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非线性时滞系统的抖振削弱自适应滑模控制

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摘 要: 针对一类非线性时滞系统的鲁棒自适应滑模控制器设计问题,提出了一种基于偏微分变换的自适应滑模控制方法,该方法能够有效地削弱系统的输入抖动. 基于自适应滑模控制技术和Lyapunov稳定方法,克服了时滞影响,不但保证系统状态可以在有限的时间内到达滑模面,而且保证了系统的渐近稳定特性. 最后给出的仿真结果验证了该控制方案的有效性.

关键词: 非线性时滞系统; 偏微分变换; 自适应滑模控制
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Chattering reduction adaptive sliding-mode control for nonlinear time-delay systems

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Abstract: The design problem of robust adaptive sliding-model controller for a class of nonlinear time-delay systems is studied in this paper. And a robust adaptive sliding mode control method is proposed for the system based on partial differential transformation, which can weaken the control input chattering effectively. Based on sliding control technique and Lyapunov stability method, the system can overcome the influence of delay, which can ensure the system state droving into a sliding-mode plane in finite time, and the system asymptotical stability is also guaranteed. Finally, the simulation results show the effectiveness of the proposed approach.

Key words: Nonlinear time-delay system; Partial differential transformation; Adaptive sliding-model control

1 引 言

在实际工程系统中,时滞经常是不可避免的,如传送系统、电力系统、化工系统等. 时滞的存在常常是系统不稳定和系统性能变坏的根源,所以对时滞系统的研究具有较强的实际意义. 近年来,时滞系统控制问题已受到广泛研究并取得了许多研究成果[1]. 与此同时,滑模控制(SMC)得到很大发展,并已广泛应用到工业控制系统中[2],成为一种强有力的鲁棒控制方法,但系统输入抖动仍是其实际应用的主要障碍. 一般通常利用较大的控制增益来处理未知参数的变化和外界干扰,但此方法有一定的局限性,譬如它会增强系统的输入抖动和导致系统的不稳定,而边界层技术[3,4]和自适应参数辨识机理[5,6]是削弱输入抖动的普遍方法. 现有的文献已验证边界层宽度可变的SMC比固定宽度的SMC具有更好的跟踪性能. 文献[7]提出了边界层宽度调整律和控制增益调整律方法. 文献[8-10]提出了调整边界层宽度的模糊算法. 但在上述研究中系统的输入抖动问题仍比较严重.

本文综合利用偏微分变换技术、鲁棒自适应滑模控制技术和Lyapunov稳定方法,研究了一类更广泛的非线性时滞系统的自适应滑模控制问题. 利用自适应滑模控制技术克服了系统时滞特性的影响,确保系统在有限的时间内能够到达滑模面,并有效地削弱了系统抖动问题. 最后通过仿真实验验证了所提出方法的有效性.

2 系统描述

考虑一类具有定常时滞特性的非线性系统,此

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系描述如下:

$$\begin{cases} \dot{x} = f(x(t), x(t-d)) + g(x(t))u, \\ x(t) = \Phi(t), \ t \in [-d, 0]. \end{cases} \tag{1}$$

其中: $x = (x_1, x_2, \cdots, x_n)^{\mathrm{T}} \in R^n$ 是状态矢量; $u \in R^1$ 是控制输入矢量; $f(x(t), x(t-d)) \in R^n$ 和 $g(x) \in R^n$ 是已知的时变矢量函数, d 是系统的定常时滞; 初始条件 $\Phi(t)$ 是 $t \in [-d, 0]$ 上的连续矢量值初始函数; R^n 是 n 维列矢量实空间.

设 $f(x(t), x(t-d))$ 和 $g(x)$ 可以化为如下形式:

$$\begin{cases} f(x(t), x(t-d)) = f_0(x(t)) + f_1(x(t-d)), \\ g(x(t)) = g_0(x(t)). \end{cases} \tag{2}$$

其中

$f_0(x) = (x_2, \cdots, x_n, f_0)^{\mathrm{T}}$, $g_0(x) = (0, \cdots, 0, 1)^{\mathrm{T}}$,
$f_1(x(t-d)) = (0, \cdots, 0, f_1)^{\mathrm{T}}$.

若存在 $Z = T(x)$ 微分变换可使系统(1) 转化为如下形式:

$$\dot{Z} = AZ + B\beta^{-1}(x(t), x(t-d)) \times (u - \alpha(x(t), x(t-d))), \tag{3}$$

则令

$$u = \alpha(x(t), x(t-d)) + \beta^{-1}(x(t), x(t-d))v,$$

并代入式(3) 得

$$\dot{Z} = AZ + Bv. \tag{4}$$

其中

$$A = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \cdots & \cdots & \ddots & \cdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ \cdots \\ 1 \end{bmatrix},$$

分别是系统(4) 的系统矩阵和输入矩阵, $v \in R^1$ 是控制输入.

由 $Z = T(x)$ 可得

$$\dot{Z} = \frac{\partial T(x)}{\partial x}\dot{x} = \frac{\partial T(x)}{\partial x}(f(x(t), x(t-d)) + g(x(t))u). \tag{5}$$

将

$$u = \alpha(x(t), x(t-d)) + \beta^{-1}(x(t), x(t-d))v$$

代入式(5) 得

$$\dot{Z} = \frac{\partial T(x)}{\partial x}(f(x(t), x(t-d)) + g(x(t))(\alpha(x(t), x(t-d)) + \beta^{-1}(x(t), x(t-d))v)). \tag{6}$$

由式(4) 和(6) 联立得出如下偏微分方程:

$$\begin{cases} \dfrac{\partial T(x)}{\partial x}(f(x(t), x(t-d)) + g(x)\alpha(x(t), x(t-d))) = AT(x), \\ \dfrac{\partial T(x)}{\partial x}g(x)\beta(x(t), x(t-d)) = B. \end{cases} \tag{7}$$

令

$$T(x) = (T_1(x), T_2(x), \cdots, T_n(x))^{\mathrm{T}},$$

偏微分方程(7) 的可解条件为

$$\begin{cases} \dfrac{\partial T_i(x)}{\partial x}f(x(t), x(t-d)) = T_{i+1}(x), \\ \qquad i = 1, 2, \cdots, n-1; \\ \dfrac{\partial T_n(x)}{\partial x}f(x(t), x(t-d)) = \\ -\beta^{-1}(x(t), x(t-d))\alpha(x(t), x(t-d)); \\ \dfrac{\partial T_i(x)}{\partial x}g(x) = 0, \ i = 1, 2, \cdots, n-1; \\ \dfrac{\partial T_n(x)}{\partial x}g(x(t)) = -\beta^{-1}(x(t), x(t-d)) \neq 0. \end{cases} \tag{8}$$

3 滑模控制器设计

采用滑模控制策略,定义滑模面函数为

$$S = CZ, \tag{9}$$

其中 $C = [c_1, c_2, \cdots, c_n]$, 数值 $c_1, c_2, \cdots, c_n$ 是正实数.

控制律使 $S \to 0$ 且一直保持下去, 控制输入 v 的选择条件为

$$S\dot{S} < 0. \tag{10}$$

在传统的滑模控制器中, 由于存在符号函数 $\mathrm{sgn}(S)$, 使系统输入存在抖动现象, 而边界层技术经常用于解决传统滑模控制中存在的抖动问题, 因此设定系统的自适应控制律为

$$v = -(CB)^{-1}(CAZ + \lambda\phi(\theta, S)). \tag{11}$$

其中: λ 和 θ 分别为控制增益和边界层参数, $\phi(\theta, S)$ 是 S 形函数, 具有

$$\phi(\theta, S) = \frac{1 - \exp(-\theta S)}{1 + \exp(-\theta S)}. \tag{12}$$

自适应律设为

$$\dot{\lambda} = \gamma CB\,\mathrm{sgn}\left(\frac{\partial S}{\partial v}\right)\left(\frac{1 - \exp(-\theta S)}{1 + \exp(-\theta S)}\right)S, \tag{13}$$

$$\dot{\theta} = \varepsilon CB\,\mathrm{sgn}\left(\frac{\partial S}{\partial v}\right), \tag{14}$$

其中 γ 和 ε 是用来改变自适应律的正实数.

定理 1 针对系统(4), 给定滑模面(9), 控制律(11), (12) 和自适应律(13), (14), 则系统(4) 稳定.

证明 取系统(4) 的 Lyapunov 函数为

$$V = S^2/2. \tag{15}$$

对 Lyapunov 函数进行求导得

$$\dot{V} = S\dot{S} =$$

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$$S\frac{\partial S}{\partial v}\frac{\partial v}{\partial \lambda}\frac{\partial \lambda}{\partial t}+S\frac{\partial S}{\partial v}\frac{\partial v}{\partial \theta}\frac{\partial \theta}{\partial t}=\dot V_1+\dot V_2,\tag{16}$$

即

$$\dot V_1=S\frac{\partial S}{\partial v}\frac{\partial v}{\partial \lambda}\frac{\partial \lambda}{\partial t}=$$
$$S\frac{\partial S}{\partial v}\frac{\partial}{\partial \lambda}\{-(CB)^{-1}(c^{\mathrm T}f_0(x)CAZ+$$
$$\lambda\Phi(\theta,S))\}\frac{\partial \lambda}{\partial t}=$$
$$-S\frac{\partial S}{\partial v}(CB)^{-1}\Big(\frac{1-\exp(-\theta S)}{1+\exp(-\theta S)}\Big)\dot\lambda.\tag{17}$$

将式(13)带入(17)得到

$$\dot V_1=-\gamma\Big|\frac{\partial S}{\partial v}\Big|\Big(\frac{1+\exp(-\theta S)}{1+\exp(-\theta S)}\Big)^2S^2\le 0,\tag{18}$$

$$\dot V_2=S\frac{\partial S}{\partial v}\frac{\partial v}{\partial \theta}\frac{\partial \theta}{\partial t}=$$
$$S\frac{\partial S}{\partial v}\frac{\partial}{\partial \theta}\{-(CB)^{-1}(CAZ+\lambda\Phi(\theta,S))\}\frac{\partial \theta}{\partial t}=$$
$$-S\frac{\partial S}{\partial v}(CB)^{-1}\lambda\Big(\frac{2S\exp(-\theta S)}{(1+\exp(-\theta S))^2}\Big)\dot\theta.\tag{19}$$

将式(14)带入(19)得到

$$\dot V_2=-\varepsilon\Big|\frac{\partial S}{\partial v}\Big|\frac{2\exp(-\theta S)}{(1+\exp(-\theta S))^2}\lambda S^2\le 0.\tag{20}$$

综上所述, $\dot V\le 0$, $\dot V=0$ 的条件是 $S=0$, 当 $\dot V<0$ 时, 可在有限时间内得到 $V\to 0$, 即 $S\to 0$, 因此系统可在有限的时间内到达滑模面, 最终得出系统(1)的控制律 u. □

注 1　本文利用偏微分变换、可变的边界层宽度和控制增益技术设计了一种新的滑模控制器, 并有效地实现了控制目标. 此种控制策略避免了符号函数直接作用于控制律, 而是将它转移到参数自适应律中, 并可以通过调整自适应律中的参数来减弱符号函数的影响, 因此可以有效地削弱系统的输入抖动.

4　系统仿真

考虑系统(1), 设函数及参数如下:

$f_0(x(t))=[x_2,x_1^2]^{\mathrm T}$, $g_0(x)=[0,\cdots,0,1]^{\mathrm T}$,

$f_1(x(t-d))=[0,x_2(t-d)]^{\mathrm T}$,

$d=0.2$, $c=[1,0.5]^{\mathrm T}$,

$\lambda(0)=2$, $\theta(0)=1$, $x(0)=[1,0]^{\mathrm T}$.

用上述参数系统对式(8)运算, 可求得 $T(x)$, $\alpha(x(t),x(t-d))$, $\beta^1(x(t),x(t-d))$, 再求式(11)得到 v, 最后代入

$$u=\alpha(x(t),x(t-d))+\beta^1(x(t),x(t-d))v,$$

便可得到原系统的控制输入. 采用定理 1 中控制律及自适应律对具有上述参数非线性时滞系统(1)进行自适应变结构滑模控制, 结果如图 1～图 3 所示.

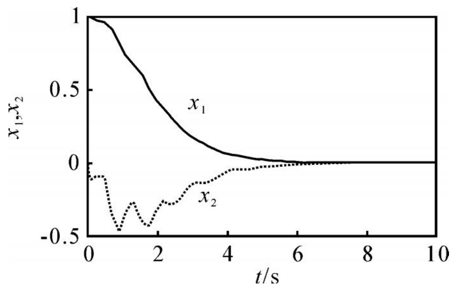

图 1　系统的状态响应

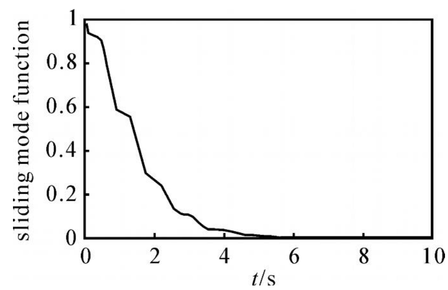

图 2　滑模面响应曲线

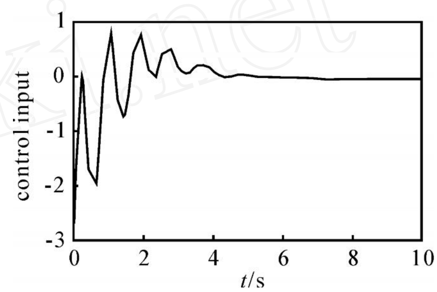

图 3　控制输入 u

从上述仿真图中可以看出: 系统很快达到稳定; 系统状态在有限的时间内能够到达滑模面; 控制输入在一定的时间段后几乎不存在抖动问题. 以上说明本文方法是有效可行的.

5　结　　论

考虑实际系统运行过程中经常存在时滞的情形, 针对一类一般形式的非线性时滞系统, 研究了非线性时滞系统基于偏微分变换的鲁棒滑模控制问题, 并在此基础上提出了一种新的鲁棒自适应滑模控制方法. 此方法可以更加有效地削弱系统的输入抖动, 并可以保证系统状态在很短的时间内到达滑模面, 获得了较好的控制效果. 最后给出的仿真结果验证了该方法的有效性.

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示.

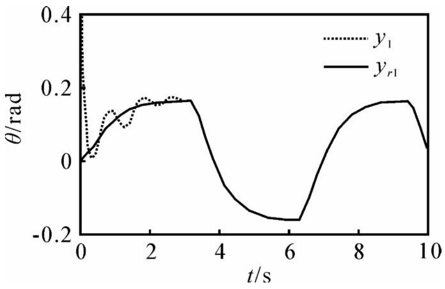

图 1　输出 y_1 和期望值 y_{r1}

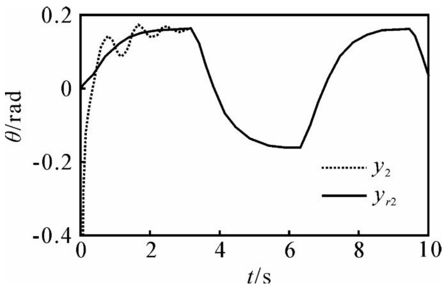

图 2　输出 y_2 和期望值 y_{r2}

6　结　论

本文综合了自适应控制和 H_∞控制,提出了一种直接自适应模糊跟踪控制方案. 构建自适应时滞模糊逻辑系统用来逼近时滞未知函数,用 H_∞补偿器抵消模糊逼近误差和系统的外部扰动. 仿真结果表明了该方案的有效性.

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