] \in R^{(n+1) \times l}$, $W = [w_1, \dots, w_l]^T \in R^l$, W, V 分别是 MNN 的第 1 层到第 2 层, 第 2 层到第 3 层的连接权; $l > 1$ 是 MNN 的隐层节点数; 同时 $S(V^T \bar{x}) = [S(v_1^T \bar{x}), \dots, S(v_{l-1}^T \bar{x}), 1]^T$, 变换函数 $s(x_\alpha) = 1/(1 + e^{-\gamma x_\alpha})$, 常数 $\gamma > 0$ 。令

$$(W^*, V^*) = \arg \min_{(W, V)} \sup_{x \in \Omega_x} |h(x, W, V) - h(x)| \quad (7)$$

$$h(x) = h(x, W^*, V^*) + \varepsilon(x); x \in \Omega_x \quad (8)$$

其中: W^*, V^* 是 MNN 的理想连接权, $\varepsilon(x)$ 是 MNN 的逼近误差。由于 $h(x)$, $h(x, W^*, V^*)$ 是有界区域 Ω_x 上的连续函数, 所以 $\exists \varepsilon > 0$, 使得:

$$|\varepsilon(x)| \leq \varepsilon; x \in \Omega_x \quad (9)$$

定义 $\hat{W}(t)$, $\hat{V}(t)$ 分别为 W^*, V^* 在 t 时刻的估计, 并记估

计误差为 $\tilde{W}(t) = \hat{W}(t) - W^*$, $\tilde{V}(t) = \hat{V}(t) - V^*$, 有:

$$h(x, W^*, V^*) - h(x, \hat{W}, \hat{V}) = -\tilde{W}^T (\hat{S} - \hat{S}' \hat{V}^T \bar{x}) - \tilde{W}^T \hat{S}' \hat{V}^T \bar{x} + d_u; \forall x \in \Omega_x \quad (10)$$

其中 $\hat{S} = S(\hat{V}^T \bar{x})$, $\hat{S}' = \text{diag}(\hat{s}'_1, \dots, \hat{s}'_l)$, $\hat{s}'_k = s'(\hat{v}_k^T \bar{x}) = \{ds(x_\alpha)/dx_\alpha \mid x_\alpha = \hat{v}_k^T \bar{x}, k = 1, \dots, l\}$, $d_u = -\tilde{W}^T \hat{S}' V^{*T} \bar{x} + W^{*T} (S(V^{*T} \bar{x}) - \hat{S} - \hat{S}'(-\tilde{V}^T \bar{x}))$, 则不难得到:

$$|d_u| \leq \|V^*\|_F \|\bar{x}\| \|\tilde{W}\|_F + \|\tilde{W}^*\|_1 \|\hat{S}' \hat{V}^T \bar{x}\| + \|W^*\|_1 \quad (11)$$

其中: $\|\cdot\|_F$, $\|\cdot\|$, $\|\cdot\|_1$ 分别表示 Frobenius 范数, 2 范数, 1 范数。由式(9)、(11)可得:

$$|d_u| + |\varepsilon(x)| \leq \|V^*\|_F \|\bar{x}\| \|\tilde{W}\|_F + \|\tilde{W}^*\|_1 \|\hat{S}' \hat{V}^T \bar{x}\| + \|W^*\|_1 + \varepsilon = K^T \varphi(x, t); x \in \Omega_x \quad (12)$$

其中: $K = [\|V^*\|_F, \|W^*\|_1, \|W^*\|_1 + \varepsilon]^T$, $\varphi(x, t) = [\|\bar{x}\| \|\tilde{W}\|_F, \|\hat{S}' \hat{V}^T \bar{x}\|, 1]^T$ 。

2 积分变结构神经网络控制器的设计

由假设 ⑤ 可知:

$$|g_r(x_r)| \leq B(x) + \sum_{i=1}^n h_i |x_i(t - \tau_i(t))| \leq B(x) + H + \Delta_{\max} \quad (13)$$

其中: $H = n(\sum_{i=1}^n h_i^2)/2 \leq H_{\max}$, $\Delta_{\max} = n(\sum_{i=1}^n x_{i, \max}^2)/2$, $x_{i, \max} = \max_{t - \tau_{\max} \leq \tau \leq t} |x_i(\tau - \tau_i(\tau))|$, H_{\max} 是已知正常数, 令 $B_1(x) = B(x) + \Delta_{\max}$ 。

由于 $f(x)$, $g(x)$ 都是未知函数, 下面分别对函数 $f(x)$, $g(x)$ 构造由式(6)定义的神经网络逼近。即:

$$\begin{cases} f(x, W_f, V_f) = W_f^T S(V_f^T \bar{x}) \\ g(x, W_g, V_g) = W_g^T S(V_g^T \bar{x}) \end{cases} \quad (14)$$

令:

$$\begin{cases} (W_f^*, V_f^*) = \arg \min_{(W_f, V_f)} [\sup_{x \in \Omega_x} |f(x, W_f, V_f) - f(x)|] \\ (W_g^*, V_g^*) = \arg \min_{(W_g, V_g)} [\sup_{x \in \Omega_x} |g(x, W_g, V_g) - g(x)|] \end{cases} \quad (15)$$

其中: $W_f^*, V_f^*, W_g^*, V_g^*$ 是 MNN 的理想连接权。由式(7)、(8)有

$$\begin{cases} f(x) = f(x, W_f^*, V_f^*) + \varepsilon_f(x) \\ g(x) = g(x, W_g^*, V_g^*) + \varepsilon_g(x) \end{cases} \quad (16)$$

其中: $x \in \Omega_x$, $\varepsilon_f(x)$, $\varepsilon_g(x)$ 是 MNN 的逼近误差。由前面分析可知, 由于 $f(x)$, $g(x)$, $f(x, W_f^*, V_f^*)$, $g(x, W_g^*, V_g^*)$ 是有界区域 Ω_x 上的连续函数, 所以 $\exists \varepsilon_f > 0$, $\exists \varepsilon_g > 0$, 使得:

$$|\varepsilon_f(x)| \leq \varepsilon_f, |\varepsilon_g(x)| \leq \varepsilon_g, x \in \Omega_x \quad (17)$$

为证明需要, 我们对权 W_f, W_g 作如下假设:

⑥ $\Omega_f = \{W_f \mid \|W_f\| \leq M_f\}$ 。

⑦ $\Omega_g = \{W_g \mid \|W_g\| \leq M_g, W_{gi} \geq w_m\}$ 。

其中: W_{gi} 是 W_g 中的某一分量, 且 w_m 是一个正常数。又由式(8)~(12) 参照分析进一步有:

$$|d_{uf}| + |\varepsilon_f(x)| \leq \|V_f^*\|_F \|\bar{x}\| \|\tilde{W}_f\|_F + \|\tilde{W}_f^*\|_1 \|\hat{S}'_f \hat{V}_f^T \bar{x}\| + \|W_f^*\|_1 + \varepsilon_f = K_f^T \varphi_f(x, t); x \in \Omega_x \quad (18)$$

$$|d_{ug}| + |\varepsilon_g(x)| \leq \|V_g^*\|_F \|\bar{x}\| \|\tilde{W}_g\|_F + \|\tilde{W}_g^*\|_1 \|\hat{S}'_g \hat{V}_g^T \bar{x}\| +$$

$$\| \hat{W}_g^* \|_1 + \varepsilon_g = K_g^T \varphi_g(x, t); x \in \Omega_x \quad (19)$$

其中: $K_f = [\|V_f^*\|_F, \|\hat{W}_f^*\|, \|\hat{W}_f^*\|_1 + \varepsilon_f]^T$, $\varphi_f(x, t) = [\|\hat{x} \hat{W}_f^T \hat{S}_f\|_F, \|\hat{S}_f' \hat{V}_f^T \hat{x}\|, 1]^T$, $K_g = [\|V_g^*\|_F, \|\hat{W}_g^*\|, \|\hat{W}_g^*\|_1 + \varepsilon_g]^T$, $\varphi_g(x, t) = [\|\hat{x} \hat{W}_g^T \hat{S}_g\|_F, \|\hat{S}_g' \hat{V}_g^T \hat{x}\|, 1]^T$.

采用如下控制律:

$$u(t) = u_f + u_s + u_c \quad (20)$$

其中:

$$u_f = [-\hat{f}(x, W_f, V_f) + y_d^{(n)} + \sum_{i=1}^n k_i e_{n-i+1} + \hat{H}]/\hat{g}(x, W_g, V_g) \quad (21)$$

$$\dot{\hat{W}}_f = \begin{cases} -\Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma, \\ \|\hat{W}_f\| < M_f \text{ 或 } (\|\hat{W}_f\| = M_f \text{ 且 } \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma \geq 0) \\ -\Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma + \hat{W}_f \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma / \|\hat{W}_f\|^2, \\ \|\hat{W}_f\| = M_f \text{ 且 } \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma < 0 \end{cases} \quad (25)$$

$$\dot{\hat{V}}_f = -\Gamma_{Vf} \hat{W}_f^T \hat{S}_f' \sigma \quad (26)$$

$$\dot{\hat{K}}_f = \Gamma_{kf} \varphi_f(x, t) \|\sigma\| \quad (27)$$

当 $\hat{W}_{gi} = w_m$ 时:

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, & \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma < 0 \\ 0, & \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma \geq 0 \end{cases} \quad (28)$$

否则:

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (29)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (30)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (31)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (32)$$

其中: $\Gamma_{wf} > 0, \Gamma_{Vf} > 0, \Gamma_{kf} > 0, \Gamma_{wg} > 0, \Gamma_{Vg} > 0, \Gamma_{kg} > 0$, 它们是对应参数的自适应调节率, \hat{W}_{gi} 表示 \hat{W}_g 中删去满足式 (28) 的分量后所有参数估计向量, \hat{W}_{gi+} 表示 \hat{W}_g 中满足式 (28) 第一个条件所有分量所构成的列向量。

3 稳定性分析

由式(1) ~ (4) 及式(20) ~ (24) 构成的控制律可得:

$$\dot{\sigma} = \hat{W}_f^T (S_f - S_f' V_f^T \hat{x}) + \hat{W}_f^T S_f' \hat{V}_f^T \hat{x} + [\hat{W}_g^T (S_g - S_g' V_g^T \hat{x}) + \hat{W}_g^T S_g' \hat{V}_g^T \hat{x}]u_f - d_{wf} - \varepsilon_f(x) - (d_{wg} + \varepsilon_g(x))u_f - g(x)u_s - g(x)u_c - g_\tau(x_\tau) - d(x, t) \quad (33)$$

因此提出如下稳定性定理:

定理 1 考虑过程(1), 其控制律由式(20) ~ (24) 确定, 自适应律由式(25) ~ (32) 确定, 并满足假设 ① ~ ⑦ 若取 $M_x = M_d + \sum_{j=1}^n 2^{j+1} \lambda^{j-n} \sqrt{V}$, $E(0) \in \Omega_c$, $\hat{W}_f(0) \in \Omega_f$, $\hat{W}_g(0) \in \Omega_g$, 则: 1) $\|\hat{W}_f\| \leq M_f$, $\|\hat{W}_g\| \leq M_g$, 且 $\dot{\hat{W}}_{gi} \geq w_m$, $\|x\| \leq M_d + \sum_{j=1}^n 2^{j+1} \lambda^{j-n} \sqrt{V}$; 2) $\lim_{t \rightarrow \infty} |e_i(t)| = 0 (i = 0, \dots, n)$, 其中 $\Omega_c = \{E(t) \mid |e_j| \leq 2^j \lambda^{j-n} c; j = 0, 1, \dots, n\}$, $c = 2\sqrt{V}$.

证明

1) 令 $P_f(t) = \hat{W}_f^T \hat{W}_f / 2$, 则有 $P_f(t) = \hat{W}_f^T \hat{W}_f$ 。如果式(25)

$$u_c = [\sigma + [\hat{K}_f^T \varphi_f(x, t) + \hat{K}_g^T \varphi_g(x, t) \mid u_f \mid + B_1(x) + \hat{H} + D(x)] \text{sgn}(\sigma)] / g_0(x) \quad (22)$$

$$u_s = I(\bar{V}) \text{sgn}(\sigma) [\mid \hat{f}(x, W_f, V_f) \mid + F(x) + \mid \hat{g}(x, W_g, V_g) u_f \mid + \mid g_1(x) u_f \mid + H_{\max} + B_1(x)] / g_0(x) \quad (23)$$

$$I(\bar{V}) = \begin{cases} 1, & V_\sigma = \sigma^2 / 2 > \bar{V} \\ 0, & V_\sigma \leq \bar{V} \end{cases} \quad (24)$$

其中: \bar{V} 是设计参数, u_f 是自适应控制项, u_s 是监督控制项, u_c 是建模误差和扰动的鲁棒自适应补偿项; $\hat{W}_f, \hat{V}_f, \hat{K}_f, \hat{W}_g, \hat{V}_g, \hat{K}_g$ 分别为 $W_f, V_f, K_f, W_g, V_g, K_g$ 在 t 时刻的估计值。

采用如下自适应律:

$$\dot{\hat{W}}_f = \begin{cases} -\Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma, \\ \|\hat{W}_f\| < M_f \text{ 或 } (\|\hat{W}_f\| = M_f \text{ 且 } \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma \geq 0) \\ -\Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma + \hat{W}_f \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma / \|\hat{W}_f\|^2, \\ \|\hat{W}_f\| = M_f \text{ 且 } \hat{W}_f^T \Gamma_{wf}(\hat{S}_f - \hat{S}_f' \hat{V}_f^T \hat{x})\sigma < 0 \end{cases} \quad (25)$$

$$\dot{\hat{V}}_f = -\Gamma_{Vf} \hat{W}_f^T \hat{S}_f' \sigma \quad (26)$$

$$\dot{\hat{K}}_f = \Gamma_{kf} \varphi_f(x, t) \|\sigma\| \quad (27)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, & \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma < 0 \\ 0, & \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma \geq 0 \end{cases} \quad (28)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (29)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (30)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (31)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (32)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (33)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (34)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (35)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (36)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (37)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (38)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (39)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (40)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (41)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (42)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (43)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (44)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (45)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (46)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (47)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (48)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (49)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (50)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (51)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (52)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (53)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (54)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (55)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (56)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (57)$$

$$\dot{\hat{K}}_g = \Gamma_{kg} \varphi_g(x, t) \|\sigma\| \|u_f\| \quad (58)$$

$$\dot{\hat{H}} = \eta \|\sigma\| \quad (59)$$

$$\dot{\hat{W}}_{gi} = \begin{cases} -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma, \\ \|\hat{W}_{gi}\| < M_g \text{ 或 } (\|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma \geq 0) \\ -\Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x})u_f \sigma + [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma / \|\hat{W}_{gi}\|^2, \\ \|\hat{W}_{gi}\| = M_g \text{ 且 } [\hat{W}_{gi}^T \Gamma_{wg}(\hat{S}_{gi} - \hat{S}_{gi}' \hat{V}_{gi}^T \hat{x}) + \hat{W}_{gi+}^T \Gamma_{wg}(\hat{S}_{gi+} - \hat{S}_{gi+}' \hat{V}_{gi+}^T \hat{x})]u_f \sigma < 0 \end{cases} \quad (60)$$

$$\dot{\hat{V}}_g = -\Gamma_{Vg} \hat{W}_g^T \hat{S}_g' u_f \sigma \quad (61)$$

$$\|x\| \leq M_d + \sum_{j=1}^n 2^{j+1} \lambda^{j-n} \sqrt{V}; \forall t \geq 0 \quad (34)$$

2) 令

$$V(t) = V_\sigma + \frac{1}{2\eta} \dot{H}^2 + \frac{1}{2} [\tilde{W}_f^T \Gamma_{W_f}^{-1} \tilde{W}_f + \text{tr}(\tilde{V}_f^T \Gamma_{V_f}^{-1} \tilde{V}_f) + \tilde{K}_f^T \Gamma_{K_f}^{-1} \tilde{K}_f + \tilde{W}_g^T \Gamma_{W_g}^{-1} \tilde{W}_g + \text{tr}(\tilde{V}_g^T \Gamma_{V_g}^{-1} \tilde{V}_g) + \tilde{K}_g^T \Gamma_{K_g}^{-1} \tilde{K}_g] \quad (35)$$

将 $V(t)$ 对时间 t 求导, 将式(20) ~ (24) 及式(25) ~ (31) 代入, 参考文献[8]⁹³ 分析, 可得:

$$\dot{V}(t) \leq -\sigma^2 \leq 0; \forall t > 0 \quad (36)$$

因此 $V(t) \in L_\infty$ 且 $V(+\infty)$ 存在, 进一步有 $\int_0^{+\infty} \sigma^2 dt \leq V(0) - V(+\infty) < +\infty$, 于是 $\sigma \in L^2$ 。又因为 $\sigma, \dot{\sigma} \in L_\infty$, 所以由 Barbalat 引理可知 $\lim_{t \rightarrow \infty} \sigma(t) = 0$ 。又因为 $\frac{s^i}{h(s)} = \frac{s^i}{(s+\lambda)^n} = \sum_{j=1}^n \frac{l_{ij}}{(s+\lambda)^j}$, 所以其脉冲响应为 $\sum_{j=1}^n \frac{l_{ij}}{(j-1)!} t^{j-1} e^{-\lambda t}$ 。进一步有 $e_i(t) = \int_0^t \sum_{j=1}^n \frac{l_{ij}}{(j-1)!} \tau^{j-1} e^{-\lambda \tau} \sigma(t-\tau) d\tau \rightarrow 0, t \rightarrow \infty, i = 0, \dots, n$ 。

4 仿真结果

考虑如下具有扰动的倒立摆问题, 其动态方程为:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{g \sin x_1 - [(m l x_2^2 \cos x_1 \sin x_1) / (m_c + m)]}{l \{ (4/3) - [(m l x_2^2 \cos x_1 \sin x_1) / (m_c + m)] \}} + \frac{\cos x_1 / (m_c + m) u}{l \{ (4/3) - [m \cos^2 x_1 / (m_c + m)] \}} + g_\tau(x_\tau) + d(t) \\ y = x_1 \end{cases} \quad (37)$$

其中: $l = 0.5 \text{ m}, m = 0.1 \text{ kg}, m_c = 1 \text{ kg}, g = 9.8 \text{ m/s}^2, g_\tau(x_\tau) = 0.3 \cos(x_1) + 0.1 x_1^2(t - \tau_1(t)), d(t) = 1.2 \cos(t)$ 。控制目标是使系统状态 x_1 跟踪参考轨迹 $y_d = \pi \sin(t)/30$ 。仿真中, 取 $g_0(x) = 1.12, F(x) = 15.78 + 0.0366 x_2^2, g_1(x) = 1.46, k_1 = 2, k_2 = 1, D(x) = 1.2, M_f = M_g = 4$, 时滞 $\tau_1(t) = 1 + 0.5 \sin(t), \tau_{\max} = 1.5, w_m = 0.001, \bar{V} = 3, x = [0.1, 0.2]^T$, 神经网络中 $W_1 = W_2 \in R^{10}, V_1, V_2 \in R^{3 \times 10}$ 及 e_0 在区间 $[-1, 1]$ 上随机选取, $K_1 = K_2 = [0.5, 0.5, 0.5]^T, \Gamma_{W_f} = \Gamma_{W_g} = 2, \Gamma_{V_f} = \Gamma_{V_g} = 4, \Gamma_{K_f} = 2, \Gamma_{K_g} = 2$, 仿真结果如图 1 ~ 5 所示。

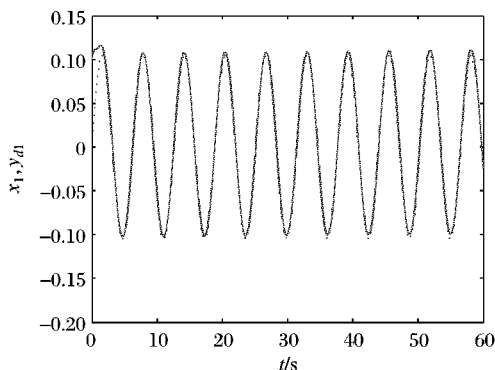


图 1 状态 x_1 (实线) 和期望信号 (虚线) 曲线

5 结语

本文利用多层神经网络的逼近能力, 针对一类未知函数增益非线性时滞系统, 提出了稳定的具有投影算法的神经网络自适应控制器设计方案。该方案基于变结构控制原理, 引入积分型切换函数, 并通过监督控制项保证闭环系统的全局稳

定性, 由此确定出用于建模的有界闭区域, 保证跟踪误差收敛到零。仿真结果进一步表明了该方法的实用性和有效性。

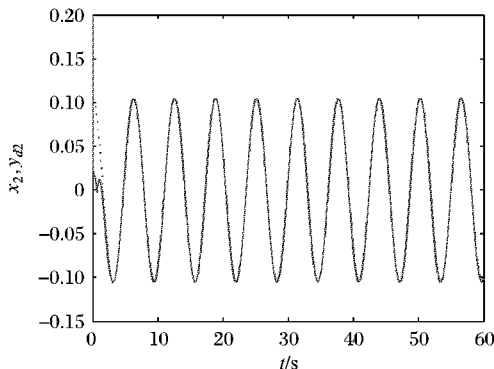


图 2 状态 x_2 (实线) 和期望信号 (虚线) 曲线

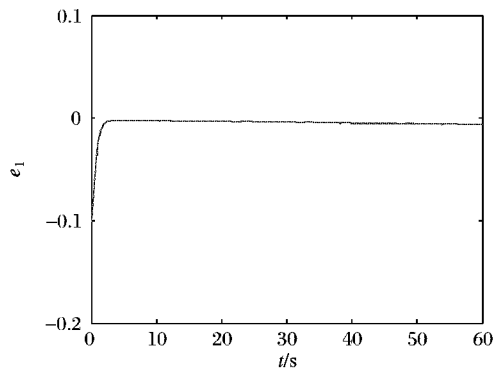


图 3 跟踪误差 e_1 曲线

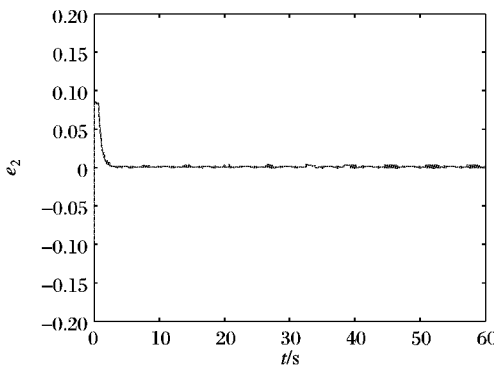


图 4 跟踪误差 e_2 曲线

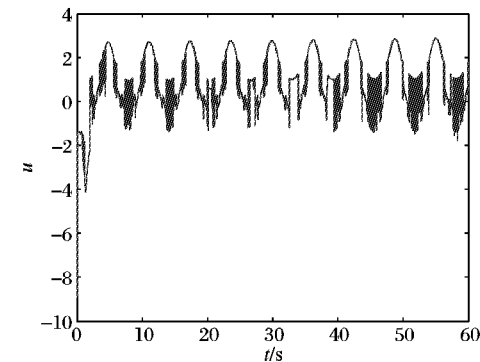
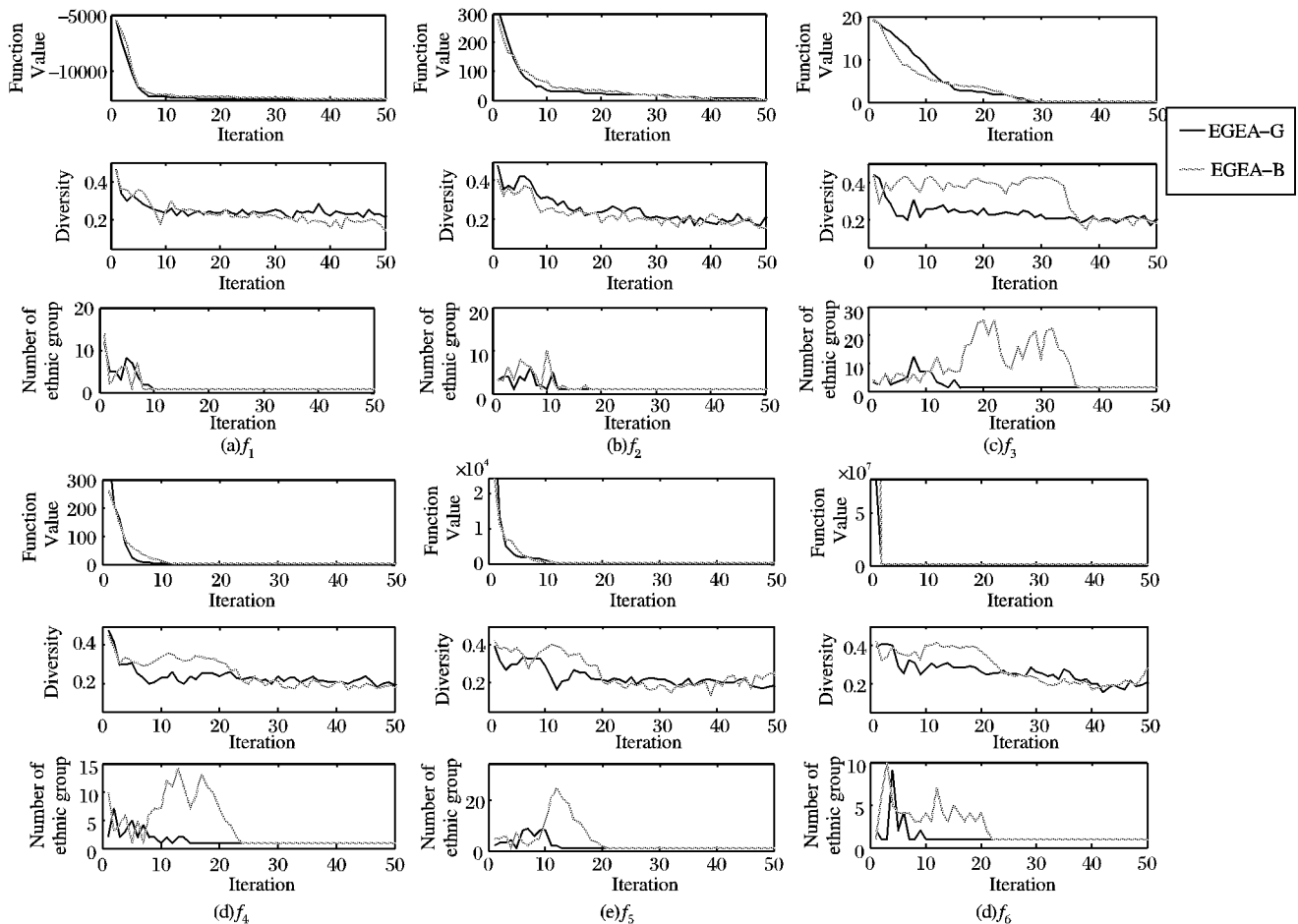


图 5 控制律 u

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图2 EGEA-B与EGEA-G对函数 $f_1 \sim f_6$ 的优化曲线

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