非线性扰动的时滞广义大系统的鲁棒稳定与 H_∞ 控制

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摘要: 针对一类非线性扰动的时滞广义大系统,研究其鲁棒 H_∞ 混合反馈控制器的设计问题. 基于有界实引理,应用线性矩阵不等式方法,构造 Lyapunov 函数,进而得出条件使得不确定广义大系统渐进稳定并且可以解得 H_∞ 混合控制器. 求解对应的线性矩阵不等式(LMIs)可以得到所需的鲁棒 H_∞ 控制器,使在控制器作用下的闭环系统渐进稳定,且满足了一定的性能指标,并且抑制了干扰的影响.

关键词: 非线性扰动; 时滞依赖; 广义大系统; 分散 H_∞ 混合控制

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0 引言

近些年来,有关不确定大系统鲁棒控制的研究取得了许多成果[1-4]. 而广义系统又是比正常系统更加广泛的一类系统,能更好的描述实际生产过程,且广义大系统理论在许多实际问题如:工程技术,社会经济,生物生态等各领域都有应用. 因此研究广义大系统有重要意义,而且在广义大系统控制方面也取得了成果. 如文献[5]针对带有控制输入时滞和关联时滞均为时变的不确定时滞大系统,利用线性矩阵不等式的方法,研究了其鲁棒镇定问题. 文献[6]对具有输入时滞的非线性不确定时滞系统,研究其鲁棒非脆弱 H_∞ 控制器设计问题. 文献[7]利用稳定理论和矩阵理论,研究了广义大系统的分散鲁棒状态反馈保性能 H_∞ 控制率问题. 关于具有参数不确定性,广义时滞大系统的状态反馈控制器设计问题都在很多文献中体现. 而对带有非线性扰动的广义时滞互联大系统的混合控制及 H_∞ 控制的研究比较少,本文通过构造广义 Lyapunov 函数及线性矩阵不等式来研究非线性广义时滞大系统的混合控制器的设计方法,并得出了使其稳定及 H_∞ 控制器存在的条件,使闭环系统在保持一定的 H_∞ 性能条件下渐进稳定.

1 问题描述与准备知识

考虑一类由 N 个子系统 Σ_i 构成的广义非线性时滞大系统 Σ,子系统 Σ_i 为

$$\Sigma_i:\begin{cases}\boldsymbol{E}_i\dot{\boldsymbol{x}}_i(t)=(\boldsymbol{A}_i+\Delta\boldsymbol{A}_i(t))\boldsymbol{x}_i(t)+(\boldsymbol{A}_{d_i}+\Delta\boldsymbol{A}_{d_i}(t))\boldsymbol{x}_i(t-d_i(t))+\\ \boldsymbol{B}_i\boldsymbol{u}_i+f_i(t,\boldsymbol{x}_i(t),\boldsymbol{\omega}_i(t),\boldsymbol{x}_i(t-d_i(t)))+\boldsymbol{D}_i\boldsymbol{\omega}_i(t)+\sum\limits_{j=1,j\neq i}^{N}\boldsymbol{H}_{ij}\boldsymbol{x}_j(t),\\ z_i(t)=\boldsymbol{C}_{1i}\boldsymbol{x}_i(t)+\boldsymbol{C}_{d_i}\boldsymbol{x}_i(t-d_i(t)),\\ \boldsymbol{x}_i(t)=\boldsymbol{\varphi}_i(t),\ \forall t\in[-\bar{d},0],\\ y_i(t)=\boldsymbol{C}_{2i}\boldsymbol{x}_i(t).\end{cases} \tag{1}$$

其中:$\boldsymbol{x}_i(t)\in\mathbf{R}^{n_i}$; $\boldsymbol{u}_i(t)\in\mathbf{R}^{m_i}$;$\boldsymbol{\omega}_i(t)\in L_2([0,\infty],\mathbf{R}^{r_i})$; $z_i(t)\in\mathbf{R}^{q_i}$分别是系统的状态向量、控制输入、干扰输入和控制输出;$\boldsymbol{E}_i,\boldsymbol{A}_i,\boldsymbol{A}_{d_i},\boldsymbol{B}_i,\boldsymbol{D}_i,\boldsymbol{C}_{1i},\boldsymbol{C}_{2i},\boldsymbol{C}_{d_i},\boldsymbol{H}_{ij}$ 是已知的适当维数的实常矩阵;$\boldsymbol{E}_i$ 是奇异矩阵且

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$\text{rank}(\boldsymbol{E}_i)=r_i\leqslant n_i$;$\Delta\boldsymbol{A}_i(t)$,$\Delta\boldsymbol{A}_{d_i}(t)$是适维不确定矩阵且满足如下条件:

$$[\Delta\boldsymbol{A}_i(t),\Delta\boldsymbol{A}_{d_i}(t)]=\boldsymbol{M}_i\boldsymbol{F}_i(t)[\boldsymbol{N}_{1i},\boldsymbol{N}_{2i}],\boldsymbol{F}_i^{\mathrm{T}}(t)\boldsymbol{F}_i(t)\leqslant\boldsymbol{I}, \tag{2}$$

其中:$\boldsymbol{M}_i,\boldsymbol{N}_{1i},\boldsymbol{N}_{2i}$是已知的适维矩阵. 对任意时刻 t,时滞 $d_i(t)$满足:$0\leqslant d_i(t)\leqslant\bar{d}<+\infty$,$\dot{d}_i(t)\leqslant\tau<1$,初始函数 $\boldsymbol{\varphi}^{\mathrm{T}}(t)=[\boldsymbol{\varphi}_1(t)^{\mathrm{T}},\boldsymbol{\varphi}_2(t)^{\mathrm{T}},\cdots,\boldsymbol{\varphi}_N(t)^{\mathrm{T}}]$,$\boldsymbol{\varphi}_i(t)\in\boldsymbol{C}^1([-\bar{d},0],\mathbf{R}^{n_i})$, 有以下形式

$$\|\varphi_i\|=\sup_{-\bar{d}\leqslant t\leqslant 0}\{\|\boldsymbol{\varphi}_i(t)\|,\|\dot{\boldsymbol{\varphi}}_i(t)\|\},\|\boldsymbol{\varphi}\|=\sqrt{\sum_{i=1}^{N}\|\boldsymbol{\varphi}_i\|^2},$$

非线性函数$f_i(\cdot)$ 满足条件:

$$\exists a_i,b_i,d_i>0:\|f_i(\cdot)\|\leqslant a_i\|\boldsymbol{x}_i(t)\|+b_i\|\boldsymbol{x}_i(t-d_i(t))\|+d_i\|\boldsymbol{\omega}_i(t)\|. \tag{3}$$

定义 1 系统$(\boldsymbol{E},\boldsymbol{A})$是正则的,如果 $\det(\boldsymbol{SE}-\boldsymbol{A})$不全等于零;系统$(\boldsymbol{E},\boldsymbol{A})$无脉冲,如果$(\boldsymbol{E},\boldsymbol{A})$正则且 $\deg(\det(\boldsymbol{SE}-\boldsymbol{A}))=\text{rank}(\boldsymbol{E})$.

假设 1 系统$(\boldsymbol{E}_i,\boldsymbol{A}_i,\boldsymbol{B}_i)$稳定且无穷能控.

对于系统(1),若采用反馈控制律

$$u_i(t)=L_iy_i(t)+\boldsymbol{K}_i\boldsymbol{x}_i(t)+\boldsymbol{K}_{d_i}\boldsymbol{x}_i(t-d_i(t)),t\geqslant 0,i=1,2,\cdots,N, \tag{4}$$

则闭环系统为:

$$\begin{aligned}\boldsymbol{E}_i\dot{\boldsymbol{x}}_i&=(\boldsymbol{A}_i+\Delta\boldsymbol{A}_i+\boldsymbol{B}_i\boldsymbol{K}_i+\boldsymbol{B}_i\boldsymbol{L}_i\boldsymbol{C}_{2i})\boldsymbol{x}_i(t)+(\boldsymbol{A}_{d_i}+\Delta\boldsymbol{A}_{d_i}+\boldsymbol{B}_i\boldsymbol{K}_{d_i})\boldsymbol{x}_i(t-d_i(t))+\\&f_i(\cdot)+\boldsymbol{D}_i\boldsymbol{\omega}_i(t)+\sum_{j=1,j\neq i}^{N}\boldsymbol{H}_{ij}\boldsymbol{x}_j(t).\end{aligned} \tag{5}$$

定义 2 考虑带有控制器(4)的系统(1),且满足下列条件:当 $\boldsymbol{\omega}(t)=0$, 带有控制器(4)的闭环系统(1)是渐进稳定的;在初始条件下 $\boldsymbol{\omega}(t)$和 $z(t)$有界:

$$\int_0^{\infty}\|z(t)\|^2\mathrm{d}t<\gamma^2\int_0^{\infty}\|\boldsymbol{\omega}(t)\|^2\mathrm{d}t,\ i.e.,\ \|z\|_2^2<\gamma^2\|\boldsymbol{\omega}\|_2^2,\forall\boldsymbol{\omega}\in L_2[0,\infty)\boldsymbol{\omega}\neq 0,$$

其中:$\gamma>0$. 在上面的条件中,系统(1)在控制器(4)作用下是渐进稳定的,控制器(4)称为系统(1)的 H_∞ 混合控制器. 变量 γ 称为 H_∞ 混合控制器的性能指标.

2 主要结果

引理 1[8] (Schur's complement)对给定的对称矩阵 $\boldsymbol{S}=\begin{pmatrix}\boldsymbol{S}_{11}&\boldsymbol{S}_{12}\\\boldsymbol{S}_{12}^{\mathrm{T}}&\boldsymbol{S}_{22}\end{pmatrix}$,其中:$\boldsymbol{S}_{11}\in\mathbf{R}^{r\times r}$, 以下 3 个条件等价:i) $\boldsymbol{S}<0$;ii) $\boldsymbol{S}_{11}<0,\boldsymbol{S}_{22}-\boldsymbol{S}_{12}^{\mathrm{T}}\boldsymbol{S}_{11}^{-1}\boldsymbol{S}_{12}<0$;iii) $\boldsymbol{S}_{22}<0,\boldsymbol{S}_{11}-\boldsymbol{S}_{12}\boldsymbol{S}_{22}^{-1}\boldsymbol{S}_{12}^{\mathrm{T}}<0$.

引理 2[8] 对适当维数的实矩阵 $\boldsymbol{A},\boldsymbol{B},\boldsymbol{X},\boldsymbol{Y},\boldsymbol{Z}$ 和奇异矩阵 $\boldsymbol{S}$,则有:

$$\begin{bmatrix}\boldsymbol{X}+\boldsymbol{B}^{\mathrm{T}}\boldsymbol{S}^{-1}\boldsymbol{B}&\boldsymbol{Z}^{\mathrm{T}}\\\boldsymbol{Z}&\boldsymbol{Y}+\boldsymbol{ASA}^{\mathrm{T}}\end{bmatrix}<0\Rightarrow\begin{bmatrix}\boldsymbol{X}&\boldsymbol{Z}^{\mathrm{T}}+\boldsymbol{B}^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}}\\\boldsymbol{Z}+\boldsymbol{AB}&\boldsymbol{Y}\end{bmatrix}<0. \tag{6}$$

引理 3[9] 若 $\boldsymbol{X},\boldsymbol{Y}$ 为具有适当维数的矩阵,对任意的矩阵 $\boldsymbol{\Gamma}=\boldsymbol{\Gamma}^{\mathrm{T}}>0$,和任意常数 $\gamma>0$,则有:

$$\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}+\boldsymbol{Y}^{\mathrm{T}}\boldsymbol{X}\leqslant\boldsymbol{X}^{\mathrm{T}}\boldsymbol{\Gamma}\boldsymbol{Y}+\boldsymbol{Y}^{\mathrm{T}}\boldsymbol{\Gamma}^{-1}\boldsymbol{X},\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}+\boldsymbol{Y}^{\mathrm{T}}\boldsymbol{X}\leqslant\gamma\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}+\gamma^{-1}\boldsymbol{Y}^{\mathrm{T}}\boldsymbol{X}. \tag{7}$$

引理 4[10] 对任意常数矩阵 $\boldsymbol{Z}=\boldsymbol{Z}^{\mathrm{T}}>0$,有下面积分不等式:

$$\begin{aligned}&-\int_{t-h}^{t}\boldsymbol{x}(s)^{\mathrm{T}}\boldsymbol{Z}\boldsymbol{x}(s)\mathrm{d}s\leqslant-\frac{1}{h}\Big(\int_{t-h}^{t}\boldsymbol{x}(s)\mathrm{d}s\Big)^{\mathrm{T}}\boldsymbol{Z}\Big(\int_{t-h}^{t}\boldsymbol{x}(s)\mathrm{d}s\Big),\\&-\int_{-h}^{0}\int_{t+s}^{t}\boldsymbol{x}(\tau)^{\mathrm{T}}\boldsymbol{Z}\boldsymbol{x}(\tau)\mathrm{d}\tau\mathrm{d}s\leqslant-\frac{2}{h^2}\Big(\int_{-h}^{0}\int_{t+s}^{t}\boldsymbol{x}(\tau)\mathrm{d}\tau\mathrm{d}s\Big)^{\mathrm{T}}\boldsymbol{Z}\Big(\int_{-h}^{0}\int_{t+s}^{t}\boldsymbol{x}(\tau)\mathrm{d}\tau\mathrm{d}s\Big).\end{aligned} \tag{8}$$

定理 1 对于系统(1), 如果对于给定的常数 $a,b,c>0$,存在适当维数的对称正定矩阵 $\boldsymbol{X},\bar{\boldsymbol{Q}},\bar{\boldsymbol{R}}$ 和矩阵 $\boldsymbol{Z}_{i1},\boldsymbol{Z}_{i2},\boldsymbol{Z}_{i3}$,满足$\begin{bmatrix}\boldsymbol{\Xi}_{11}&\boldsymbol{\Xi}_{12}&C_{12}\\ *&\boldsymbol{\Xi}_{22}&0\\ *&*&\boldsymbol{C}_{22}\end{bmatrix}<0$,$\boldsymbol{C}_{12}=\begin{bmatrix}\boldsymbol{A}_{d_i}\boldsymbol{X}+\boldsymbol{B}_i\boldsymbol{Z}_{i3}&\boldsymbol{0}_{1\times 3}\\ *&\boldsymbol{0}_{5\times 3}\end{bmatrix}$, $\boldsymbol{\Xi}_{22}=-\boldsymbol{I}_{6\times 2(N-1)}$,

$$\Xi_1=\begin{bmatrix} T_2 & XE_{i1}^{\mathrm T} & XC_{1i}^{\mathrm T} & D_i^{\mathrm T} & X & M_i^{\mathrm T}\\ * & -u_1^{-1} & 0 & 0 & 0 & 0\\ * & * & -I & 0 & 0 & 0\\ * & * & * & -\frac{\gamma_i}{4}I & 0 & 0\\ * & * & * & * & -\frac{1}{a_i}I & 0\\ * & * & * & * & * & -(u_1^{-1}+u_2^{-1})^{-1}\end{bmatrix},C_{22}=\begin{bmatrix} -(1-\tau)\overline{Q} & XC_{d_i}^{\mathrm T} & XE_{i2}^{\mathrm T} & 0\\ * & -I & 0 & 0\\ * & * & -u_2^{-1} & 0\\ * & * & * & -\overline{R}\end{bmatrix},$$

$$\Xi_{12}=(M_{ij})_{6\times2(N-1)},M_{1j}=\begin{cases}H_{ij},j=1,\cdots,N-1\\ X,j=N,\cdots,2(N-1)\end{cases},M_{ij}=0,i\neq1.$$

$$T_2=A_iX+XA_i^{\mathrm T}+B_iZ_{i1}+Z_{i1}^{\mathrm T}B_i^{\mathrm T}+B_iZ_{i2}+Z_{i2}^{\mathrm T}B_i^{\mathrm T}+\overline{Q}+d^2\overline{R}+\varepsilon_iI. \tag{9}$$

则在控制器(4)的作用下,闭环系统(5)渐进稳定且具有 H_∞ 性能指标 γ.

证明　考虑闭环系统(5)和 Lyapunov-Krasovskii 函数:

$$V(t)=\sum_{i=1}^{4}V_i(t);V_{i1}=x_i^{\mathrm T}(t)P_iE_ix_i(t);V_{i2}=\int_{t-d_i(t)}^{t}x_i^{\mathrm T}(s)Q_ix_i(s)\mathrm ds;$$

$$V_{i3}=\int_{t-d_i(t)}^{t}\Big[\int_s^t x_i^{\mathrm T}(\theta)\mathrm d\theta\Big]R_i\Big[\int_s^t x(\theta)\mathrm d\theta\Big]\mathrm ds;V_{i4}=-\int_{d_i(t)}^{0}\mathrm ds\int_{t-s}^{t}(\theta-t+s)x_i^{\mathrm T}(\theta)R_ix(\theta)\mathrm d\theta. \tag{10}$$

对式(10)沿闭环系统(5)求导并由引理3和条件(3)得:

$$\begin{aligned}\dot V_i(\cdot)\leqslant\ & x_i^{\mathrm T}(t)[P_i(A_i+\Delta A_i+B_iK_i+B_iL_iC_{2i})+(A_i+\Delta A_i+B_iK_i+B_iL_iC_{2i})^{\mathrm T}P_i+\\ & Q_i+\overline{d}^2R_i+\sum_{j=1,j\neq i}^{N}P_iH_{ij}H_{ij}^{\mathrm T}P_i+\frac{4}{\gamma_i}P_iD_iD_i^{\mathrm T}P_i+\sum_{j=1,j\neq i}^{N}I+\varepsilon_iP_i^2+a_iI]x_i(t)+\\ & 2x_i^{\mathrm T}(t)P_i(A_{d_i}+\Delta A_{d_i}+B_iK_{d_i})x_i(t-d_i(t))-(1-\tau)x_i^{\mathrm T}(t-d_i(t))Q_ix_i(t-d_i(t))+\\ & b_i\,\|x_i(t-d_i(t))\|^2+\gamma_i\omega_i^{\mathrm T}(t)\omega_i(t)-\Big[\int_{t-d_i(t)}^{t}x_i^{\mathrm T}(\theta)\mathrm d\theta\Big]R_i\Big[\int_{t-d_i(t)}^{t}x_i(\theta)\mathrm d\theta\Big].\end{aligned}$$

进而可以得到 $\dot V(\cdot)\leqslant\sum_{i=1}^{N}\gamma_i\,\|\omega_i(t)\|^2+\sum_{i=1}^{N}\alpha_i^{\mathrm T}(t)\Lambda\alpha_i(t)-\sum_{i=1}^{N}[\,\|C_{1i}x_i(t)\|^2+\|C_{d_i}x_i(t-d_i(t))\|^2].$

其中:$\alpha_i^{\mathrm T}(t)=[x_i^{\mathrm T}(t),x_i^{\mathrm T}(t-d_i(t)),\int_{t-d_i(t)}^{t}x_i^{\mathrm T}(\theta)\mathrm d\theta]$,

$$\Lambda=\begin{bmatrix}\Gamma_1 & P_i(A_{d_i}+B_iK_{d_i}+\Delta A_{d_i}) & 0\\ * & -(1-\tau)Q_i+C_{d_i}C_{d_i}^{\mathrm T} & 0\\ * & * & -R_i\end{bmatrix},i=1,2,\cdots,N,\ \Xi_1=\Gamma_1-P_i\Delta A_i+\Delta A_i^{\mathrm T}P,$$

$$\begin{aligned}\Gamma_1=\ & P_i(A_i+\Delta A_i+B_iK_i+B_iL_iC_{2i})+(A_i+\Delta A_i+B_iK_i+B_iL_iC_{2i})^{\mathrm T}P_i+Q_i+\overline{d}^2R_i+\\ & \sum_{j=1,j\neq i}^{N}P_iH_{ij}H_{ij}^{\mathrm T}P_i+\frac{4}{\gamma_i}P_iD_iD_i^{\mathrm T}P_i+C_{1i}C_{1i}^{\mathrm T}\sum_{j=1,j\neq i}^{N}I+\varepsilon_iP_i^2+a_iI.\end{aligned}$$

又由条件(2)和引理2可得:

$$\Lambda\leqslant\begin{bmatrix}\Xi_1+(\mu_1^{-1}+\mu_2^{-1})P_iM_iM_i^{\mathrm T}P_i+\mu_1E_{i1}^{\mathrm T}E_{i1} & P_i(A_{d_i}+B_iK_{d_i}) & 0\\ * & -(1-\tau)Q_i+C_{d_i}C_{d_i}^{\mathrm T}+\mu_2E_{i2}^{\mathrm T}E_{i2} & 0\\ * & * & -R_i\end{bmatrix}. \tag{11}$$

令 $X_i=P_i^{-1},X_iQ_iX_i=\overline{Q}_i,X_iR_iX_i=\overline{R}_i,K_iX_i=Z_{i1},K_{d_i}X_i=Z_{i3},L_iX_i=Z_{i2}$,则式(11)小于0,等价于下面不等式:

$$\begin{bmatrix}T_1 & (A_{d_i}+B_iK_{d_i})X_i & 0\\ * & -(1-\tau)\overline{Q}_i+X_iC_{d_i}C_{d_i}^{\mathrm T}X_i+\mu_2X_iE_{i2}^{\mathrm T}E_{i2}X_i & 0\\ * & * & -\overline{R}_i\end{bmatrix}<0, \tag{12}$$

$$\boldsymbol{T}_1 = (\boldsymbol{A}_i + \boldsymbol{B}_i\boldsymbol{K}_i + \boldsymbol{B}_i\boldsymbol{L}_i\boldsymbol{C}_{2i})\boldsymbol{X}_i + \boldsymbol{X}_i(\boldsymbol{A}_i + \boldsymbol{B}_i\boldsymbol{K}_i + \boldsymbol{B}_i\boldsymbol{L}_i\boldsymbol{C}_{2i})^{\mathrm{T}} + \bar{\boldsymbol{Q}}_i + \bar{d}^2\bar{\boldsymbol{R}}_i + \sum_{j=1,j\neq i}^{N}\boldsymbol{H}_{ij}\boldsymbol{H}_{ij}^{\mathrm{T}} + \frac{4}{\gamma_i}\boldsymbol{D}_i\boldsymbol{D}_i^{\mathrm{T}} + \sum_{j=1,j\neq i}^{N}\boldsymbol{X}_i^2 + \varepsilon_i\boldsymbol{I} + a_i\boldsymbol{X}_i^2 + \boldsymbol{X}_i\boldsymbol{C}_{1i}\boldsymbol{C}_{1i}^{\mathrm{T}}\boldsymbol{X}_i + (\mu_1^{-1} + \mu_2^{-1})\boldsymbol{M}_i\boldsymbol{M}_i^{\mathrm{T}} + \mu_1\boldsymbol{X}_i\boldsymbol{E}_{i1}^{\mathrm{T}}\boldsymbol{E}_{i1}\boldsymbol{X}_i,$$

由 Schur 式(12)等价于式(9),所以

$$\dot{\boldsymbol{V}}(\cdot) \leqslant \sum_{i=1}^{N}\gamma_i \|\boldsymbol{\omega}_i(t)\|^2 - \sum_{i=1}^{N}[\|\boldsymbol{C}_{1i}\boldsymbol{x}_i(t)\|^2 + \|\boldsymbol{C}_{d_i}\boldsymbol{x}_i(t-d_i(t))\|^2]. \tag{13}$$

令 $\boldsymbol{\omega}_i(t)=0$,因为 $-\sum_{i=1}^{N}[\|\boldsymbol{C}_{1i}\boldsymbol{x}_i(t)\|^2 + \|\boldsymbol{C}_{d_i}\boldsymbol{x}_i(t-d_i(t))\|^2] \leqslant 0$. 由式(13)可得:$\dot{\boldsymbol{V}}(\cdot)\leqslant 0, \forall t\geqslant 0$,所以系统(1)在控制器(4)下是渐进稳定的,并且 $\boldsymbol{K}_i, \boldsymbol{K}_{d_i}, \boldsymbol{L}_i$ 在渐进稳定控制器中的设计为,$\boldsymbol{K}_i = \boldsymbol{Z}_{i1}\boldsymbol{X}_i^+, \boldsymbol{K}_{d_i} = \boldsymbol{Z}_{i3}\boldsymbol{X}_i^+, \boldsymbol{L}_i = \boldsymbol{Z}_{i2}\boldsymbol{X}_i^+\boldsymbol{C}_{2i}^+$. 因为

$$\int_0^s\sum_{i=1}^{N}[\|\boldsymbol{z}_i(t)\|^2 - \gamma_i\|\boldsymbol{\omega}_i(t)\|^2]\mathrm{d}t = \int_0^s\sum_{i=1}^{N}[\|\boldsymbol{z}_i(t)\|^2 - \gamma_i\|\boldsymbol{\omega}_i(t)\|^2 + \dot{\boldsymbol{V}}(t,\boldsymbol{x}_t)]\mathrm{d}t - \int_0^s\dot{\boldsymbol{V}}(t,\boldsymbol{x}_t)\mathrm{d}t,$$

$\forall s \geqslant 0$,且 $\boldsymbol{V}(t,\boldsymbol{x}_t) \geqslant 0, \forall t \geqslant 0$. 所以有 $\int_0^s\dot{\boldsymbol{V}}(t,\boldsymbol{x}_t)\mathrm{d}t = \boldsymbol{V}(0,x_0) - \boldsymbol{V}(s,\boldsymbol{x}_s) \leqslant \boldsymbol{V}(0,x_0)$.

因此,$\forall s \geqslant 0$,有

$$\int_0^s\sum_{i=1}^{N}[\|\boldsymbol{z}_i(t)\|^2 - \gamma_i\|\boldsymbol{\omega}_i(t)\|^2]\mathrm{d}t = \int_0^s\sum_{i=1}^{N}[\|\boldsymbol{z}_i(t)\|^2 - \gamma_i\|\boldsymbol{\omega}_i(t)\|^2 + \dot{\boldsymbol{V}}(t,\boldsymbol{x}_t)]\mathrm{d}t + \boldsymbol{V}(0,x_0).$$

所以联合式(13)可以得 $\int_0^s\sum_{i=1}^{N}[\|\boldsymbol{z}_i(t)\|^2 - \gamma_i\|\boldsymbol{\omega}_i(t)\|^2]\mathrm{d}t \leqslant \int_0^s 0\mathrm{d}t + \boldsymbol{V}(0,x_0) = \boldsymbol{V}(0,x_0), \forall s \geqslant 0$,又由零初始条件可得 $\forall s \geqslant 0, \int_0^s\sum_{i=1}^{N}\|\boldsymbol{z}_i(t)\|^2\mathrm{d}t \leqslant \gamma\int_0^s\sum_{i=1}^{N}\|\boldsymbol{\omega}_i(t)\|^2\mathrm{d}t$,令 $s\to+\infty$,有 $\int_0^{\infty}\sum_{i=1}^{N}\|\boldsymbol{z}_i(t)\|^2\mathrm{d}t \leqslant \gamma\int_0^{\infty}\sum_{i=1}^{N}\|\boldsymbol{\omega}_i(t)\|^2\mathrm{d}t$.

证毕.

3 总结

本文利用 Lyapunov 和线性矩阵不等式方法,针对具有不确定性和非线性扰动的时滞广义大系统,考虑到不确定性和非线性扰动对此系统稳定性的影响,研究了使该系统稳定及 H_∞ 混合反馈控制器的设计方法,在保证闭环系统满足一定的性能指标条件下,使闭环系统渐进稳定,抑制干扰的影响.

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Physical Properties of Phosphorene Surface Adsorption with Nonmetal Atoms

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Abstract: Basic physical properties of phosphorene surface adsorption with nonmetal atoms(C,N,O), including the most favorable adsorption sites, geometric structure and electron shift have been studied. Data were systematically analyzed. Then, after adatoms adsorbed on the surface of phosphorene, the change of band structure and the variation of electronic density of states with energy were also explored. Through systematic analysis of the phosphorene system, it can be found that adatom adsorption changed the properties of phosphorene because of the interactions between different adatoms and electron shift. It could be useful for future study of phosphorene.

Key words: phosphorene; density functional theory; adsorption sites; band structure; electronic density of state

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Robust Stabilization and H_∞ Hybrid Control for Nonlinear Time-delay Singular Large-scale Systems

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Abstract: The research of stabilization and H_∞ control for the nonlinear large-scale time-delay systems with nonlinear perturbation was studied. Based on the bounded real lemma, LMI method and a novel Lyapunov-Krasovskii functional, a new delay-dependent sufficient condition for the existence of stabilization and hybrid controller had been given. The controller could be obtained by solving the corresponding linear matrix inequality. This controller designed could make the closed-loop systems asymptotically stable, as well as satisfying H_∞ properties to achieve disturbance attenuation.

Key words: decentralized H_∞ hybrid control; singular large-scale system; time-delay; nonlinear perturbation

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