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同时具有状态与控制时变时滞系统的 H_∞ 输出反馈控制*

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摘要: 针对同时具有状态与控制时变时滞的线性系统,基于代数 Riccati 方程方法,给出了一个 H_∞ 输出反馈控制器设计方案.该方案既能使闭环系统稳定,又能保证系统具有一定的 H_∞ 性能.

关键词: H_∞ 输出反馈控制; 代数 Riccati 方程; 时变时滞
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H_∞ Control via Output Feedback for Linear Systems with Time-Varying Delayed State and Control

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Abstract: Based on algebraic Riccati equation, this paper provides a design scheme of H_∞ output feedback controller aimed at linear systems with time-varying delayed state and control, which can stabilize the systems and guarantee a prescribed H_∞ performance.

Key words: H_∞ control via output feedback; algebraic Riccati equation; time-varying delays

1 引言(Introduction)

在实际工程系统中,由于信号的传递和观测需要时间以及被控对象的元件老化等原因,时滞现象普遍存在.近年来已提出许多有用的技术以分析时滞系统的性能和稳定性,其中 H_∞ 控制技术倍受关注[1-16].

时滞系统的 H_∞ 状态反馈控制研究已取得较大进展.1994 年 Lee 等[1]通过求解代数 Riccati 方程,给出了一个无记忆 H_∞ 状态反馈控制器用于状态时滞系统.1995 年,Choi 和 Chung[2]讨论了同时具有状态和控制时滞的线性时不变系统的 H^∞ 状态反馈控制问题.1998 年,Su 等[3]讨论了带时变状态与控制时滞的时变不确定系统的情况.在时滞系统的 H_∞ 输出反馈控制方面,1996 年,Ge 等[4]提出了状态时滞系统的 H_∞ 输出反馈控制问题,Jeung 等[5]考虑了时变状态时滞的情况,1997 年,Choi 和 Chung[6]采用 Riccati 方程方法,提出了一个基于观测器的鲁棒 H_∞ 控制,用于带有界时变不确定性的线性时滞系统.但是目前对同时具有状态与控制时滞系统的 H_∞ 输出反馈控制问题还未见探讨.

本文针对同时具有状态与控制时变时滞的线性系统,基于代数 Riccati 方程方法,设计 H_∞ 输出反馈控制器,使闭环系统稳定,且满足 $\|z(t)\|_2 < \gamma\|w(t)\|_2$.

2 H_∞ 输出反馈控制(H_∞ control via output feedback)

本文考虑如下同时具有状态与控制时变时滞的系统:

$$\begin{cases} \dot{x}(t) = Ax(t) + A_d x(t-\tau_1(t)) + B_1 w(t) + \\ \qquad\quad B_2 u(t) + B_d u(t-\tau_2(t)), \\ z(t) = C_1 x(t) + D_{11} w(t) + D_{12} u(t), \\ y(t) = C_2 x(t) + D_{21} w(t), \\ x(t) = 0,\ t \leqslant 0. \end{cases} \tag{1}$$

式中, $x(t) \in \mathbb{R}^n$ 为系统状态, $w(t) \in \mathbb{R}^q$ 为干扰输入, $u(t) \in \mathbb{R}^m$ 为控制输入, $z(t) \in \mathbb{R}^{p_1}$ 为系统控制输出, $y(t) \in \mathbb{R}^{p_2}$ 为测量输出, $A, B_1, B_2, A_d, B_d, C_1, C_2, D_{11}, D_{12}, D_{21}$ 是具有适当维数的常矩阵, $\tau_1(t), \tau_2(t)$ 分别为状态和控制时变时滞,且满足下列假设:

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$$0 \leqslant \tau_1(t) < \tau_1 < \infty,\ \dot{\tau}_1(t) \leqslant d_{\tau_1} < 1, \quad (2)$$

$$0 \leqslant \tau_2(t) < \tau_2 < \infty,\ \dot{\tau}_2(t) \leqslant d_{\tau_2} < 1. \quad (3)$$

对于系统(1),采用以下输出反馈控制:

$$\begin{cases} \dot{x}_c(t) = A_c x_c(t) + B_c y(t), \\ u(t) = C_c x_c(t), \\ x_c(t) = 0,\ t \leqslant 0. \end{cases} \quad (4)$$

式中, $x_c(t) \in \mathbb{R}^n$ 是控制器状态, A_c, B_c, C_c 是控制器参数.

闭环系统可表示为:

$$\begin{cases} \begin{bmatrix} \dot{x}(t) \\ \dot{x}_c(t) \end{bmatrix} = \begin{bmatrix} A & B_2C_c \\ B_cC_2 & A_c \end{bmatrix} \begin{bmatrix} x(t) \\ x_c(t) \end{bmatrix} + \begin{bmatrix} A_d & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x(t-\tau_1) \\ x_c(t-\tau_1) \end{bmatrix} + \\ \qquad \begin{bmatrix} 0 & B_dC_c \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x(t-\tau_2) \\ x_c(t-\tau_2) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_cD_{21} \end{bmatrix} w(t), \\ z(t) = \begin{bmatrix} C_1 & D_{12}C_c \end{bmatrix} \begin{bmatrix} x(t) \\ x_c(t) \end{bmatrix} + D_{11}w(t). \end{cases} \quad (5)$$

取坐标变换阵 $T = \begin{bmatrix} I & 0 \\ I & -I \end{bmatrix}$, 则闭环系统(5)可转化为:

$$\begin{cases} \dot{\eta}(t) = A_{cl}\eta(t) + A_{cld}\eta(t-\tau_1(t)) + \\ \qquad B_{cld}C_{cld}\eta(t-\tau_2(t)) + B_{cl}w(t), \\ z(t) = C_{cl}\eta(t) + D_{cl}w(t), \\ \eta(t) = 0,\ t \leqslant 0. \end{cases} \quad (6)$$

其中

$$\eta(t) = \begin{bmatrix} x(t) \\ x(t) - x_c(t) \end{bmatrix},$$

$$A_{cl} = \begin{bmatrix} A + B_2C_c & -B_2C_c \\ A + B_2C_c - B_cC_2 - A_c & A_c - B_2C_c \end{bmatrix},$$

$$A_{cld} = \begin{bmatrix} A_d & 0 \\ A_d & 0 \end{bmatrix},\ B_{cld} = \begin{bmatrix} B_d \\ B_d \end{bmatrix},$$

$$C_{cld} = \begin{bmatrix} C_c & -C_c \end{bmatrix},\ B_{cl} = \begin{bmatrix} B_1 \\ B_1 - B_cD_{21} \end{bmatrix},$$

$$C_{cl} = \begin{bmatrix} C_1 + D_{12}C_c & -D_{12}C_c \end{bmatrix},\ D_{cl} = D_{11}.$$

为方便定理证明,引入以下两个引理:

引理 1[13]　对具有适当维数的矩阵 X, Y, 任取常数 $a > 0$, 有下式成立:

$$X^TY + Y^TX \leqslant \frac{1}{a}X^TX + aY^TY.$$

引理 2[17]　对具有适当维数的矩阵 F, G, 有下式成立:

$$(I - FG)^{-1} = I + F(I - GF)^{-1}G.$$

定理 1　对常数 $\alpha_1 > 0, \alpha_2 > 0$, 若有 $\gamma^2 I - D_{cl}^TD_{cl} > 0$, 且存在正定对称阵 $P > 0$ 满足下式:

$$S = A_{cl}^TP + PA_{cl} + C_{cl}^TC_{cl} + (PB_{cl} + C_{cl}^TD_{cl})(\gamma^2I - D_{cl}^TD_{cl})^{-1}(B_{cl}^TP + D_{cl}^TC_{cl}) + \frac{PA_{cld}A_{cld}^TP}{\alpha_1(1-d_{\tau_1})} + \alpha_1 I + \frac{PB_{cld}B_{cld}^TP}{\alpha_2(1-d_{\tau_2})} + \alpha_2 C_{cld}^TC_{cld} < 0, \quad (7)$$

则闭环系统(6)渐近稳定,并且满足 $\|z(t)\|_2 < \gamma\|w(t)\|_2$.

证　对闭环系统(6),取 Lyapunov 泛函为如下形式:

$$V(\eta(t),t) = \eta^T(t)P\eta(t) + \alpha_1\int_{t-\tau_1(t)}^{t}\eta^T(\tau)\eta(\tau)d\tau + \alpha_2\int_{t-\tau_2(t)}^{t}\eta^T(\tau)C_{cld}^TC_{cld}\eta(\tau)d\tau > 0, \quad (8)$$

则有:

$$\begin{aligned} \dot{V}(\eta(t),t) = {} & \eta^T(t)A_{cl}^TP\eta(t) + \eta^T(t-\tau_1(t))A_{cld}^TP\eta(t) + \\ & \eta^T(t-\tau_1(t))C_{cld}^TB_{cld}^TP\eta(t) + w^T(t)B_{cl}^TP\eta(t) + \\ & \eta^T(t)PA_{cl}\eta(t) + \eta^T(t)PA_{cld}\eta(t-\tau_1(t)) + \\ & \eta^T(t)PB_{cld}C_{cld}\eta(t-\tau_2(t)) + \eta^T(t)PB_{cl}w(t) + \\ & \alpha_1\eta^T(t)\eta(t) - \alpha_1(1-\dot{\tau}_1(t))\eta^T(t-\tau_1(t))\eta(t-\tau_1(t)) + \\ & \alpha_2\eta^T(t)C_{cld}^T\eta(t) - \alpha_2(1-\dot{\tau}_2(t))\eta^T(t-\tau_2(t))C_{cld}^TC_{cld}\eta(t-\tau_2(t)). \end{aligned} \quad (9)$$

由式(2),(3)和引理 1 可得:

$$\begin{aligned} \dot{V}(\eta(t),t) \leqslant {} & \eta^T(t)\Big[A_{cld}^TP + PA_{cl} + \frac{PA_{cld}A_{cld}^TP}{\alpha_1(1-d_{\tau_1})} + \alpha_1 I + \\ & \frac{PB_{cld}B_{cld}^TP}{\alpha_2(1-d_{\tau_2})} + \alpha_2C_{cld}^TC_{cld}\Big]\eta(t) + \\ & w^T(t)B_{cl}^TP\eta(t) + \eta^T(t)PB_{cl}w(t). \end{aligned} \quad (10)$$

①考虑稳定性时,令 $w(t) = 0$, 则由式(10)可得:

$$\dot{V}(\eta(t),t) \leqslant \eta^T(t)\Big[A_{cl}^TP + PA_{cl} + \frac{PA_{cld}A_{cld}^TP}{\alpha_1(1-d_{\tau_1})} + \alpha_1 I + \frac{PB_{cld}B_{cld}^TP}{\alpha_2(1-d_{\tau_2})} + \alpha_2C_{cld}^TC_{cld}\Big]\eta(t).$$

由式(7)可知: $\dot{V}(\eta(t),t) < 0$, 所以闭环系统(6)渐近稳定.

② 定义

$$J = \int_0^\infty[z^T(t)z(t) - \gamma^2w^T(t)w(t) + \dot{V}(\eta(t),t)]dt.$$

将式(6),(10)代入可得:

$$J \leqslant \int_0^\infty [\eta^T(t) S \eta(t) - T^T(\gamma^2 I - D_{cl}^T D_{cl})^{-1} T] dt,$$

其中

$$T = (B_{cl}^T P + D_{cl}^T C_{cl})\eta(t) - (\gamma^2 I - D_{cl}^T D_{cl}) w(t).$$

由式(7)可知: $J < 0$. 因系统(6)是渐近稳定,故 $V(\eta(\infty),\infty) = 0$,且由式(6)零初始条件可知: $V(\eta(0),0) = 0$. 所以:

$$\int_0^\infty z^T(t) z(t) dt < \gamma^2 \int_0^\infty w^T(t) w(t) dt,$$

即:

$$\| z(t) \|_2 < \gamma \| w(t) \|_2.$$

3 H_∞输出反馈控制器设计(H_∞ output feedback controller design)

根据定理1,以下给出同时具有状态与控制时变时滞的线性系统存在 H_∞ 输出反馈控制的充分条件.

定理2 对于系统(1)及任意常数 $\alpha_1 > 0, \alpha_2 > 0$,若 $\gamma^2 I - D_{11}^T D_{11} > 0$ 成立,且满足下列条件:

① 存在正定对称矩阵 $X > 0$ 使得:

$$A_F^T X + X A_F + C_F^T C_F + (X B_1 + C_F^T D_{11}) \Omega_1 (B_1^T X + D_{11}^T C_F) + \frac{X A_d A_d^T X}{\alpha_1 (1 - d_{\tau_1})} + \alpha_1 I + \frac{X B_d B_d^T X}{\alpha_2 (1 - d_{\tau_2})} + \alpha_2 X B_2 B_2^T X < 0. \quad (11)$$

其中 $A_F = A - B_2 F, C_F = C_1 - D_{12} F, F = B_2^T X, \Omega_1 = (\gamma^2 I - D_{11}^T D_{11})^{-1}$.

② 存在正定对称矩阵 $Y > 0$, 使得:

$$Y A_G^T + A_G Y + B_G B_G^T + (Y C_1^T + B_G D_{11}^T) \Omega_2 (C_1 Y + D_{11} B_G^T) + \frac{\gamma^2 A_d A_d^T}{\alpha_1 (1 - d_{\tau_1})} + \frac{2\alpha_1}{\gamma^2} YY + \frac{\gamma^2 B_d B_d^T}{\alpha_2 (1 - d_{\tau_2})} < 0. \quad (12)$$

其中 $A_G = A - G C_2, B_G = B_1 - G D_{21}, G = Y C_2^T, \Omega_2 = (\gamma^2 I - D_{11} D_{11}^T)^{-1}$.

③ $\gamma^2 Y^{-1} > X. \quad (13)$

则存在输出反馈控制(4)使闭环系统(6)渐近稳定,且满足 $\| z(t) \|_2 < \gamma \| w(t) \|_2$.

满足上述条件的一组输出反馈控制器为:

$$C_c = - B_2^T X, \quad (14)$$

$$B_c = \gamma^2 (\gamma^2 Y^{-1} - X)^{-1} C_2^T, \quad (15)$$

$$A_c = A_F - B_c C_2 + \frac{A_d A_d^T X}{\alpha_1 (1 - d_{\tau_1})} + \frac{B_d B_d^T X}{\alpha_2 (1 - d_{\tau_2})} - (\gamma^2 Y^{-1} - X)^{-1} M. \quad (16)$$

其中

$$M = C_c^T B_2^T X + C_c^T D_{12}^T C_F + \alpha_2 C_c^T C_c + H + [(\gamma^2 Y^{-1} - X)(B_c D_{21} - B_1) + C_c^T D_{12}^T D_{11}] \Omega_1 (B_1^T X + D_{11}^T C_F),$$

$$H = - A_F^T X - X A_F - C_F^T C_F - (X B_1 + C_F^T D_{11}) \Omega_1 (B_1^T X + D_{11}^T C_F) - \frac{X A_d A_d^T X}{\alpha_1 (1 - d_{\tau_1})} - \alpha_1 I - \frac{X B_d B_d^T X}{\alpha_2 (1 - d_{\tau_2})} - \alpha_2 X B_2 B_2^T X > 0. \quad (17)$$

证 选择正定对称矩阵 P:

$$P = \begin{bmatrix} X & 0 \\ 0 & \gamma^2 Y^{-1} - X \end{bmatrix} > 0.$$

定义 $$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix},$$

其中, $S_{11}, S_{12}, S_{21}, S_{22} \in \mathbb{R}^{n \times n}, S_{12} = S_{21}^T$.

则式(7)可分解成:

$$S_{11} = A_F^T X + X A_F + (X B_1 + C_F^T D_{11}) \Omega_1 (B_1^T X + D_{11}^T C_F) + C_F^T C_F + \frac{X A_d A_d^T X}{\alpha_1 (1 - d_{\tau_1})} + \alpha_1 I + \frac{X B_d B_d^T X}{\alpha_2 (1 - d_{\tau_2})} + \alpha_2 C_c^T C_c,$$

$$S_{12} = (A_F - B_c C_2 - A_c)^T (\gamma^2 Y^{-1} - X) - X B_2 C_c - C_F^T D_{12} C_c + (X B_1 + C_F^T D_{11}) \Omega_1 [(B_1^T - D_{21}^T B_c^T)(\gamma^2 Y^{-1} - X) - D_{11}^T D_{12} C_c] + \frac{X A_d A_d^T (\gamma^2 Y^{-1} - X)}{\alpha_1 (1 - d_{\tau_1})} + \frac{X B_d B_d^T (\gamma^2 Y^{-1} - X)}{\alpha_2 (1 - d_{\tau_2})} - \alpha_2 C_c^T C_c,$$

$$S_{22} = (A_c - B_2 C_c)^T (\gamma^2 Y^{-1} - X) + (\gamma^2 Y^{-1} - X)(A_c - B_2 C_c) + C_c^T D_{12}^T D_{12} C_c + [(\gamma^2 Y^{-1} - X)(B_1 - B_c D_{21}) - C_c^T D_{12}^T D_{11}] \Omega_1 [(B_1^T - D_{21}^T B_c^T)(\gamma^2 Y^{-1} - X) - D_{11}^T D_{12} C_c] + \alpha_1 I + \alpha_2 C_c^T C_c + \frac{(\gamma^2 Y^{-1} - X) A_d A_d^T (\gamma^2 Y^{-1} - X)}{\alpha_1 (1 - d_{\tau_1})} + \frac{(\gamma^2 Y^{-1} - X) B_d B_d^T (\gamma^2 Y^{-1} - X)}{\alpha_1 (1 - d_{\tau_2})}.$$

若按式(14)选择控制器参数 C_c, 由式(11),(17)可知: $S_{11} = - H < 0$.

若按式(16),(15)选择控制器参数 A_c, B_c, 并由式(17)可得:

$$S_{12} = S_{21} = H > 0,$$

$$S_{22} = \gamma^2 A_G^T Y^{-1} + \gamma^2 Y^{-1} A_G + C_1^T C_1 + 2\alpha_1 I + \frac{\gamma^4 Y^{-1} A_d A_d^T Y^{-1}}{\alpha_1 (1 - d_{\tau_1})} + \frac{\gamma^4 Y^{-1} B_d B_d^T Y^{-1}}{\alpha_2 (1 - d_{\tau_2})} - H + (\gamma^2 Y^{-1} B_G + C_1^T D_{11}) \Omega_1 (\gamma^2 Y^{-1} B_G + C_1^T D_{11})^T. \quad (18)$$

根据引理2,有:

$$(\gamma^2 - D_{11}^T D_{11})^{-1} = \gamma^{-2}[I + D_{11}^T(\gamma^2 I - D_{11}D_{11}^T)^{-1}D_{11}].$$

则式(18)可化为:

$$S_{22} = \gamma^2 A_G^T Y^{-1} + \gamma^2 Y^{-1}A_G + \gamma^2 Y^{-1}B_G B_G^T Y^{-1} + 2\alpha_1 I + \frac{\gamma^4 Y^{-1}A_d A_d^T Y^{-1}}{\alpha_1(1-d_{\tau_1})} + \frac{\gamma^4 Y^{-1}B_d B_d^T Y^{-1}}{\alpha_2(1-d_{\tau_2})} - H + \gamma^2(Y^{-1}B_G D_{11}^T + C_1^T)\Omega_2(Y^{-1}B_G D_{11}^T + C_1^T)^T = \tilde{S}_{22} - H,$$

$$\tilde{S}_{22} = \gamma^2 Y^{-1}[YA_G^T + A_G Y + B_G B_G^T + (YC_1^T + B_G D_{11}^T)\Omega_2(YC_1^T + B_G D_{11}^T)^T + \frac{\gamma^2 A_d A_d^T}{\alpha_1(1-d_{\tau_1})} + \frac{2\alpha_1 YY}{\gamma^2} + \frac{\gamma^2 B_d B_d^T}{\alpha_2(1-d_{\tau_2})}]Y^{-1}.$$

由式(12)可知:

$$\tilde{S}_{22} < 0.$$

则有:

$$\begin{bmatrix} I & 0 \\ I & I \end{bmatrix} S \begin{bmatrix} I & I \\ 0 & I \end{bmatrix} =$$

$$\begin{bmatrix} I & 0 \\ I & I \end{bmatrix}\begin{bmatrix} -H & H \\ H & \tilde{S}_{22}-H \end{bmatrix}\begin{bmatrix} I & I \\ 0 & I \end{bmatrix} = \begin{bmatrix} -H & 0 \\ 0 & \tilde{S}_{22} \end{bmatrix} < 0,$$

所以 S 负定. 证毕.

4 设计实例(Example)

设一个同时具有状态与控制时变时滞系统(1)的参数如下:

$$A = \begin{bmatrix} 0 & 1 \\ -1 & -2 \end{bmatrix},\ B_1 = \begin{bmatrix} 0 \\ 0.1 \end{bmatrix},\ B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$A_d = \begin{bmatrix} 0 & 0 \\ 0.2 & 0.1 \end{bmatrix},\ B_d = \begin{bmatrix} 0.1 \\ 0 \end{bmatrix},$$

$$C_1 = [0 \quad 1],\ C_2 = [0 \quad 1],$$

$$D_{11} = 0.2,\ D_{12} = 0.5,\ D_{21} = 0.2,$$

$$\tau_1(t) = 2 + 0.5\sin(t),\ \tau_2(t) = 3 + 0.3\cos(t),$$

$$d_{\tau_1} = 0.5,\ d_{\tau_2} = 0.3.$$

由于式(11)和(12)是不等式,我们选择 $Q_1 = 10^{-5}I, Q_2 = 10^{-5}I$ 分别使不等式(11),(12)成为等式,并取 $\alpha_1 = 1, \alpha_2 = 1$,利用 MATLAB 语言求得次优解为:

$$\gamma_{opt} = 0.2838.$$

此时相应的 Riccati 方程的解为:

$$X = \begin{bmatrix} 2.0705 & 0.4614 \\ 0.4614 & 0.7159 \end{bmatrix},\ Y = \begin{bmatrix} 0.0202 & -0.0067 \\ -0.0067 & 0.0191 \end{bmatrix}.$$

控制器参数为:

$$A_c = \begin{bmatrix} 0.0152 & 1.1288 \\ -1.4317 & -2.0805 \end{bmatrix},$$

$$B_c = \begin{bmatrix} -0.0104 \\ 0.0227 \end{bmatrix},\ C_c = [-0.4614 \quad -0.7159].$$

5 结论(Conclusion)

本文针对同时具有状态与控制时变时滞的线性系统,给出了使整个闭环系统稳定并使其满足 $\|z(t)\|_2 < \gamma\|w(t)\|_2$ 的基于代数 Riccati 方程的解,通过求解两个代数 Riccati 方程即可得到 H^∞ 输出反馈控制器.该方法的一个特点是这两个代数 Riccati 方程可以独立求解.本文仅研究同时具有状态与控制时变时滞的线性系统,对同时具有状态与控制时滞的不确定时变系统的 H^∞ 输出反馈控制问题将进一步研究.

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