短文

不确定性时滞大系统的分散鲁棒H_∞控制[1)]

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摘 要 研究一类具有状态时滞的内联不确定性动态大系统的分散鲁棒H_∞控制问题. 系统的不确定性参数满足范数有界条件. 得到了由无记忆状态反馈分散控制器使每一个子系统和整个大系统都可镇定且满足给定H_∞性能的充分条件. 所得结果与系统时滞的大小有关，并以线性矩阵不等式的形式给出.

关键词 分散控制，鲁棒控制，H_∞控制，不确定性动态系统，时滞.

DECENTRALIZED ROBUST H_∞ CONTROL OF UNCERTAIN DELAY LARGE-SCALE SYSTEMS

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Abstract This paper deals with the problem of decentralized robust H_∞ control for a class of interconnected uncertain dynamic systems with state delays. The parameter uncertainties are unknown but norm-bounded. A sufficient condition is obtained for each subsystem and overall system to be stabilizable and satisfy the given H_∞ performance via linear memoryless state feedback decentralized controllers. The results depend on the size of the delays and are given in terms of linear matrix inequalities.

Key words Decentralized control, robust control, H_∞ control, uncertain dynamic system, time delay.

1 引言

大系统普遍存在，如动力系统、通讯系统、社会系统、经济系统等等. 因此，大系统的鲁

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棒控制问题越来越引起人们的关注[1,2].

由于各种各样的原因,绝大部分实际的系统模型含有不确定性,使得控制系统达不到满意的性能,甚至不能保证控制系统的稳定性.这就促使更多的人致力于鲁棒控制的研究[3,4].

工程系统中经常会遇到时滞现象,人们对时滞系统的研究越来越热[5,6].

上述文献均采用了黎卡提方程方法,得到的结果常包含一些需要调整的参数,这给实际应用带来不便.而且对于时滞大系统,所得结果与系统时滞无关,比较保守.而线性矩阵不等式(LMI)方法可避免参数调整的困难,且较容易得到依赖于时滞的结论[7,8].

本文研究具有状态时滞的不确定性大系统的分散鲁棒 H_∞ 控制问题.系统的不确定性参数只需满足范数有界条件,而不需要更强的限制——满足匹配条件[4].为了避免调整参数的困难,我们采用 LMI 方法,并得到了依赖于系统时滞的保守性低的结论.

2 系统描述和预备知识

考虑由 N 个相互关联的子系统 $\Sigma_i(i=1,\cdots,N)$ 构成的大系统

$$\Sigma_i:\quad \dot{\boldsymbol{x}}_i(t)=[A_i+\Delta A_i(\boldsymbol{r}_i(t))]\boldsymbol{x}_i(t)+[A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(t))]\boldsymbol{x}_i(t-d_i)+ [B_i+\Delta B_i(\boldsymbol{s}_i(t))]\boldsymbol{u}_i(t)+[H_i+\Delta H_i(\boldsymbol{h}_i(t))]\sum_{j=1}^{N}H_{ij}\boldsymbol{x}_j(t)+B_{wj}\boldsymbol{w}_i(t), \tag{1a}$$

$$z_i(t)=C_i\boldsymbol{x}_i(t)+D_i\boldsymbol{u}_i(t), \tag{1b}$$

$$\boldsymbol{x}_i(t)=\psi_i(t),\qquad t\in[-\bar{d}_i,0], \tag{1c}$$

其中 $\boldsymbol{x}_i(t)\in\mathscr{R}^{n_i}$,$\boldsymbol{u}_i(t)\in\mathscr{R}^{m_i}$分别表示状态向量和控制向量,$\boldsymbol{w}_i\in\mathscr{R}^{p_{w_i}}$是平方可积的干扰输入,$\boldsymbol{z}_i\in\mathscr{R}^{l_i}$是控制输出.系统不确定性满足以下条件:

$$\boldsymbol{r}_i(t)\in\boldsymbol{\Phi}_i\subseteq\mathscr{R}^{p_i},\boldsymbol{r}_{di}(t)\in\boldsymbol{\Phi}_{di}\subseteq\mathscr{R}^{p_{di}},\boldsymbol{s}_i(t)\in\boldsymbol{\Psi}_i\subseteq\mathscr{R}^{q_i},\boldsymbol{h}_i(t)\in\boldsymbol{\Psi}_{hi}\subseteq\mathscr{R}^{q_{hi}},$$

其中 $\boldsymbol{\Phi}_i,\boldsymbol{\Phi}_{di},\boldsymbol{\Psi}_i,\boldsymbol{\Psi}_{hi}$均为紧集,$H_{ij}$是内联矩阵且 $H_{ii}=0$.设 $h_{ij}=\|H_{ij}\|$,其中范数$\|\cdot\|$定义为矩阵或向量的最大奇异值.系统时滞 d_i 满足$0\leqslant d_i\leqslant\bar{d}_i\leqslant\tau$,$\tau$ 为常数.

进一步假设系统不确定性表示为

$$\Delta A_i(\boldsymbol{r}_i(t))=\sum_{j=1}^{p_i}A_{ij}\boldsymbol{r}_{ij}(t),\qquad |\boldsymbol{r}_{ij}(t)|\leqslant\bar{\boldsymbol{r}}_{ij},\qquad j=1,\cdots,p_i,$$

$$\Delta A_{di}(\boldsymbol{r}_{di}(t))=\sum_{j=1}^{p_{di}}A_{dij}\boldsymbol{r}_{dij}(t),\qquad |\boldsymbol{r}_{dij}(t)|\leqslant\bar{\boldsymbol{r}}_{dij},\qquad j=1,\cdots,p_{di},$$

$$\Delta B_i(\boldsymbol{s}_i(t))=\sum_{j=1}^{q_i}B_{ij}\boldsymbol{s}_{ij}(t),\qquad |\boldsymbol{s}_{ij}(t)|\leqslant\bar{\boldsymbol{s}}_{ij},\qquad j=1,\cdots,q_i,$$

$$\Delta H_i(\boldsymbol{h}_i(t))=\sum_{j=1}^{q_{hi}}\hat{H}_{ij}\boldsymbol{h}_{ij}(t),\qquad |\boldsymbol{h}_{ij}(t)|\leqslant\bar{\boldsymbol{h}}_{ij},\qquad j=1,\cdots,q_{hi},$$

其中不确定性元素 $\boldsymbol{r}_i(t)$,$\boldsymbol{r}_{di}(t)$,$\boldsymbol{s}_i(t)$和 $\boldsymbol{h}_i(t)(i=1,\cdots,N)$是 Lebesgue 可测得.利用文[4]中的技巧易得系统不确定性的界

$$\Delta A_i(\boldsymbol{r}_i(t))(\Delta A_i(\boldsymbol{r}_i(t)))^{\mathrm T} \leqslant \overline{A}_i^2,\quad \Delta A_{di}(\boldsymbol{r}_{di}(t))(\Delta A_{di}(\boldsymbol{r}_{di}(t)))^{\mathrm T} \leqslant \overline{A}_{di}^2, \tag{2a}$$

$$\Delta B_i(\boldsymbol{s}_i(t))(\Delta B_i(\boldsymbol{s}_i(t)))^{\mathrm T} \leqslant \overline{B}_1^2,\quad \Delta H_i(\boldsymbol{h}_i(t))(\Delta H_i(\boldsymbol{h}_i(t)))^{\mathrm T} \leqslant \overline{H}_i^2, i = 1,\cdots,N, \tag{2b}$$

其中 $\overline{A}_i,\overline{A}_{di},\overline{B}_i$ 和 $\overline{H}_i$ 是常值半正定对称矩阵.

假设

$$(H_i + \Delta H_i(\boldsymbol{h}_i(t)))(H_i + \Delta H_i(\boldsymbol{h}_i(t)))^{\mathrm T} \leqslant \overline{h}_i^2 I,\quad H_{ij}H_{ij}^{\mathrm T} \leqslant h_{ij}^2 I,$$

$$i = 1,\cdots,N,\quad j = 1,\cdots,k_h,\quad j \neq i, \tag{3}$$

其中 $\overline{h}_i$ 和 h_{ij}是已知常数.

注1. 由于式(2)和式

$$\Delta A_i(t) = \overline{A}_iF_i(t),\quad \Delta A_{di}(t) = \overline{A}_{di}F_{di}(t),\quad \Delta B_i(t) = \overline{B}_iF_{bi}(t),\quad \Delta H_i(t) = \overline{H}_iF_{hi}(t), \tag{4a}$$

$$\|F_i(t)\| \leqslant 1, \|F_{di}(t)\| \leqslant 1, \|F_{bi}(t)\| \leqslant 1, \|F_{hi}(t)\| \leqslant 1 \tag{4b}$$

描述的不确定性具有相同的范数界,因此在推导公式时可根据需要选择适当的描述方式.

分散鲁棒 H_∞控制 已知常数 $\rho,\rho_1,\rho_2,\cdots,\rho_N>0$,其中 $\rho=\sum_{i=1}^{N}\rho_i$,设计分散线性状态反馈控制 $\boldsymbol{u}_i=K_i\boldsymbol{x}_i(t)(i=1,\cdots,N)$使得对应的闭环大系统和每一个闭环子系统都是鲁棒稳定的,且分别具有给定的 H_∞范数界 ρ 和 ρ_i.

命题1. 对任何具有适当维数的矩阵或向量 X,Z 和 Y 和任意正常数 $\alpha,\beta>0$总成立不等式

$$X^{\mathrm T}Y + Y^{\mathrm T}X \leqslant \alpha X^{\mathrm T}X + \frac{1}{\alpha}Y^{\mathrm T}Y, 2Z^{\mathrm T}Y \leqslant \beta Z^{\mathrm T}Z + \frac{1}{\beta}Y^{\mathrm T}Y.$$

命题2. 已知 A 和 ΔA 是 $n\times n$ 实矩阵且不等式 $\Delta A(t)(\Delta A(t))^{\mathrm T}\leqslant\overline{A}^2$成立,其中 $\overline{A}$ 是半正定对称矩阵,则对任何满足$1>\varepsilon>0$的 ε 成立

$$(A + \Delta A)(A + \Delta A)^{\mathrm T} \leqslant \frac{1}{1-\varepsilon}AA^{\mathrm T} + \frac{1}{\varepsilon}\overline{A}^2.$$

命题3. 已知 A 和 ΔA 是 $n\times n$ 实矩阵且不等式 $\Delta A(t)(\Delta A(t))^{\mathrm T}\leqslant\overline{A}^2$成立,其中 $\overline{A}$ 是半正定对称矩阵,则对任何满足 $I-\varepsilon\overline{A}^2>0$的正常数 ε 成立

$$(A + \Delta A)^{\mathrm T}(A + \Delta A) \leqslant A^{\mathrm T}(I - \varepsilon\overline{A}^2)^{-1}A + \frac{1}{\varepsilon}\sigma I.$$

其中 $\sigma=\begin{cases}0, & \text{当 } \Delta A\equiv 0,\\ 1, & \text{其它},\end{cases}$ 本文中总假设 $\sigma=1$成立.

证明. 命题1是人们熟知的不等式,证明从略. 以下将证明命题2和3. 因为

$$(A + \Delta A)(A + \Delta A)^{\mathrm T} = AA^{\mathrm T} + A\Delta A^{\mathrm T} + \Delta AA^{\mathrm T} + \Delta A\Delta A^{\mathrm T} \leqslant$$

$$AA^{\mathrm T} + \alpha AA^{\mathrm T} + \frac{1}{\alpha}\Delta A\Delta A^{\mathrm T} + \Delta A\Delta A^{\mathrm T} \leqslant (1 + \alpha)AA^{\mathrm T} + (1 + \frac{1}{\alpha})\overline{A}^2.$$

令 $\varepsilon=\frac{\alpha}{1+\alpha}$,则有$1+\alpha=\frac{1}{1-\varepsilon}$,$1+\frac{1}{\alpha}=\frac{1}{\varepsilon}$,因此命题2成立.

注意到 $\Delta A(t)(\Delta A(t))^{\mathrm T}\leqslant\overline{A}^2$知存在满足条件$\|F(t)\|\leqslant1$的矩阵 $F(t)$使得 $\Delta A(t)=\overline{A}F(t)$. 令

$$G(t) = (\frac{1}{\varepsilon}I - \overline{A}^2)^{-1/2}\overline{A}A - (\frac{1}{\varepsilon}I - \overline{A}^2)^{1/2}F(t).$$

展开 $G^{\mathrm{T}}(t)G(t)\geqslant 0$再利用矩阵逆引理可知命题3成立. 证毕.

3 主要结果

由公式$\int_a^b \dot f(t)\mathrm{d}t = f(b)-f(a)$ 可得闭环子系统为

$$\dot{\boldsymbol{x}}_i(t)=[A_i+\Delta A_i(\boldsymbol{r}_i(t))+A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(t))]\boldsymbol{x}_i(t)-\int_{-d_i}^{0}[A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(t)))]\{[A_i+\Delta A_i(\boldsymbol{r}_i(t+\theta))]\boldsymbol{x}_j(t+\theta)+[A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(t+\theta))]\boldsymbol{x}_i(t-d_i+\theta)+[B_i+\Delta B_i(\boldsymbol{s}_i(t+\theta))]\boldsymbol{u}_i(t+\theta)+[H_i+\Delta H_i(\boldsymbol{h}_i(t+\theta))]\sum_{j=1}^{s}H_{ij}\boldsymbol{x}_j(t+\theta)+B_{wi}\boldsymbol{w}_i(t+\theta)\}\mathrm{d}\theta+B_{wi}\boldsymbol{w}_i(t)+[B_i+\Delta B_i(\boldsymbol{s}_i(t))]\boldsymbol{u}_i(t)+(H_i+\Delta H_i(\boldsymbol{h}_i(t)))\sum_{j=1}^{s}H_{ij}\boldsymbol{x}_j(t)]. \tag{5}$$

选择李雅普诺夫函数为 $V(\boldsymbol{x},t)=V_1(\boldsymbol{x},t)+V_2(\boldsymbol{x},t)$,其中

$$V_1(\boldsymbol{x},t)=\sum_{i=1}^{N}\boldsymbol{x}_i^{\mathrm{T}}(t)P_i\boldsymbol{x}_i(t),$$

$$V_2(\boldsymbol{x},t)=\sum_{i=1}^{N}\int_{-d_i}^{0}\int_{t+\theta}^{t}\boldsymbol{x}_i^{\mathrm{T}}(\pi)(A_i+\Delta A_i(\boldsymbol{r}_i(\pi)))^{\mathrm{T}}(A_i+\Delta A_i(\boldsymbol{r}_i(\pi)))\boldsymbol{x}_i(\pi)\mathrm{d}\pi\mathrm{d}\theta+\sum_{i=1}^{N}\int_{-d_i}^{0}\int_{t-d_i+\theta}^{t}\boldsymbol{x}_i^{\mathrm{T}}(\pi)(A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(\pi+d_i)))^{\mathrm{T}}(A_{di}+\Delta A_{di}(\boldsymbol{r}_{di}(\pi+d_i)))\boldsymbol{x}_i(\pi)\mathrm{d}\pi\mathrm{d}\theta+\sum_{i=1}^{N}\int_{-d_i}^{0}\int_{t+\theta}^{t}\boldsymbol{x}_i^{\mathrm{T}}(\pi)K_i^{\mathrm{T}}(B_i+\Delta B_i(\boldsymbol{s}_i(\pi)))^{\mathrm{T}}(B_i+\Delta B_i(\boldsymbol{s}_i(\pi)))K_i\boldsymbol{x}_i(\pi)\mathrm{d}\pi\mathrm{d}\theta+\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\int_{-d_i}^{0}\int_{t+\theta}^{t}\boldsymbol{x}_j^{\mathrm{T}}(\pi)\boldsymbol{x}_j(\pi)\mathrm{d}\pi\mathrm{d}\theta+\sum_{i=1}^{N}\int_{-d_i}^{0}\int_{t+\theta}^{t}\boldsymbol{w}_i^{\mathrm{T}}(\pi)B_{wi}^{\mathrm{T}}B_{wi}\boldsymbol{w}_i(\pi)\mathrm{d}\pi\mathrm{d}\theta,$$

P_i 是正定对称矩阵. 为简单起见,下文中与时滞无关的变量的时间变量将不再标明,例如 $\Delta A_i(\boldsymbol{r}_i(t))$简记为 ΔA_i. 利用命题1～3可得

$$\dot V(\boldsymbol{x},t)\leqslant\sum_{i=1}^{N}\{\boldsymbol{x}_i^{\mathrm{T}}[(A_i+A_{di})^{\mathrm{T}}P_i+P_i(A_i+A_{di})+\alpha_iP_i\overline{A}_i^2P_i+\frac{1}{\alpha_i}I_i+\alpha_{di}P_i\overline{A}_{di}^2P_i+\frac{1}{\alpha_{di}}I_i+K_i^{\mathrm{T}}B_i^{\mathrm{T}}P_i+P_iB_iK_i+\beta_iP_i\overline{B}_i^2P_i+\frac{1}{\beta_i}K_i^{\mathrm{T}}K_i+\sum_{j=1}^{N}\overline{h}_i^2h_{ij}^2P_iP_i+(N-1)I_i+4\overline{d}_iP_i(\frac{1}{1-\gamma_i}A_{di}A_{di}^{\mathrm{T}}+\frac{1}{\gamma_i}\overline{A}_{di}^2)P_i+\sum_{j=1}^{N}\overline{d}_i\overline{h}_i^2h_{ij}^2P_i(\frac{1}{1-\gamma_i}A_{di}A_{di}^{\mathrm{T}}+\frac{1}{\gamma_i}\overline{A}_{di}^2)P_i+\overline{d}_iA_i^{\mathrm{T}}(I_i-\eta_i\overline{A}_i^2)^{-1}A_i+\frac{\overline{d}_i}{\eta_i}I_i+\overline{d}_iA_{di}^{\mathrm{T}}(I_i-\mu_i\overline{A}_{di}^2)^{-1}A_{di}+\frac{\overline{d}_i}{\mu_i}I_i+\overline{d}_iK_i^{\mathrm{T}}B_i^{\mathrm{T}}(I_i-v_i\overline{B}_i^2)^{-1}B_iK_i+\frac{\overline{d}_i}{v_i}K_i^{\mathrm{T}}K_i+\dot d_iI_i]\boldsymbol{x}_i+2\boldsymbol{x}_i^{\mathrm{T}}P_iB_{wi}\boldsymbol{w}_i(t)+\overline{d}_i\boldsymbol{w}_i^{\mathrm{T}}(t)B_{wi}^{\mathrm{T}}B_{wi}\boldsymbol{w}_i(t)\}, \tag{6}$$

其中

$$I_i - \eta_i \overline{A}_i^2 > 0,\quad I_i - \mu_i \overline{A}_{di}^2 > 0,\quad I_i - v_i \overline{B}_i^2 > 0. \tag{7}$$

因此当 $w_i(t)=0$时，如果下面定理中 LMI(8)成立，则系统(1)是渐近稳定的.

为证明$\|z\|_2<\rho\|w\|_2$成立，其中 $z=(z_1^T, z_2^T, \cdots, z_N^T)^T, w=(w_1^T, w_2^T, \cdots, w_N^T)^T, \rho=\sum_{i=1}^N \rho_i$，假设系统满足零初始条件，并令 $J=\sum_{i=1}^N \int_0^\infty (z_i^T z_i - \rho_i^2 w_i^T w_i)dt$.

从以上讨论可得

$$J = \int_0^\infty \left(\sum_{i=1}^N (z_i^T z_i - \rho_i^2 w_i^T w_i) + \frac{d}{dt}V(x,t) \right) dt - V(\infty) \leqslant$$

$$\sum_{i=1}^N \int_0^\infty \begin{bmatrix} x_i(t) \\ w_i(t) \end{bmatrix}^T \begin{bmatrix} S_i & P_i B_{wi} \\ B_{wi}^T P_i & -(\rho_i^2 I - \overline{\tau} B_{wi}^T B_{wi}) \end{bmatrix} \begin{bmatrix} x_i(t) \\ w_i(t) \end{bmatrix} dt - V(\infty).$$

至此不难得到如下的主要结果.

定理. 给定不确定性时滞大系统(1). 已知常数 $\overline{d}_i, \rho, \rho_i (i=1,2,\cdots,N)$和 τ 满足$0\leqslant d_i \leqslant \overline{d}_i \leqslant \tau$，则系统(1)分散鲁棒镇定且具有给定 H_∞范数界 ρ, ρ_i 的充分条件是对称正定矩阵 X_i、矩阵 Y_i 和常数 $\alpha_i, \beta_i, 0<\gamma_i<1, \eta_i, \mu_i, v_i$ 满足 $\rho_i^2 I - \overline{d}_i B_{wi}^T B_{wi} > 0$和 LMIs

$$\begin{bmatrix} S_i & H_i^T & \overline{d}_i Y_i^T B_i^T & B_{wi} & (CX+DY)^T \\ H_i & -G_i & & & \\ \overline{d}_i B_i Y_i & & -\overline{d}_i (I_i - v_i \overline{B}_i^2) & & \\ B_{wi}^T & & & -(\rho_i^2 I - \overline{d}_i B_{wi}^T B_{wi}) & \\ CX+DY & & & & -I \end{bmatrix} < 0, \tag{8a}$$

$$I_i - \eta_i \overline{A}_i^2 > 0, I_i - \mu_i \overline{A}_{di}^2 > 0, I_i - v_i \overline{B}_i^2 > 0, \tag{8b}$$

且相应的分散鲁棒 H_∞控制器为

$$u_i(t) = Y_i X_i^{-1} x_i(t),\quad i=1,\cdots,N.$$

上式中

$$S_i = X_i(A_i + A_{di})^T + (A_i + A_{di})X_i + Y_i^T B_i^T + B_i Y_i + \alpha_i \overline{A}_i^2 + \alpha_{di} \overline{A}_{di}^2 + \beta_i \overline{B}_i^2 + \sum_{j=1}^N \overline{h}_i^2 h_{ij}^2 I_i,$$

$$H_{1i}^T = [\widetilde{d}_i A_{di} \quad \widetilde{d}_i \overline{A}_{di}],\qquad G_{1i} = \mathrm{diag}[\widetilde{d}_i (1-\gamma_i) I_i, \quad \widetilde{d}_i \gamma_i I_i],$$

$$H_{2i}^T = [\overline{d}_i X_i A_i^T \quad \overline{d}_i X_i A_{di}^T],\qquad G_{2i} = \mathrm{diag}[\overline{d}_i (I_i - \eta_i \overline{A}_i^2) \quad \overline{d}_i (I_i - \mu_i \overline{A}_{di}^2)],$$

$$H_{3i}^T = [Y_i^T \quad \overline{d}_i Y_i^T],\qquad G_{3i} = \mathrm{diag}[\beta_i I_{m_i \times m_i}, \quad \overline{d}_i v_i I_{m_i \times m_i}],$$

$$H_{4i}^T = [X_i \quad X_i \quad \overline{d}_i X_i \quad \overline{d}_i X_i (N-1) X_i \quad \hat{d}_i X_i],$$

$$G_{4i} = \mathrm{diag}[\alpha_i I_i \quad , \alpha_{di} I_i, \quad \overline{d}_i \eta_i I_i, \quad \overline{d}_i \mu_i I_i, \quad (N-1) I_i, \quad \hat{d}_i I_i],$$

$$H_i^T = [H_{1i}^T, \quad H_{2i}^T, \quad H_{3i}^T, \quad H_{4i}^T],\quad G_i^T = \mathrm{diag}(G_{1i}, \quad G_{2i}, \quad G_{3i}, \quad G_{4i}),$$

$$\widetilde{d}_i = 4\overline{d}_i + \sum_{j=1}^N \overline{d}_i \overline{h}_i^2 h_{ij}^2,\quad \hat{d}_i = \sum_{j=1, j\neq i}^N \overline{d}_j.$$

证明. 令 $X_i = P_i^{-1}, Y_i = K_i X_i$，易导出 LMI(8). 此外，由$\|z_i\|_2<\rho_i\|w_i\|_2$可得

$$\|z\|_2 \leqslant \sum_{i=1}^N \|z_i\|_2 < \sum_{i=1}^N \rho_i \|w_i\|_2 \leqslant \sum_{i=1}^N \rho_i \|w\|_2 = \rho \|w\|_2.$$

证毕.

注2. 如果系统(1)不包含时滞项且 $B_i + \Delta B_i(s_i(t)) = H_i + \Delta H_i(h_i(t)), w_i(t) \equiv 0$成立，

则本文考虑的系统就是文[2]中的系统(1).

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