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含有执行器故障的非线性切换互联大系统的自适应模糊 Backstepping 容错控制

摘要

本文研究了一类存在执行器故障的非线性互联切换大系统的自适应模糊 Backstepping 容错控制.首先定义了一个分段右连续函数作为系统的切换信号,系统依据切换信号改变模型.不失一般性,考虑执行器发生两种类型的故障,即卡死故障和失效故障,通过模糊逻辑系统逼近未知非线性函数,并设计自适应模糊容错控制器补偿执行器故障给系统带来的影响.通过 Lyapunov 定理证明了系统及相关变量的有界性,并基于数值仿真,验证了所提出方法的有效性.

关键词

互联大系统;切换系统;自适应模糊 Backstepping 控制;执行器故障;容错控制

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0 引言

互联大系统[1-11]是一类由多个子系统组成的结构复杂的非线性系统,典型特点是不同子系统之间具有互联性.由于该系统往往具有复杂性和较强的耦合性,因此互联大系统的研究具有普适性.早期对大系统的研究主要集中在线性大系统.Lee 等[12-13]研究了线性多输入多输出大系统在含有时滞情形下的稳定性问题,并得到反馈增益矩阵与系统稳定性的关系.随着分散控制思想的出现,大量学者开始研究分散控制在大系统中的应用.Hu[14]研究了具有线性互联项的大系统的分散控制问题,通过求解 Riccati 方程,设计分散控制器,并给出了分散控制器与系统互联项时滞无关的充分条件.

由于实际系统中均不可避免地存在非线性元件及非线性成分,即不存在严格线性的系统,因此对非线性系统的研究更具有一般意义.文献[15-16]研究了基于 Lyapunov 函数递归设计状态反馈分散控制器的方法,通过反馈控制动态调节控制器最终实现系统的稳定性分析.由于实际系统中系统状态并不一定是完全可测的,文献[17-18]研究了非线性互联大系统的输出反馈镇定问题.通过引入状态观测器克服了系统状态不可测量的局限性,Yan 等[18]考虑了更为一般的时变参数大系统,所得出的结论对匹配不确定性系统及非匹配不确定性系统均具有可适性.上述文献都是基于大系统互联项精确已知的情形,若系统互联项未知,上述理论则不再适用.为了更具有一般性,Jain 等[19]研究了一类具有未知互联项的非线性大系统的稳定性问题,依据微分几何理论,将非线性互联大系统转换为一类严格反馈分散控制系统,大大降低了非线性大系统控制器设计难度,并通过自适应控制方法克服了互联项未知的问题.文献[20]研究了一类具有未知互联项的非线性大系统的自适应输出跟踪控制,采用 Backstepping 设计方法,解决了不满足匹配条件时的控制器设计问题;同时,引入光滑函数补偿了各个子系统分散控制器设计过程中其他子系统的影响.文献[21]研究了系统中存在更大的不确定性即存在未知非线性函数的情形,利用模糊逻辑系统逼近未知非线性函数,以此为基础设计了非线性互联大系统的自适应模糊分散控制器,保证了系统的渐近稳定性及跟踪误差的收敛性.上述文献对互联大系统的研究没有考虑到被控

对象的结构由于环境因素或外界扰动变化而变化的情形,而实际系统中这种现象是普遍存在的,因此本文选择非线性互联切换大系统作为研究对象,当系统模型发生变化时,适当改变控制策略.同时,由于人为因素或使用寿命限制,在实际系统中,执行器故障运行是一种较为常见的状态.执行器的非正常运行大大降低了系统的性能,甚至可能会导致原系统不稳定,在实际生产中,可能带来巨大的经济损失,因此有必要在执行器发生故障时,对故障进行补偿和抵消,从而使系统恢复到原始的正常运行状态,容错控制便是可以实现这一功能的控制方法. 因此,在本文中,基于非线性互联切换大系统设计了自适应模糊分散控制器.

1 问题描述

考虑如下由 N 个子系统组成的含有执行器故障的非线性切换互联大系统,其第 i 个子系统的系统模型如下($i=1,2,\cdots,N$):

$$\begin{cases}\dot{x}_{i,1}=x_{i,2}+f_{i,1}^{\sigma(t)}(x_{i,1})+h_{i,1}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{i,1}^{\sigma(t)},\\ \dot{x}_{i,2}=x_{i,3}+f_{i,2}^{\sigma(t)}(x_{i,1},x_{i,2})+h_{i,2}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{i,2}^{\sigma(t)},\\ \vdots\\ \dot{x}_{i,j}=x_{i,j+1}+f_{i,j}^{\sigma(t)}(x_{i,1},\cdots,x_{i,j})+h_{i,j}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{i,j}^{\sigma(t)},\\ \vdots\\ \dot{x}_{i,n_i}=(\tilde{\boldsymbol{\omega}}_i^{\sigma(t)})^{\mathrm{T}}\boldsymbol{u}_i^{\sigma(t)}+f_{i,n_i}^{\sigma(t)}(x_{i,1},\cdots,x_{i,n_i})+\\ \qquad h_{i,n_i}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{i,n_i}^{\sigma(t)},\\ y_i=x_{i,1},\end{cases}\tag{1}$$

其中,$y_i\in\mathbf{R}$ 及 $\boldsymbol{u}_i=[u_{i,1},u_{i,2},\cdots,u_{i,q}]^{\mathrm{T}}\in\mathbf{R}^{i,q}$ 为相应子系统的输出与执行器输入向量(若系统中发生执行器故障,则为相应的执行器故障输入向量),q 为执行器个数.$f_{i,j}$ 是未知连续非线性函数($j=1,\cdots,n_i$),$\tilde{\boldsymbol{\omega}}_i=[\tilde{\omega}_{i,1},\tilde{\omega}_{i,2},\cdots,\tilde{\omega}_{i,q}]^{\mathrm{T}}\in\mathbf{R}^{i,q}$ 为已知常数向量,$\bar{\boldsymbol{x}}_{i,j}=[x_{i,1},\cdots,x_{i,j}]^{\mathrm{T}}\in\mathbf{R}^{i,j}$ 为系统的状态向量,$d_{i,j}\in\mathbf{R}$ 为附加未知外部有界扰动,$\bar{\boldsymbol{y}}=[y_1,\cdots,y_N]^{\mathrm{T}}$. $h_{i,j}(\bar{\boldsymbol{y}})$ 为第 i 个子系统与其他系统之间的关联项,$\boldsymbol{\sigma}(t)$ 为系统的分段右连续切换信号.

1.1 切换系统

$\sigma(t)$ 为系统切换信号,是定义在$[0,\infty)\to\bar{S}=\{1,2,\cdots,s\}$ 上的分段右连续函数.$\sigma(t)=s$ 表示系统的第 s 个切换子系统被激活,其余子系统没有被激活. 则可得如下含有执行器故障的非线性切换大系统:

$$\begin{cases}\dot{x}_{i,1}=x_{i,2}+f_{i,1}^{s}(x_{i,1})+h_{i,1}^{s}(\bar{\boldsymbol{y}})+d_{i,1}^{s},\\ \dot{x}_{i,2}=x_{i,3}+f_{i,2}^{s}(x_{i,1},x_{i,2})+h_{i,2}^{s}(\bar{\boldsymbol{y}})+d_{i,2}^{s},\\ \vdots\\ \dot{x}_{i,j}=x_{i,j+1}+f_{i,j}^{s}(x_{i,1},\cdots,x_{i,j})+h_{i,j}^{s}(\bar{\boldsymbol{y}})+d_{i,j}^{s},\\ \vdots\\ \dot{x}_{i,n_i}=(\tilde{\boldsymbol{\omega}}_i^{s})^{\mathrm{T}}\boldsymbol{u}_i^{s}+f_{i,n_i}^{s}(x_{i,1},\cdots,x_{i,n_i})+\\ \qquad h_{i,n_i}^{s}(\bar{\boldsymbol{y}})+d_{i,n_i}^{s},\\ y_i=x_{i,1}.\end{cases}\tag{2}$$

假设 1 外界扰动 $d_{i,j}^s$ 未知,但有界,即 $|d_{i,j}^s|<\bar{d}_{i,j}^s$,其中 $\bar{d}_{i,j}^s$ 为已知常数.

假设 2 当 $1\leqslant i\leqslant N$ 且 $1\leqslant j\leqslant n_i$ 时,$|h_{i,j}^s(\bar{\boldsymbol{y}})|\leqslant p_{i,j}^s\sum_{l=1}^{N}\varphi_{ijl}^s(|y_l|)$,其中 $p_{i,j}^s$ 为未知常数,且 $p_{i,j}^s>0$,φ_{ijl}^s 为已知非线性光滑函数.

1.2 执行器故障

为不失一般性,本文考虑执行器发生卡死故障和失效故障的情形.定义如下卡死故障及失效故障模型:

1) 卡死故障模型

$$u_g(t)=\bar{u}_g,t\geqslant t_g,g\in\{g_1,g_2,\cdots,g_k\}\subset\{1,2,\cdots,q\},\tag{3}$$

其中,t_g 为执行器卡死故障发生的时刻,$\bar{u}_g$ 为执行器卡死常值.

2) 失效故障模型

$$u_l(t)=\rho_l v_l(t),\quad t\geqslant t_l,$$
$$l\in\{\overline{g_1,g_2,\cdots,g_k}\}\subset\{1,2,\cdots,q\},\tag{4}$$

其中,t_l 为执行器失效故障发生的时刻,$v_l(t)$ 为控制输入,ρ_l 为执行器失效比例,$\rho_l\in[\underline{\rho_l},1]$,且 $0<\underline{\rho_l}<1$,$\underline{\rho_l}$ 为 ρ_l 的下界.若 $\underline{\rho_l}=1$,则执行器未发生失效故障.

假设系统中部分执行器发生卡死故障,部分执行器发生失效故障,则

$$\boldsymbol{u}_i(t)=\boldsymbol{\rho}_i\boldsymbol{v}_i(t)+\boldsymbol{\sigma}_i(\bar{\boldsymbol{u}}_i-\boldsymbol{\rho}_i\boldsymbol{v}_i(t)),\tag{5}$$

其中,$\boldsymbol{v}_i(t)=[v_{i,1}(t),v_{i,2}(t),\cdots,v_{i,q}(t)]^{\mathrm{T}}$,$\bar{\boldsymbol{u}}_i(t)=[\bar{u}_{i,1}(t),\bar{u}_{i,2}(t),\cdots,\bar{u}_{i,q}(t)]^{\mathrm{T}}$,$\bar{u}_{i,g}$ 为执行器卡死常值,且 $g=1,2,\cdots,q$.$\boldsymbol{\rho}_i=\mathrm{diag}\{\rho_{i,1},\rho_{i,2},\cdots,\rho_{i,q}\}$,$\rho_{i,g}$ 为执行器失效比例,$\boldsymbol{\sigma}_i=\mathrm{diag}\{\sigma_{i,1},\sigma_{i,2},\cdots,\sigma_{i,q}\}$,$\sigma_{i,g}$ 为常数.

$$\sigma_{i,g}=\begin{cases}1, & \text{若第}\ i\ \text{个子系统的第}\ g\ \text{个执行器发生卡死故障},\\ 0, & \text{其他}\end{cases}\tag{6}$$

引理1[22] 对于任意的定义在紧集Ω上的光滑未知非线性函数$f(x)$,存在模糊逻辑系统使得对于任意的$\varepsilon>0$,有下式成立:

$$\sup_{x\in\Omega}|f(x)-\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{\varphi}(x)|\leqslant\varepsilon, \tag{7}$$

其中,自适应参数向量$\boldsymbol{\theta}=[\theta_1,\theta_2,\cdots,\theta_M]^{\mathrm{T}}$,模糊基函数向量$\boldsymbol{\varphi}(x)=[\varphi_1(x),\varphi_2(x),\cdots,\varphi_M(x)]^{\mathrm{T}}$,模糊基函数$\varphi_j$可表示为

$$\varphi_j=\frac{\prod_{i=1}^{n}\mu_{A_i^j}(x_i)}{\sum_{j=1}^{M}\left[\prod_{i=1}^{n}\mu_{A_i^j}(x_i)\right]}. \tag{8}$$

2 控制器设计及系统稳定性分析

依据Backstepping方法设计控制器.引入如下坐标变换:

$$e_{i,1}=x_{i,1}-y_{i,d}, \tag{9}$$

$$e_{i,j}=x_{i,j}-\alpha_{i,j-1}^{s},\quad j=2,\cdots,n_i-1, \tag{10}$$

其中,$y_{i,d}$为第i个子系统的跟踪参考信号,$\alpha_{i,j-1}^{s}$为中间虚拟控制器.

第1步.由$e_{i,1}=x_{i,1}-y_{i,d}$得:

$$\dot{e}_{i,1}=\dot{x}_{i,1}-\dot{y}_{i,d}=x_{i,2}+f_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})+h_{i,1}^{s}(\bar{\boldsymbol{y}})+d_{i,1}^{s}-\dot{y}_{i,d}. \tag{11}$$

用模糊逻辑系统逼近$f_{i,1}(\bar{x}_{i,1})$可得:

$$f_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})=(\theta_{i,1}^{*s})^{\mathrm{T}}\varphi_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})+\varepsilon_{i,1}^{s}. \tag{12}$$

将式(12)代入式(11)且由$e_{i,2}=x_{i,2}-\alpha_{i,1}^{s}$可以得到跟踪误差$e_{i,1}$的导数为

$$\dot{e}_{i,1}=\dot{x}_{i,1}-\dot{y}_{i,d}=e_{i,2}+\alpha_{i,1}^{s}+(\theta_{i,1}^{*s})^{\mathrm{T}}\varphi_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})+\varepsilon_{i,1}^{s}+h_{i,1}^{s}(\bar{\boldsymbol{y}})+d_{i,1}^{s}-\dot{y}_{i,d}. \tag{13}$$

假设3 模糊逻辑系统逼近误差有界,即存在已知常数$\bar{\varepsilon}_{i,j}^{s}$,且满足$|\varepsilon_{i,j}^{s}|<\bar{\varepsilon}_{i,j}^{s}$.

定义如下Lyapunov函数:

$$V_1=\sum_{i=1}^{N}\left(\frac{1}{2}e_{i,1}^2+\frac{1}{2\gamma_{i,1}^{s}}(\tilde{\theta}_{i,1}^{s})^2\right), \tag{14}$$

其中,$\gamma_{i,1}^{s}$为设计参数且$\gamma_{i,1}^{s}>0$,$\tilde{\theta}_{i,1}^{s}=\theta_{i,1}^{*s}-\hat{\theta}_{i,1}^{s}$,$\hat{\theta}_{i,1}^{s}$为对参数$\theta_{i,1}^{*s}$的估计.

对V_1求导且将式(13)代入可得:

$$\dot{V}_1=\sum_{i=1}^{N}\left[e_{i,1}(e_{i,2}+\alpha_{i,1}^{s}+(\theta_{i,1}^{*s})^{\mathrm{T}}\varphi_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})+\varepsilon_{i,1}^{s}+h_{i,1}^{s}(\bar{\boldsymbol{y}})+d_{i,1}^{s}-\dot{y}_{i,d})+\frac{1}{\gamma_{i,1}^{s}}\tilde{\theta}_{i,1}^{s}\cdot\dot{\tilde{\theta}}_{i,1}^{s}\right]. \tag{15}$$

考虑式(15)中的关联项且由假设2可得:

$$|h_{i,1}^{s}(\bar{\boldsymbol{y}})|\leqslant\sum_{l=1}^{N}p_{i,1}^{s}\varphi_{i1l}^{s}(|y_l|)\leqslant\frac{1}{2}\sum_{l=1}^{N}(\varphi_{i1l}^{s}(|y_l|))^2+\frac{N}{2}(p_{i,1}^{s})^2. \tag{16}$$

由于φ_{i1l}为光滑函数,因此存在光滑非负定函数$\eta_{i1l}(y_l)$满足:

$$\frac{1}{2}\sum_{l=1}^{N}(\varphi_{i1l}^{s}(|y_l|))^2\leqslant\sum_{l=1}^{N}\eta_{i1l}^{s}(y_l)y_l^2+\sum_{l=1}^{N}2(\varphi_{i1l}^{s}(0))^2. \tag{17}$$

将式(16)及(17)代入式(15)中的互联项可得:

$$\begin{aligned}\sum_{i=1}^{N}e_{i,1}h_{i,1}^{s}(\bar{\boldsymbol{y}})&\leqslant\sum_{i=1}^{N}|e_{i,1}|\cdot p_{i,1}^{s}\sum_{l=1}^{N}\varphi_{i1l}^{s}(|y_l|)\leqslant\\&\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+\frac{1}{2}(p_{i,1}^{s})^2\sum_{l=1}^{N}(\varphi_{i1l}^{s}(|y_l|))^2\right]\leqslant\\&\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+\frac{1}{4}\sum_{l=1}^{N}(\varphi_{i1l}^{s}(|y_l|))^4+\frac{N}{4}(p_{i,1}^{s})^4\right]\leqslant\\&\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+\sum_{l=1}^{N}\eta_{i1l}^{s}(y_l)y_l^4+2\sum_{l=1}^{N}(\varphi_{i1l}^{s}(0))^4+\frac{N}{4}(p_{i,1}^{s})^4\right].\end{aligned} \tag{18}$$

由$\sum_{i=1}^{N}\sum_{l=1}^{N}\eta_{i1l}(y_l)y_l^4=\sum_{i=1}^{N}\sum_{l=1}^{N}\eta_{l1i}(y_i)y_i^4$,代入式(18)可得:

$$\begin{aligned}\sum_{i=1}^{N}e_{i,1}h_{i,1}^{s}(\bar{\boldsymbol{y}})&\leqslant\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+\sum_{l=1}^{N}\eta_{l1i}(y_i)y_i^4+2\sum_{l=1}^{N}(\varphi_{i1l}^{s}(0))^4+\frac{N}{4}(p_{i,1}^{s})^4\right]\leqslant\\&\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+\sum_{l=1}^{N}\eta_{l1i}(e_{i,1}+y_{i,d})^4+2\sum_{l=1}^{N}(\varphi_{i1l}^{s}(0))^4+\frac{N}{4}(p_{i,1}^{s})^4\right]\leqslant\\&\sum_{i=1}^{N}\left[\frac{N}{2}e_{i,1}^2+8\sum_{l=1}^{N}\eta_{l1i}^{s}(y_i)e_{i,1}^4+8\sum_{l=1}^{N}\eta_{l1i}^{s}(y_i)y_{i,d}^4+2\sum_{l=1}^{N}(\varphi_{i1l}^{s}(0))^4+\frac{N}{4}(p_{i,1}^{s})^4\right].\end{aligned} \tag{19}$$

由Young's不等式及假设1、假设3可得:

$$e_{i,1}(\varepsilon_{i,1}^{s}+d_{i,1}^{s})\leqslant e_{i,1}^2+\frac{1}{2}(\bar{\varepsilon}_{i,1}^{s})^2+\frac{1}{2}(\bar{d}_{i,1}^{s})^2. \tag{20}$$

将式(19)及式(20)代入式(15)可得:

$$\dot{V}_1\leqslant\sum_{i=1}^{N}\left[e_{i,1}\left(e_{i,2}+\alpha_{i,1}^{s}+(\hat{\theta}_{i,1}^{s})^{\mathrm{T}}\varphi_{i,1}^{s}(\bar{\boldsymbol{x}}_{i,1})+\frac{2+N}{2}e_{i,1}+8\sum_{l=1}^{N}\eta_{i1l}^{s}(y_l)e_{i,1}^3-\dot{y}_{i,d}\right)+\xi_{i,1}^{s}+\tilde{\theta}_{i,1}^{s}\left(e_{i,1}\varphi_{i,1}^{s}-\frac{1}{\gamma_{i,1}^{s}}\dot{\hat{\theta}}_{i,1}^{s}\right)\right]. \tag{21}$$

其中,$\xi_{i,1}^s = 8\sum_{l=1}^N \eta_{l1i}^s(y_i)y_{i,d}^4 + 2\sum_{l=1}^N(\varphi_{i1l}^s(0))^4 + \frac{N}{4}(p_{i,1}^s)^4 + \frac{1}{2}(\bar{\varepsilon}_{i,1}^s)^2 + \frac{1}{2}(\bar{d}_{i,1}^s)^2$.

选择如下虚拟控制器 $\alpha_{i,1}^s$ 及参数自适应率 $\dot{\hat{\theta}}_{i,1}^s$:

$$\alpha_{i,1}^s = -b_{i,1}^s e_{i,1} - \frac{2+N}{2}e_{i,1} - (\hat{\theta}_{i,1}^s)^{\mathrm{T}}\varphi_{i,1}^s - 8\sum_{l=1}^N\sum_{h=1}^{n_i}\eta_{lhi}^s(y_i)e_{i,1}^3 - 8\sum_{h=2}^{n_i}\sum_{m=1}^{h-1}\sum_{l=1}^N\eta_{lmi}^s(y_i)e_{i,1}^3 + \dot{y}_{i,d}, \tag{22}$$

$$\dot{\hat{\theta}}_{i,1}^s = -\gamma_{i,1}^s c_{i,1}^s\hat{\theta}_{i,1}^s + \gamma_{i,1}^s e_{i,1}\varphi_{i,1}^s, \tag{23}$$

其中,$b_{i,1}^s > 0$ 为控制器设计参数,$\gamma_{i,1}^s > 0$,$c_{i,1}^s > 0$ 为自适应率设计参数.

将式(22)及(23)代入式(21)可得:

$$\dot{V}_1 \leqslant \sum_{i=1}^N\Big[e_{i,1}e_{i,2} - b_{i,1}^s e_{i,1}^2 + c_{i,1}^s\tilde{\theta}_{i,1}^s\hat{\theta}_{i,1}^s + \xi_{i,1}^s - 8\sum_{l=1}^N\sum_{h=2}^{n_i}\eta_{lhi}^s(y_i)e_{i,1}^4 - 8\sum_{h=2}^{n_i}\sum_{m=1}^{h-1}\sum_{l=1}^N\eta_{lmi}^s(y_i)e_{i,1}^4\Big]. \tag{24}$$

第 j 步.由 $e_{i,j} = x_{i,j} - \alpha_{i,j-1}^s$ 得:

$$\dot{e}_{i,j} = \dot{x}_{i,j} - \dot{\alpha}_{i,j-1}^s = x_{i,j+1} + f_{i,j}^s(\bar{x}_{i,j}) + h_{i,j}^s(\bar{y}) + d_{i,j}^s - \dot{\alpha}_{i,j-1}^s. \tag{25}$$

用模糊逻辑系统逼近 $f_{i,j}^s(\bar{x}_{i,j})$ 可得:

$$f_{i,j}^s(\bar{\boldsymbol{x}}_{i,j}) = (\theta_{i,j}^{*s})^{\mathrm{T}}\varphi_{i,j}^s(\bar{\boldsymbol{x}}_{i,j}) + \varepsilon_{i,j}^s. \tag{26}$$

将式(26)代入式(25)且由 $e_{i,j+1} = x_{i,j+1} - \alpha_{i,j}^s$ 可以得:

$$\dot{e}_{i,j} = e_{i,j+1} + \alpha_{i,j}^s + (\theta_{i,j}^{*s})^{\mathrm{T}}\varphi_{i,j}^s(\bar{\boldsymbol{x}}_{i,j}) + \varepsilon_{i,j}^s + h_{i,j}^s(\bar{\boldsymbol{y}}) + d_{i,j}^s - \dot{\alpha}_{i,j-1}^s. \tag{27}$$

定义如下 Lyapunov 函数:

$$V_j = \sum_{r=1}^{j-1}V_r + \sum_{i=1}^N\left(\frac{1}{2}e_{i,j}^2 + \frac{1}{2\gamma_{i,j}^s}(\tilde{\theta}_{i,j}^s)^2\right), \tag{28}$$

其中,$\gamma_{i,j}^s$ 为设计参数且 $\gamma_{i,j}^s > 0$,$\tilde{\theta}_{i,j}^s = \theta_{i,j}^{*s} - \hat{\theta}_{i,j}^s$,$\hat{\theta}_{i,1}^s$ 为对参数 $\theta_{i,j}^{*s}$ 的估计.

对 V_j 求导且将式(27)代入可得:

$$\dot{V}_j \leqslant \sum_{i=1}^N\Big[e_{i,j-1}e_{i,j} - \sum_{r=1}^{j-1}b_{i,r}^s e_{i,r}^2 + \sum_{r=1}^{j-1}c_{i,r}^s\tilde{\theta}_{i,r}^s\hat{\theta}_{i,r}^s + \frac{1}{2}\sum_{r=1}^{j-2}\sum_{m=1}^{r}(\tilde{\theta}_{i,m}^s)^2 + \sum_{r=1}^{j-1}\xi_{i,r}^s - 8\sum_{l=1}^N\sum_{h=j}^{n_i}\eta_{lhi}^s(y_i)e_{i,1}^4 - 8\sum_{h=j}^{n_i}\sum_{m=1}^{h-1}\sum_{l=1}^N\eta_{lmi}^s(y_i)e_{i,1}^4\Big] + \sum_{i=1}^N\Big[e_{i,j}\Big(e_{i,j+1} + \alpha_{i,j}^s + (\theta_{i,j}^{*s})^{\mathrm{T}}\varphi_{i,j}^s(\bar{x}_{i,j}) + \varepsilon_{i,j}^s + h_{i,j}^s(\bar{y}) + d_{i,j}^s - \sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}(x_{i,m+1} + (\tilde{\theta}_{i,m}^s)^{\mathrm{T}}\varphi_{i,m}^s + (\hat{\theta}_{i,j}^s)^{\mathrm{T}}\varphi_{i,j}^s + \varepsilon_{i,m}^s + h_{i,m}^s(\bar{y}) + d_{i,m}^s) - \sum_{m=1}^{j}\frac{\partial\alpha_{i,j-1}^s}{\partial y_{i,d}^{(m-1)}}y_{i,d}^{(m)} - \sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}^s}{\partial\hat{\theta}_{i,m}^s}\dot{\hat{\theta}}_{i,m}^s\Big) + \frac{1}{\gamma_{i,j}^s}\tilde{\theta}_{i,j}^s\dot{\hat{\theta}}_{i,j}^s\Big]. \tag{29}$$

考虑其中的关联项,类似第 1 步可得:

$$|h_{i,j}^s(\bar{\boldsymbol{y}})| \leqslant \sum_{l=1}^N\eta_{i1l}^s(y_l)y_l^2 + \sum_{l=1}^N 2(\varphi_{i1l}^s(0))^2 + \frac{N}{2}(p_{i,j}^s)^2, \tag{30}$$

则将式(30)代入式(29)中的互联项 $e_{i,j}h_{i,j}^s(\bar{\boldsymbol{y}})$ 进一步化简可得:

$$\sum_{i=1}^N e_{i,j}h_{i,j}^s(\bar{\boldsymbol{y}}) \leqslant \sum_{i=1}^N\Big[\frac{N}{2}e_{i,j}^2 + \sum_{l=1}^N\eta_{ijl}^s(y_l)y_l^4 + 2\sum_{l=1}^N(\varphi_{ijl}^s(0))^4 + \frac{N}{4}(p_{i,j}^s)^4\Big]. \tag{31}$$

由 $\sum_{i=1}^N\sum_{l=1}^N\eta_{ijl}(y_l)y_l^4 = \sum_{i=1}^N\sum_{l=1}^N\eta_{lji}(y_i)y_i^4$,代入式(31)可得:

$$\sum_{i=1}^N e_{i,j}h_{i,j}^s(\bar{\boldsymbol{y}}) \leqslant \sum_{i=1}^N\Big[\frac{N}{2}e_{i,j}^2 + \sum_{l=1}^N\eta_{lji}(y_i)y_i^4 + 2\sum_{l=1}^N(\varphi_{ijl}^s(0))^4 + \frac{N}{4}(p_{i,j}^s)^4\Big] \leqslant \sum_{i=1}^N\Big[\frac{N}{2}e_{i,1}^2 + 8\sum_{l=1}^N\eta_{lji}^s(y_i)e_{i,1}^4 + 8\sum_{l=1}^N\eta_{lji}^s(y_i)y_{i,d}^4 + 2\sum_{l=1}^N(\varphi_{ijl}^s(0))^4 + \frac{N}{4}(p_{i,j}^s)^4\Big]. \tag{32}$$

考虑式(29)中由于对虚拟控制器 $\alpha_{i,j-1}^s$ 微分引入的关联项 $-e_{i,j}\sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}h_{i,m}^s$,用与上面类似的方法处理可得:

$$\sum_{i=1}^N\left(-e_{i,j}\sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}h_{i,m}^s\right) \leqslant \sum_{i=1}^N\Big[\frac{N}{2}e_{i,j}^2\sum_{m=1}^{j-1}\left(\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}\right)^2 + 8\sum_{m=1}^{j-1}\sum_{l=1}^N\eta_{lmi}^s(y_i)e_{i,1}^4 + 8\sum_{m=1}^{j-1}\sum_{l=1}^N\eta_{lmi}^s(y_i)y_{i,d}^4 + 2\sum_{m=1}^{j-1}\sum_{l=1}^N(\varphi_{iml}^s(0)) + \sum_{m=1}^{j-1}\frac{N}{4}(p_{i,m}^s)^4\Big]^4. \tag{33}$$

同理,由 Young's 不等式及假设 1、假设 3 可得:

$$e_{i,j}(\varepsilon_{i,j}^s + d_{i,j}^s) \leqslant e_{i,j}^2 + \frac{1}{2}(\bar{\varepsilon}_{i,j}^s)^2 + \frac{1}{2}(\bar{d}_{i,j}^s)^2, \tag{34}$$

$$-e_{i,j}\sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}((\tilde{\theta}_{i,m}^s)^{\mathrm{T}}\varphi_{i,m}^s + \varepsilon_{i,m}^s + d_{i,m}^s) \leqslant \frac{3}{2}e_{i,j}^2\sum_{m=1}^{j-1}\left(\frac{\partial\alpha_{i,j-1}^s}{\partial x_{i,m}}\right)^2 + \frac{1}{2}\sum_{m=1}^{j-1}(\tilde{\theta}_{i,m}^s)^2 +$$

$$\frac{1}{2}\sum_{m=1}^{j-1}(\bar{\varepsilon}^s_{i,m})^2+\frac{1}{2}\sum_{m=1}^{j-1}(\bar{d}^s_{i,m})^2. \tag{35}$$

将式(32)—(35) 代入式(29) 可得:

$$\begin{aligned}\dot{V}_j=&\sum_{i=1}^{N}\Bigg[e_{i,j-1}e_{i,j}-\sum_{r=1}^{j-1}b^s_{i,r}e^2_{i,r}+\sum_{r=1}^{j-1}c^s_{i,r}\tilde{\theta}^s_{i,r}\hat{\theta}^s_{i,r}+\\&\frac{1}{2}\sum_{r=1}^{j-2}\sum_{m=1}^{r}(\tilde{\theta}^s_{i,m})^2+\sum_{r=1}^{j-1}\xi^s_{i,r}-8\sum_{l=1}^{N}\sum_{h=j}^{n_i}\eta^s_{lhi}(y_i)e^4_{i,1}-\\&8\sum_{h=j}^{n_i}\sum_{m=1}^{h-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Bigg]+\sum_{i=1}^{N}\Bigg[e_{i,j}\Bigg(e_{i,j+1}+\\&\alpha^s_{i,j}+(\hat{\theta}^s_{i,j})^{\mathrm{T}}\varphi^s_{i,j}(\bar{\boldsymbol{x}}_{i,j})+\frac{2+N}{2}e_{i,j}-\\&\sum_{m=1}^{j-1}\frac{\partial\alpha^s_{i,j-1}}{\partial x_{i,m}}(x_{i,m+1}+(\hat{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m})+\\&\frac{3+N}{2}e_{i,j}\sum_{m=1}^{j-1}\left(\frac{\partial\alpha^s_{i,j-1}}{\partial x_{i,m}}\right)^2-\sum_{m=1}^{j}\frac{\partial\alpha_{i,j-1}}{\partial y^{(m-1)}_{i,d}}y^{(m)}_{i,d}-\\&\sum_{m=1}^{j-1}\frac{\partial\alpha_{i,j-1}}{\partial\hat{\theta}_{i,m}}\dot{\hat{\theta}}_{i,m}\Bigg)+\tilde{\theta}^s_{i,j}\left(e_{i,j}\varphi^s_{i,j}-\frac{1}{\gamma^s_{i,j}}\dot{\hat{\theta}}^s_{i,j}\right)+\xi^s_{i,j}+\\&\frac{1}{2}\sum_{m=1}^{j-1}(\tilde{\theta}^s_{i,m})^2+8\sum_{l=1}^{N}\eta^s_{lji}(y_i)e^4_{i,1}+\\&8\sum_{m=1}^{j-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Bigg],\end{aligned}\tag{36}$$

其中,

$$\begin{aligned}\xi^s_{i,j}=&8\sum_{l=1}^{N}\eta^s_{lji}(y_i)y^4_{i,d}+2\sum_{l=1}^{N}(\varphi^s_{ijl}(0))^4+\\&\frac{N}{4}(p^s_{i,j})^4+\frac{1}{2}(\bar{\varepsilon}^s_{i,j})^2+\frac{1}{2}(\bar{d}^s_{i,j})^2+\\&8\sum_{m=1}^{j-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)y^4_{i,d}+2\sum_{m=1}^{j-1}\sum_{l=1}^{N}(\varphi^s_{iml}(0))^4+\\&\frac{N}{4}\sum_{m=1}^{j-1}(p^s_{i,m})^4+\frac{1}{2}\sum_{m=1}^{j-1}(\bar{\varepsilon}^s_{i,m})^2+\frac{1}{2}\sum_{m=1}^{j-1}(\bar{d}^s_{i,m})^2.\end{aligned}$$

与第1步类似,选择如下虚拟控制器 $\alpha^s_{i,j}$ 及参数自适应率 $\dot{\hat{\theta}}^s_{i,j}$:

$$\begin{aligned}a^s_{i,j}=&-b^s_{i,j}e_{i,j}-e_{i,j-1}-\frac{N+2}{2}e_{i,j}-(\hat{\theta}^s_{i,j})^{\mathrm{T}}\varphi^s_{i,j}+\\&\sum_{m=1}^{j-1}\frac{\partial\alpha^s_{i,j-1}}{\partial x_{i,m}}(x_{i,m+1}+(\hat{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m}(\bar{x}_{i,m}))-\\&\frac{3+N}{2}e_{i,j}\sum_{m=1}^{j-1}\left(\frac{\partial\alpha^s_{i,j-1}}{\partial x_{i,m}}\right)^2+\sum_{m=1}^{j}\frac{\partial\alpha^s_{i,j-1}}{\partial y^{(m-1)}_{i,d}}y^{(m)}_{i,d}+\\&\sum_{m=1}^{j-1}\frac{\partial\alpha^s_{i,j-1}}{\partial\hat{\theta}^s_{i,m}}\dot{\hat{\theta}}^s_{i,m},\end{aligned}\tag{37}$$

$$\dot{\hat{\theta}}^s_{i,j}=-\gamma^s_{i,j}c^s_{i,j}\hat{\theta}^s_{i,j}+\gamma^s_{i,j}e_{i,j}\varphi^s_{i,j},\tag{38}$$

其中,$b^s_{i,j}>0$ 为控制器设计参数,$\gamma^s_{i,j}>0$,$c^s_{i,j}>0$ 为自适应率设计参数.

将式(37)及(38)代入式(36)可得:

$$\begin{aligned}\dot{V}_j\leqslant&\sum_{i=1}^{N}\Bigg[e_{i,j}e_{i,j+1}-\sum_{r=1}^{j}b^s_{i,r}e^2_{i,r}+\sum_{r=1}^{j}c^s_{i,r}\tilde{\theta}^s_{i,r}\hat{\theta}^s_{i,r}+\\&\frac{1}{2}\sum_{r=1}^{j-1}\sum_{m=1}^{r}(\tilde{\theta}^s_{i,m})^2+\sum_{r=1}^{j}\xi^s_{i,r}-8\sum_{l=1}^{N}\sum_{h=j+1}^{n_i}\eta^s_{lhi}(y_i)e^4_{i,1}-\\&8\sum_{h=j+1}^{n_i}\sum_{m=1}^{h-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Bigg].\end{aligned}\tag{39}$$

第 n_i 步. 由 $e_{i,j}=x_{i,j}-\alpha^s_{i,j-1}$ 得:

$$\begin{aligned}\dot{e}_{i,n_i}=&\dot{x}_{i,n_i}-\dot{\alpha}^s_{i,n_i-1}=(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}\boldsymbol{u}^s_i+f^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,j})+\\&h^s_{i,n_i}(\bar{\boldsymbol{y}})+d^s_{i,n_i}-\dot{\alpha}^s_{i,n_i-1}.\end{aligned}\tag{40}$$

结合式(5)可知:

$$\begin{aligned}(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}\boldsymbol{u}^s_i=&(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}[\boldsymbol{\rho}_i\boldsymbol{v}^s_i+\boldsymbol{\sigma}_i(\bar{\boldsymbol{u}}^s_i-\boldsymbol{\rho}_i\boldsymbol{v}^s_i)]=\\&(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}[\boldsymbol{\rho}_i\boldsymbol{v}^s_i+\boldsymbol{\sigma}_i\bar{\boldsymbol{u}}^s_i-\boldsymbol{\sigma}_i\boldsymbol{\rho}_i\boldsymbol{v}^s_i]=\\&(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}[(\boldsymbol{I}-\boldsymbol{\sigma}_i)\boldsymbol{\rho}_i\boldsymbol{v}^s_i+\boldsymbol{\sigma}_i\bar{\boldsymbol{u}}^s_i]=\\&\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}^s_{i,g}+\sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}v^s_{i,g},\end{aligned}\tag{41}$$

假设控制器的结构为

$$v^s_{i,g}=\psi_{i,g}(\bar{\boldsymbol{x}}_{i,n_i})u^s_{i,0},\tag{42}$$

其中,$0\leqslant\underline{\psi}_{i,g}\leqslant\psi_{i,g}(\bar{x}_{i,n})\leqslant\bar{\psi}_{i,g}$,$\underline{\psi}_{i,g}$ 和 $\bar{\psi}_{i,g}$ 分别是 $\psi_{i,g}(\bar{x}_{i,n})$ 的下界和上界. 将式(42)代入式(41)可得:

$$(\tilde{\boldsymbol{\omega}}^s_i)^{\mathrm{T}}\boldsymbol{u}^s_i=\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}^s_{i,g}+\sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}\psi_{i,g}u^s_{i,0}.\tag{43}$$

用模糊逻辑系统逼近 $f^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,n_i})$ 可得:

$$f^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,n_i})=(\theta^{*s}_{i,n_i})^{\mathrm{T}}\varphi^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,n_i})+\varepsilon^s_{i,n_i}.\tag{44}$$

将式(43)及(44)代入式(40)可得:

$$\begin{aligned}\dot{e}_{i,n_i}=&\dot{x}_{i,n_i}-\dot{\alpha}^s_{i,n_i-1}=\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}_{i,g}+\\&\sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}\psi_{i,g}u_{i,0}+(\theta^{*s}_{i,n_i})^{\mathrm{T}}\varphi^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,n_i})+\\&\varepsilon^s_{i,n_i}+h^s_{i,n_i}(\bar{\boldsymbol{y}})+d^s_{i,n_i}-\dot{\alpha}^s_{i,n_i-1}.\end{aligned}\tag{45}$$

定义如下 Lyapunov 函数:

$$V_{n_i}=\sum_{r=1}^{n_i-1}V_r+\sum_{i=1}^{N}\left(\frac{1}{2}e^2_{i,n_i}+\frac{1}{2\gamma^s_{i,n_i}}(\tilde{\theta}^s_{i,n_i})^2\right),\tag{46}$$

其中,γ^s_{i,n_i} 为设计参数且 $\gamma^s_{i,n_i}>0$,$\tilde{\theta}^s_{i,n_i}=\theta^{*s}_{i,n_i}-\hat{\theta}^s_{i,n_i}$,$\hat{\theta}^s_{i,n_i}$ 为对参数 θ^{*s}_{i,n_i} 的估计.

对 V_{n_i} 求导且将式(45)代入可得:

$$\begin{aligned}\dot{V}_{n_i}\leqslant&\sum_{i=1}^{N}\Bigg[e_{i,n_i-1}e_{i,n_i}-\sum_{r=1}^{n_i-1}b^s_{i,r}e^2_{i,r}+\sum_{r=1}^{n_i-1}c^s_{i,r}\tilde{\theta}^s_{i,r}\hat{\theta}^s_{i,r}+\\&\frac{1}{2}\sum_{r=1}^{n_i-2}\sum_{m=1}^{r}(\tilde{\theta}^s_{i,m})^2+\sum_{r=1}^{n_i-1}\xi^s_{i,r}-8\sum_{l=1}^{N}\eta^s_{ln_ii}(y_i)e^4_{i,1}-\\&8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Bigg]+\sum_{i=1}^{N}\Bigg[e_{i,n_i}\Bigg(\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}^s_{i,g}+\end{aligned}$$

$$\sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}\psi_{i,g}u^s_{i,0}+(\theta^{*s}_{i,n_i})^{\mathrm{T}}\varphi^s_{i,j}(\bar{\boldsymbol{x}}_{i,n_i})+\varepsilon^s_{i,n_i}+ h^s_{i,n_i}(\bar{y})+d^s_{i,n_i}-\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}(x_{i,m+1}+(\tilde{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m}+ (\hat{\theta}^s_{i,n_i})^{\mathrm{T}}\varphi^s_{i,n_i}+\varepsilon^s_{i,m}+h^s_{i,m}(\bar{\boldsymbol{y}})+d^s_{i,m})- \sum_{m=1}^{n_i}\frac{\partial\alpha^s_{i,n_i-1}}{\partial y^{(m-1)}_{i,d}}y^{(m)}_{i,d}-\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial\hat{\theta}^s_{i,m}}\dot{\hat{\theta}}^s_{i,m}\Big)+ \frac{1}{\gamma^s_{i,n_i}}\tilde{\theta}^s_{i,n_i}\dot{\hat{\theta}}^s_{i,n_i}\Big]. \tag{47}$$

考虑 e_{i,n_i} 中的关联项以及由于对虚拟控制器 α^s_{i,n_i-1} 微分引入的关联项,且由 $\sum_{i=1}^{N}\sum_{l=1}^{N}\eta_{in_il}(y_l)y_l^4=\sum_{i=1}^{N}\sum_{l=1}^{N}\eta_{\ln_i i}(y_i)y_i^4$,类似第 j 步可得:

$$\sum_{i=1}^{N}e_{i,j}h^s_{i,n_i}(\bar{\boldsymbol{y}})\leqslant\sum_{i=1}^{N}\Big[\frac{N}{2}e^2_{i,1}+8\sum_{l=1}^{N}\eta^s_{\ln_i i}(y_i)e^4_{i,1}+ 8\sum_{l=1}^{N}\eta^s_{\ln_i i}(y_i)y^4_{i,d}+2\sum_{l=1}^{N}(\varphi^s_{in_il}(0))^4+\frac{N}{4}(p^s_{i,n_i})^4\Big], \tag{48}$$

$$\sum_{i=1}^{N}\Big(-e_{i,n_i}\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}h^s_{i,m}\Big)\leqslant\sum_{i=1}^{N}\Big[\frac{N}{2}e^2_{i,n_i}\sum_{m=1}^{n_i-1}\Big(\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}\Big)^2+ 8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}+8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)y^4_{i,d}+ 2\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}(\varphi^s_{iml}(0))^4+\sum_{m=1}^{n_i-1}\frac{N}{4}(p^s_{i,m})^4\Big]. \tag{49}$$

同理,由 Young's 不等式及假设 1、假设 3 可得:

$$e_{i,n_i}(\varepsilon^s_{i,n_i}+d^s_{i,n_i})\leqslant e^2_{i,n_i}+\frac{1}{2}(\bar{\varepsilon}^s_{i,n_i})^2+\frac{1}{2}(\bar{d}_{i,n_i})^2, \tag{50}$$

$$-e_{i,n_i}\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}((\tilde{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m}+\varepsilon^s_{i,m}+d^s_{i,m})\leqslant \frac{3}{2}e^2_{i,n_i}\sum_{m=1}^{n_i-1}\Big(\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}\Big)^2+\frac{1}{2}\sum_{m=1}^{n_i-1}(\tilde{\theta}^s_{i,m})^2+ \frac{1}{2}\sum_{m=1}^{n_i-1}(\bar{\varepsilon}^s_{i,m})^2+\frac{1}{2}\sum_{m=1}^{n_i-1}(\bar{d}^s_{i,m})^2. \tag{51}$$

将式(48)—(51) 代入式(47) 可得:

$$\dot{V}_{n_i}=\sum_{i=1}^{N}\Big[e_{i,n_i-1}e_{i,n_i}-\sum_{r=1}^{n_i-1}b^s_{i,r}e^2_{i,r}+\sum_{r=1}^{n_i-1}c^s_{i,r}\tilde{\theta}^s_{i,r}\hat{\theta}^s_{i,r}+ \frac{1}{2}\sum_{r=1}^{n_i-2}\sum_{m=1}^{r}(\tilde{\theta}^s_{i,m})^2+\sum_{r=1}^{n_i-1}\xi^s_{i,r}-8\sum_{l=1}^{N}\eta^s_{\ln_i i}(y_i)e^4_{i,1}- 8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Big]+\sum_{i=1}^{N}\Big[e_{i,n_i}\Big(\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}^s_{i,g}+ \sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}\psi_{i,g}u^s_{i,0}+(\hat{\theta}^s_{i,n_i})^{\mathrm{T}}\varphi^s_{i,n_i}(\bar{\boldsymbol{x}}_{i,n_i})+ \frac{2+N}{2}e_{i,n_i}-\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}(x_{i,m+1}+(\hat{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m})+ \frac{3+N}{2}e_{i,n_i}\sum_{m=1}^{j-1}\Big(\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}\Big)^2-\sum_{m=1}^{n_i}\frac{\partial\alpha_{i,n_i-1}}{\partial y^{(m-1)}_{i,d}}y^{(m)}_{i,d}- \sum_{m=1}^{n_i-1}\frac{\partial\alpha_{i,n_i-1}}{\partial\hat{\theta}_{i,m}}\dot{\hat{\theta}}_{i,m}\Big)+\tilde{\theta}^s_{i,n_i}\Big(e_{i,n_i}\varphi^s_{i,n_i}-\frac{1}{\gamma^s_{i,n_i}}\dot{\hat{\theta}}^s_{i,n_i}\Big)+ \xi^s_{i,n_i}+\frac{1}{2}\sum_{m=1}^{n_i-1}(\tilde{\theta}^s_{i,m})^2+8\sum_{l=1}^{N}\eta^s_{\ln_i i}(y_i)e^4_{i,1}+ 8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)e^4_{i,1}\Big], \tag{52}$$

其中,

$$\xi^s_{i,n_i}=8\sum_{l=1}^{N}\eta^s_{\ln_i i}(y_i)y^4_{i,d}+2\sum_{l=1}^{N}(\varphi^s_{in_il}(0))^4+\frac{N}{4}(p^s_{i,n_i})^4+ \frac{1}{2}(\bar{\varepsilon}^s_{i,n_i})^2+\frac{1}{2}(\bar{d}^s_{i,n_i})^2+8\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}\eta^s_{lmi}(y_i)y^4_{i,d}+ 2\sum_{m=1}^{n_i-1}\sum_{l=1}^{N}(\varphi^s_{iml}(0))^4+\frac{N}{4}\sum_{m=1}^{n_i-1}(p^s_{i,m})^4+ \frac{1}{2}\sum_{m=1}^{n_i-1}(\bar{\varepsilon}^s_{i,m})^2+\frac{1}{2}\sum_{m=1}^{n_i-1}(\bar{d}^s_{i,m})^2.$$

同理,选择如下实际控制器 $u_{i,0}$ 及参数自适应率 $\dot{\hat{\theta}}^s_{i,n_i}$:

$$u^s_{i,0}=(g_i')^{-1}\Big(-b^s_{i,n_i}e_{i,n_i}-e_{i,n_i-1}-\frac{N+2}{2}e_{i,n_i}- (\hat{\theta}^s_{i,n_i})^{\mathrm{T}}\varphi^s_{i,n_i}+\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}(x_{i,m+1}+ (\hat{\theta}^s_{i,m})^{\mathrm{T}}\varphi^s_{i,m}(\bar{\boldsymbol{x}}_{i,m}))-\frac{3+N}{2}e_{i,n_i}\sum_{m=1}^{n_i-1}\Big(\frac{\partial\alpha^s_{i,n_i-1}}{\partial x_{i,m}}\Big)^2+ \sum_{m=1}^{n_i}\frac{\partial\alpha^s_{i,n_i-1}}{\partial y^{(m-1)}_{i,d}}y^{(m)}_{i,d}+\sum_{m=1}^{n_i-1}\frac{\partial\alpha^s_{i,n_i-1}}{\partial\hat{\theta}^s_{i,m}}\dot{\hat{\theta}}^s_{i,m}-\sum_{g=g_1,\cdots,g_z}\tilde{\omega}^s_{i,g}\bar{u}^s_{i,g}\Big), \tag{53}$$

$$\dot{\hat{\theta}}^s_{i,n_i}=-\gamma^s_{i,n_i}c^s_{i,n_i}\hat{\theta}^s_{i,n_i}+\gamma^s_{i,n_i}e_{i,n_i}\varphi^s_{i,n_i}, \tag{54}$$

其中,$g'_i=\sum_{g\neq g_1,\cdots,g_z}\rho_{i,g}\tilde{\omega}^s_{i,g}\psi_{i,g}b^s_{i,n_i}>0$,$c^s_{i,n_i}>0$ 为自适应率设计参数.

将式(53) 及(54) 代入式(52) 可得:

$$\dot{V}_{n_i}\leqslant\sum_{i=1}^{N}\Big[-\sum_{r=1}^{n_i}b^s_{i,r}e^2_{i,r}+\sum_{r=1}^{n_i}c^s_{i,r}\tilde{\theta}^s_{i,r}\hat{\theta}^s_{i,r}+ \frac{1}{2}\sum_{r=1}^{n_i-1}\sum_{m=1}^{r}(\tilde{\theta}^s_{i,m})^2+\sum_{r=1}^{n_i}\xi^s_{i,r}\Big]. \tag{55}$$

由 Young's 不等式,可得下式成立:

$$\tilde{\theta}_{i,r}\hat{\theta}_{i,r}=(\theta^{*s}_{i,r}-\hat{\theta}_{i,r})\hat{\theta}_{i,r}\leqslant\frac{1}{2}(\theta^{*s}_{i,r})^2-\frac{1}{2}(\hat{\theta}_{i,r})^2. \tag{56}$$

将式(56)代入式(55)可得:

$$\dot{V}_{n_i} \leqslant \sum_{i=1}^{N}\left[-\sum_{r=1}^{n_i} b_{i,r}^s e_{i,r}^2-\frac{1}{2}\sum_{r=1}^{n_i}(r+c_{i,r}^s-n_i)(\tilde{\theta}_{i,r}^s)^2+\frac{1}{2}\sum_{r=1}^{n_i} c_{i,r}^s(\theta_{i,r}^{*s})^2+\sum_{r=1}^{n_i}\xi_{i,r}^s\right]. \tag{57}$$

令 $\chi_{i,r}^s=r+c_{i,r}^s-n_i>0$,并对上式积分可得:

$$V_{n_i}(t)+\sum_{i=1}^{N}\sum_{r=1}^{n_i}\int_0^t b_{i,r}^s e_{i,r}^2\mathrm{d}t+\frac{1}{2}\sum_{i=1}^{N}\sum_{r=1}^{n_i}\chi_{i,r}^s(\tilde{\theta}_{i,r}^s)^2\mathrm{d}t \leqslant V_{n_i}(0)+\sum_{i=1}^{N}\sum_{r=1}^{n_i}\int_0^t \xi_{i,r}^s\mathrm{d}t+\frac{1}{2}\sum_{i=1}^{N}\sum_{r=1}^{n_i}\int_0^t c_{i,r}^s(\theta_{i,r}^{*s})^2\mathrm{d}t. \tag{58}$$

因此,由式(58)可得 V_{n_i},$\tilde{\theta}_{i,r}^s$ 及 $e_{i,r}(i=1,\cdots,N;r=1,\cdots,n_i)$ 有界,进而依据 Lyapunov 函数 V_n 表达式(46),$\hat{\theta}_{i,r}^s$ 有界,且由跟踪误差定义式(9)可知,$y_i=x_{i,1}$ 有界,因此由虚拟控制器表达式(22)知 $\alpha_{i,1}^s$ 有界.同理,虚拟控制器 $\alpha_{i,q}^s$、状态变量 $x_{i,q}$、系统真正的控制器 $u_{i,0}^s$ 均有界.因此该切换大系统的所有信号均有界,系统稳定.

3 仿真分析

考虑如下具有执行器故障的非线性切换互联大系统:

$$\begin{cases}\dot{x}_{1,1}=x_{1,2},\\ \dot{x}_{1,2}=(\tilde{\boldsymbol{\omega}}_1^{\sigma(t)})^{\mathrm{T}}\boldsymbol{u}_1+f_{1,2}^{\sigma(t)}(\bar{\boldsymbol{x}}_{1,2})+h_{1,2}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{1,2}^{\sigma(t)},\\ y_1=x_{1,1},\end{cases} \tag{59}$$

$$\begin{cases}\dot{x}_{2,1}=x_{2,2},\\ \dot{x}_{2,2}=(\tilde{\boldsymbol{\omega}}_2^{\sigma(t)})^{\mathrm{T}}\boldsymbol{u}_2+f_{2,2}^{\sigma(t)}(\bar{\boldsymbol{x}}_{2,2})+h_{2,2}^{\sigma(t)}(\bar{\boldsymbol{y}})+d_{2,2}^{\sigma(t)},\\ y_2=x_{2,1},\end{cases} \tag{60}$$

其中,分段切换信号 $\sigma(t)=s\in\{1,2\}$,子系统1中常数向量 $\tilde{\boldsymbol{\omega}}_1^1=[\tilde{\omega}_{1,1}^1,\tilde{\omega}_{1,2}^1]^{\mathrm{T}}=[1,1]^{\mathrm{T}}$,$\tilde{\boldsymbol{\omega}}_1^2=[\tilde{\omega}_{1,1}^2,\tilde{\omega}_{1,2}^2]^{\mathrm{T}}=[1,1]^{\mathrm{T}}$,执行器控制输入向量 $\boldsymbol{u}_1=[u_{1,1},u_{1,2}]^{\mathrm{T}}$,非线性函数 $f_{1,2}^1=-\sin(x_{1,1})\sin(x_{1,2})$,$f_{1,2}^2=-\cos(x_{1,1})\cos(x_{1,2})$,系统互联项 $h_{1,2}^1=\sin(y_1)\cdot\sin(y_2)$,$h_{1,2}^2=\cos(y_1)\cos(y_2)$,系统外部扰动 $d_{1,2}^1=0.01\cos(0.000\,5t)$,$d_{1,2}^2=0.01\cos(0.000\,5t)$;子系统2中常数向量 $\tilde{\boldsymbol{\omega}}_2^1=[\tilde{\omega}_{2,1}^1,\tilde{\omega}_{2,2}^1]^{\mathrm{T}}=[1,1]^{\mathrm{T}}$,$\tilde{\boldsymbol{\omega}}_2^2=[\tilde{\omega}_{2,1}^2,\tilde{\omega}_{2,2}^2]^{\mathrm{T}}=[1,1]^{\mathrm{T}}$,执行器控制输入向量 $\boldsymbol{u}_2=[u_{2,1},u_{2,2}]^{\mathrm{T}}$,非线性函数 $f_{2,2}^1=-\sin(x_{2,1})\cdot\sin(x_{2,2})$,$f_{2,2}^2=-\cos(x_{2,1})\cos(x_{2,2})$,系统中互联项 $h_{2,2}^1=\sin(y_1)\sin(y_2)$,$h_{2,2}^2=\cos(y_1)\cos(y_2)$,系统外部扰动 $d_{2,2}^1=0.01\cos(0.000\,5t)$,$d_{2,2}^2=0.01\cos(0.000\,5t)$.

选取参考信号 $y_r=0.5\sin(t)$,则 $\dot{y}_r=0.5\cos(t)$,$\ddot{y}_r=-0.5\sin(t)$.

通过定义模糊隶属度函数,得如下模糊基函数及模糊逻辑系统:

1)子系统1

$$\varphi_{1,2,j}^1(x_{1,1},x_{1,2})=\exp[-(x_{1,1}-3+j)^2/8]\cdot\exp[-(x_{1,2}-3+j)^2/8]\cdot\left\{\sum_{j=1}^{5}\exp[-(x_{1,1}-3+j)^2/8]\cdot\exp[-(x_{1,2}-3+j)^2/8]\right\}^{-1},\quad j=1,\cdots,5, \tag{61}$$

$$\varphi_{1,2,j}^2(x_{1,1},x_{1,2})=\exp[-(x_{1,1}-3+j)^2/16]\cdot\exp[-(x_{1,2}-3+j)^2/16]\cdot\left\{\sum_{j=1}^{5}\exp[-(x_{1,1}-3+j)^2/16]\cdot\exp[-(x_{1,2}-3+j)^2/16]\right\}^{-1},\quad j=1,\cdots,5, \tag{62}$$

$$\hat{f}_{1,2}^1(\bar{\boldsymbol{x}}_{1,2})=(\hat{\theta}_{1,2}^1)^{\mathrm{T}}\varphi_{1,2}^1(\bar{\boldsymbol{x}}_{1,2})=\sum_{j=1}^{5}(\hat{\theta}_{1,2,j}^1)^{\mathrm{T}}\varphi_{1,2,j}^1, \tag{63}$$

$$\hat{f}_{1,2}^2(\bar{\boldsymbol{x}}_{1,2})=(\hat{\theta}_{1,2}^2)^{\mathrm{T}}\varphi_{1,2}^2(\bar{\boldsymbol{x}}_{1,2})=\sum_{j=1}^{5}(\hat{\theta}_{1,2,j}^2)^{\mathrm{T}}\varphi_{1,2,j}^2. \tag{64}$$

2)子系统2

$$\varphi_{2,2,j}^1(x_{2,1},x_{2,2})=\exp[-(x_{2,1}-3+j)^2/8]\cdot\exp[-(x_{2,2}-3+j)^2/8]\cdot\left\{\sum_{j=1}^{5}\exp[-(x_{2,1}-3+j)^2/8]\cdot\exp[-(x_{2,2}-3+j)^2/8]\right\}^{-1},\quad j=1,\cdots,5, \tag{65}$$

$$\varphi_{2,2,j}^2(x_{2,1},x_{2,2})=\exp[-(x_{2,1}-3+j)^2/16]\cdot\exp[-(x_{2,2}-3+j)^2/16]\cdot\left\{\sum_{j=1}^{5}\exp[-(x_{2,1}-3+j)^2/16]\cdot\exp[-(x_{2,2}-3+j)^2/16]\right\}^{-1},\quad j=1,\cdots,5, \tag{66}$$

$$\hat{f}_{2,2}^1(\bar{\boldsymbol{x}}_{2,2})=(\hat{\theta}_{2,2}^1)^{\mathrm{T}}\varphi_{2,2}^1(\bar{\boldsymbol{x}}_{2,2})=\sum_{j=1}^{5}(\hat{\theta}_{2,2,j}^1)^{\mathrm{T}}\varphi_{2,2,j}^1, \tag{67}$$

$$\hat{f}_{2,2}^2(\bar{\boldsymbol{x}}_{2,2})=(\hat{\theta}_{2,2}^2)^{\mathrm{T}}\varphi_{2,2}^2(\bar{\boldsymbol{x}}_{2,2})=\sum_{j=1}^{5}(\hat{\theta}_{2,2,j}^2)^{\mathrm{T}}\varphi_{2,2,j}^2. \tag{68}$$

由式(22)、(53)、(54)设计如下虚拟控制器、自适应模糊控制器及参数自适应律:

1)子系统1

$$\alpha_{1,1}^s=-b_{1,1}^s e_{1,1}-8\sum_{l=1}^{2}\eta_{l21}^s e_{1,1}^3+\dot{y}_r, \tag{69}$$

$$u_{1,0}^{s}=(g_1')^{-1}\Big(-b_{1,2}^{s}e_{1,2}-e_{1,1}-2e_{1,2}-(\hat{\theta}_{1,2}^{s})^{\mathrm{T}}\varphi_{1,2}^{s}+\frac{\partial\alpha_{1,1}^{s}}{\partial x_{1,1}}x_{1,2}+\sum_{m=1}^{2}\frac{\partial\alpha_{1,1}^{s}}{\partial y_r^{(m-1)}}y_r^{(m)}-\sum_{g=g_1,\cdots,g_z}\tilde{\omega}_{1,g}^{s}\bar{u}_{1,g}^{s}\Big),\tag{70}$$

$$\dot{\hat{\theta}}_{1,2}^{s}=-\gamma_{1,2}^{s}c_{1,2}^{s}\hat{\theta}_{1,2}^{s}+\gamma_{1,2}^{s}e_{1,2}\varphi_{1,2}^{s},\tag{71}$$

其中,$g'_1=\sum\limits_{g\neq g_1,\cdots,g_z}\rho_{1,g}\tilde{\omega}_{1,g}^{s}\psi_{1,g}$,误差变量 $e_{1,1}=x_{1,1}-y_r$,$e_{1,2}=x_{1,2}-\alpha_{1,1}^{s}$.

2) 子系统 2

$$\alpha_{2,1}^{s}=-b_{2,1}^{s}e_{2,1}-8\sum_{l=1}^{2}\eta_{l22}^{s}e_{2,1}^{3}+\dot{y}_r,\tag{72}$$

$$u_{2,0}^{s}=(g_2')^{-1}\Big(-b_{2,2}^{s}e_{2,2}-e_{2,1}-2e_{2,2}-(\hat{\theta}_{2,2}^{s})^{\mathrm{T}}\varphi_{2,2}^{s}+\frac{\partial\alpha_{2,1}^{s}}{\partial x_{2,1}}x_{2,2}+\sum_{m=1}^{2}\frac{\partial\alpha_{2,1}^{s}}{\partial y_r^{(m-1)}}y_r^{(m)}-\sum_{g=g_1,\cdots,g_z}\tilde{\omega}_{2,g}^{s}\bar{u}_{2,g}^{s}\Big),\tag{73}$$

$$\dot{\hat{\theta}}_{2,2}^{s}=-\gamma_{2,2}^{s}c_{2,2}^{s}\hat{\theta}_{2,2}^{s}+\gamma_{2,2}^{s}e_{2,2}\varphi_{2,2}^{s},\tag{74}$$

其中,$g'_2=\sum\limits_{g\neq g_1,\cdots,g_z}\rho_{2,g}\tilde{\omega}_{2,g}^{s}\psi_{2,g}$,误差变量 $e_{2,1}=x_{2,1}-y_r$,$e_{2,2}=x_{2,2}-\alpha_{2,1}^{s}$.

选择如下控制器参数及自适应律参数:$b_{1,1}^{1}=b_{1,1}^{2}=3$,$b_{1,2}^{1}=b_{1,2}^{2}=3$,$\eta_{121}^{1}=\eta_{121}^{2}=0.5$,$\eta_{221}^{1}=\eta_{221}^{2}=0.5$,$\gamma_{1,2}^{1}=\gamma_{1,2}^{2}=0.5$,$c_{1,2}^{1}=c_{1,2}^{2}=0.5$;$b_{2,1}^{1}=b_{2,1}^{2}=3$,$b_{2,2}^{1}=b_{2,2}^{2}=3$,$\eta_{122}^{1}=\eta_{122}^{2}=0.5$,$\eta_{222}^{1}=\eta_{222}^{2}=0.5$,$\gamma_{2,2}^{1}=\gamma_{2,2}^{2}=0.5$,$c_{2,2}^{1}=c_{2,2}^{2}=0.5$.

假设 $t>10$ s,执行器发生卡死故障,$\bar{u}_{1,g}^{s}=\bar{u}_{2,g}^{s}=0.02$;$t>20$ s,剩余执行器发生失效故障,$\rho_{1,g}^{s}=\rho_{2,g}^{s}=0.5$,$\psi_{1,g}^{s}=\psi_{2,g}^{s}=1$.可得仿真结果如图 1—12 所示,其中,图 1—3 分别展示了两个子系统输出及其参考信号轨迹曲线、状态变量 $x_{i,2}$ 轨迹曲线、跟踪误差轨迹曲线.图 4 及图 5 分别展示了子系统 1 及 2 的执行器卡死与失效输出曲线,图 6 及图 7 分别展示了子系统 1 及 2 的控制器输出曲线,图 8 及图 9 分别展示了子系统 1 及 2 中自适应参数 $\hat{\theta}_{1,2}$、$\hat{\theta}_{2,2}$ 的变化曲线.若执行器发生故障时,系统未采取容错控制策略,两个子系统的输出轨迹曲线及其对应的跟踪误差曲线分别如图 10 和图 11 所示,本文中采取的切换信号 $\sigma(t)$ 如图 12 所示.

由图 1—3 可知,在如式(53)所示的自适应模糊控制器及如式(54)所示的自适应率的作用下,各个子系统的输出 y_i 可以较好地跟踪参考信号 y_r 且跟踪误差 $e_{i,1}$ 收敛到原点的小邻域内,各子系统状态变量 $x_{i,2}$ 有界;由图 6—9 可知,两个子系统的控制信号 $u_{i,0}$,两个子系统的自适应参数 $\hat{\theta}_{i,2}$ 均有界.由未采取容错控制的各子系统输出及跟踪误差曲线图 10 及

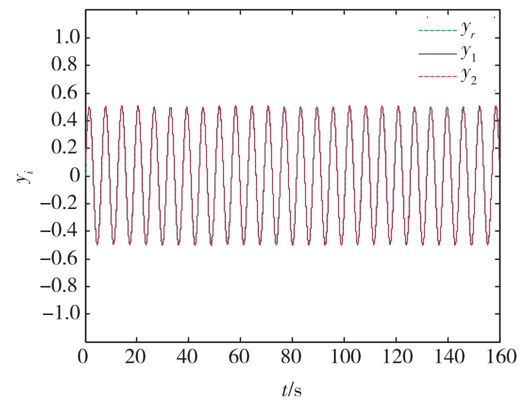

图 1 各子系统输出 y_i 及其参考信号 y_r

Fig. 1 The output of each subsystem y_i and its reference signal y_r

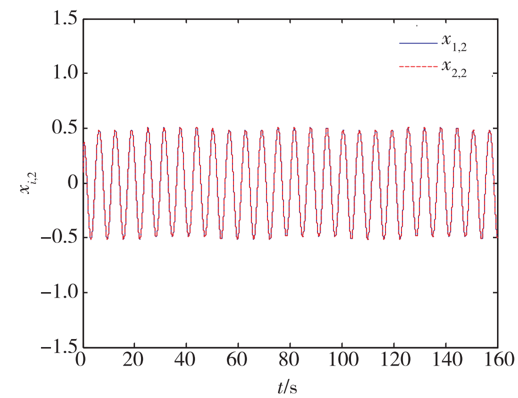

图 2 状态变量 $x_{i,2}$

Fig. 2 The states $x_{i,2}$

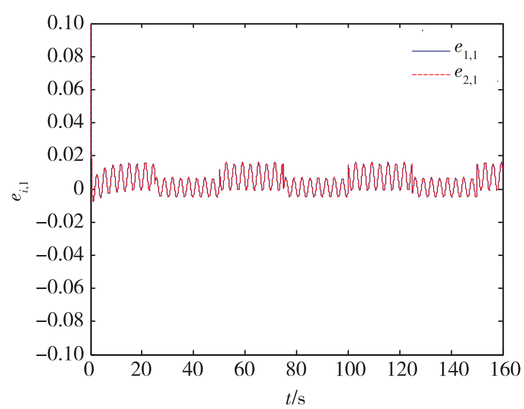

图 3 跟踪误差 $e_{i,1}$

Fig. 3 The tracking error $e_{i,1}$

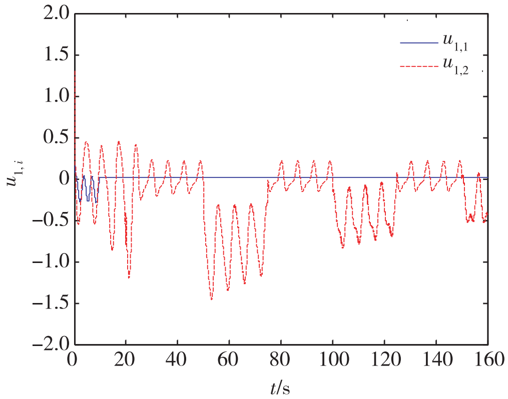

图 4 执行器 $u_{1,1}$ 及执行器 $u_{1,2}$

Fig. 4 The actuator $u_{1,1}$ and $u_{1,2}$

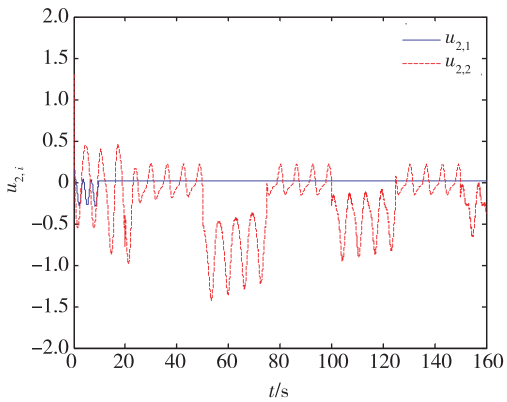

图 5 执行器 $u_{2,1}$ 及执行器 $u_{2,2}$

Fig. 5 The actuator $u_{2,1}$ and $u_{2,2}$

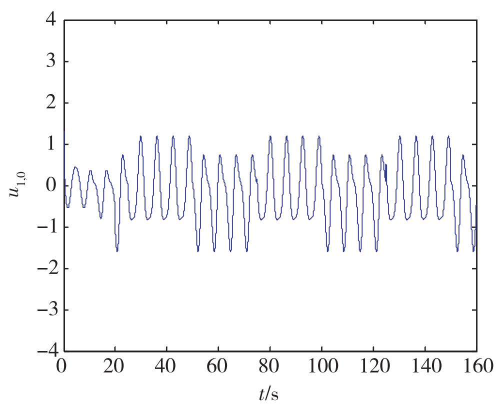

图 6 控制器 $u_{1,0}$

Fig. 6 The controller $u_{1,0}$

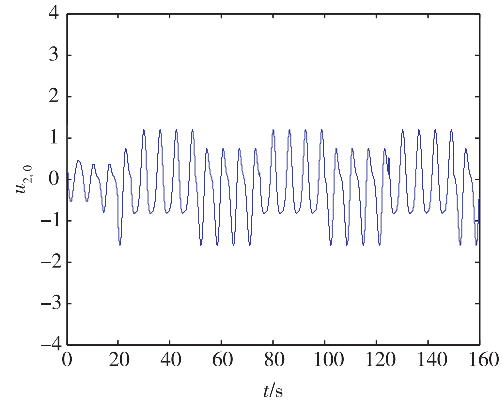

图 7 控制器 $u_{2,0}$

Fig. 7 The controller $u_{2,0}$

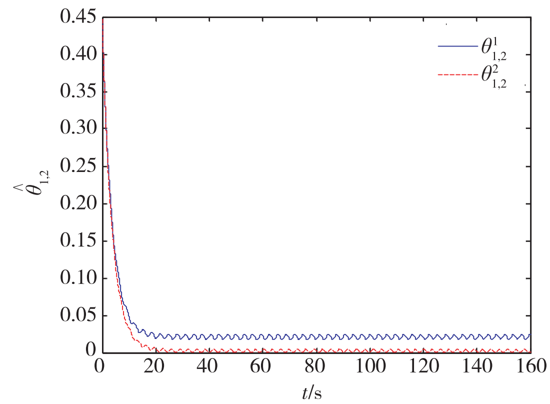

图 8 自适应参数 $\hat{\theta}_{1,2}$

Fig. 8 The adaptive parameter $\hat{\theta}_{1,2}$

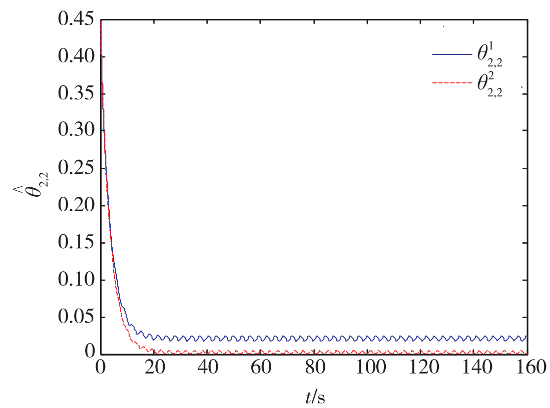

图 9 自适应参数 $\hat{\theta}_{2,2}$

Fig. 9 The adaptive parameter $\hat{\theta}_{2,2}$

图 11 可知,各子系统输出发散、跟踪误差发散,相应子系统不稳定.由上述仿真结果可知,本文所提出的控制器对于一类含有执行器故障的非线性切换互联大系统具有良好的控制效果.

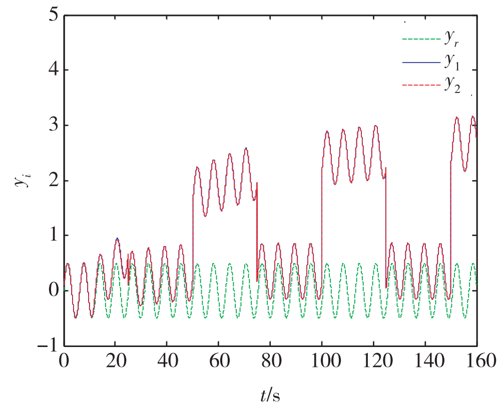

图 10　未采取容错控制的各子系统输出

Fig. 10　The output of each subsystem without fault-tolerant control strategy

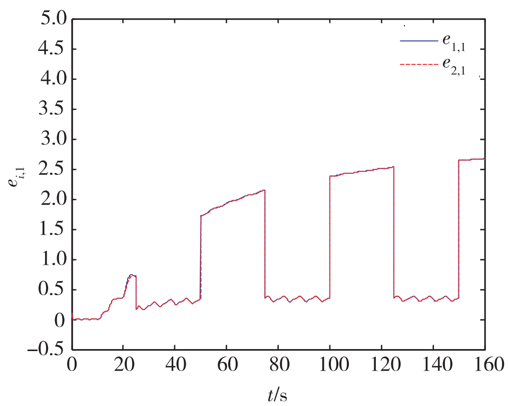

图 11　未采取容错控制的跟踪误差 $e_{i,1}$

Fig. 11　The tracking error $e_{i,1}$ without fault-tolerant control strategy

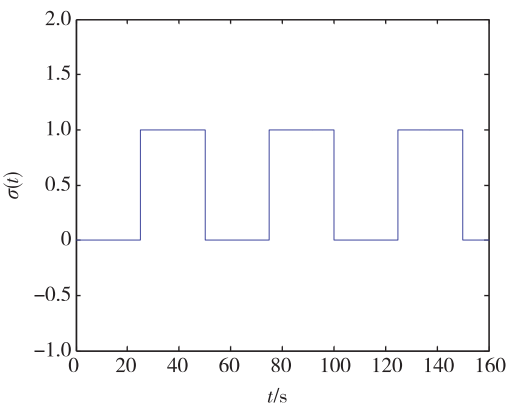

图 12　系统切换信号 $\sigma(t)$

Fig. 12　The switching signal $\sigma(t)$

4　结论

本文针对一类含有执行器故障的非线性切换互联大系统设计了自适应模糊 Backstepping 分散控制器.首先引入一个分段常数信号用来表示系统模型的切换,并考虑了两种类型的执行器故障:执行器卡死故障和执行器失效故障,分别对以上两类故障进行补偿,使得系统维持在故障前的稳定运行状态.同时考虑到各个子系统之间的互联对系统性能的影响,在各子系统控制器设计过程中,附加相关的补偿项,抵消了互联项对系统的影响.文中依据模糊逻辑系统的"万能逼近"特性逼近系统中的未知非线性函数,设计了自适应模糊控制器,通过选择恰当的 Lyapunov 函数分析得到,在自适应模糊控制器的作用下系统所有变量有界.最后通过数值仿真验证了上述理论的有效性.

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Adaptive fuzzy backstepping fault-tolerant control for nonlinear large-scale interconnected switched systems with actuator failures

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Abstract Adaptive fuzzy backstepping fault-tolerant control for a class of nonlinear large-scaleinterconnected switched systems with actuator failures is investigated in this paper.The system switches dynamically according to a piecewise right continuous function.Without loss of generality,stuck faults and the faults loss of effectiveness are considered.Fuzzy logic systems are utilized to approximate the unknown nonlinear functions.Considering the actuator failures,an adaptive fuzzy fault-tolerant controller is designed.It is proved that the proposed control method can guarantee that all the signals of the closed-loop system are bounded according to the Lyapunov theorem.A simulation example is presentedto demonstratethe effectiveness of the proposed control strategy.

Key words interconnected large-scale systems;switched systems;adaptive fuzzy backstepping control;actuator failures;fault-tolerant control