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离散时间输入时滞广义系统的 RHC 镇定控制

王晓静,刘晓华

(鲁东大学 数学与统计科学学院,山东 烟台 264039)

摘要: 本文研究离散时间具有输入时滞的广义系统的 RHC 镇定问题. 构造了一个包含两个终端加权矩阵的性能指标,在满足正则性和无脉冲的前提条件下,通过使该性能指标单调递减得到系统可镇定的充分条件,该条件可通过线性矩阵不等式进行求解. 在满足可镇定的条件下,运用 LQR 的方法得到系统可镇定的显式 RHC 控制器.

关键词: 输入时滞; 滚动时域控制; 广义系统; 镇定

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由于在建模中物理变量可能不被选择为状态变量,或者因果关系原则在某些情况下不成立,针对经典状态空间模型存在的这些约束,一类更为一般的广义系统已在电力系统、经济系统、生物系统等实际问题中有着广泛的应用[1—3]. 关于广义系统的控制问题取得了丰富的研究成果,其中包括分散控制[4]、鲁棒控制[5]、H_∞ 控制[6]、自适应控制[7]、预测控制[8]及最优控制[9]等. 近年来,具有时滞的广义系统成为研究的热点[10—12].

滚动时域控制[13](receding horizon control,RHC)有易于计算,保证闭环系统稳定性,以及对模型要求较低等优点,已在实际的工业过程中得到成功的应用[14—16]. RHC 的基本思想是每一时刻求解一个有限时域的最优控制问题,且只把得到的第一个解作为当前时刻的控制施加于被控系统,到下一时刻重复上述过程,所以 RHC 是一种在线的滚动优化[17].

本文基于 RHC 方法研究具有输入时滞的离散时间广义系统的镇定问题. 文中构造一个条件期望形式的性能指标,运用线性矩阵不等式的方法,通过使最优性能指标单调递减,得到输入时滞广义系统可镇定的充分条件. 在满足正则性和无脉冲的前提条件下,运用极值原理和 LQR 方法求解一个有限时域的最优控制问题,建立伴随状态与系统状态之间的关系,通过求解一组耦合的具有时滞的正倒向差分方程,得到系统可镇定的显式 RHC 镇定控制器.

1 问题描述

考虑具有输入时滞的离散时间广义系统

$$E_0x_{k+1} = Ax_k + B_0u_k + B_du_{k-d}, \tag{1}$$

其中: $E_0 \in \mathbf{R}^{n\times n}$ 为奇异矩阵,且满足 $0 < \mathrm{rank}(E_0) \leqslant n$; $x_k \in \mathbf{R}^n$ 和 $u_k \in \mathbf{R}^m$ 分别为状态和控制输入; d 为常数时滞; x_0 和 $u_{-i}, i = 1,2,\cdots,d$ 为给定的初始值; A 以及 $B_i, i = 0,d$ 为适当维数的矩阵.

下面定义系统(1)的镇定问题.

定义 1 系统(1)称为可镇定的,若对任意给定的 $x_0, u_{-i}, i = 1,2,\cdots,d$,存在线性反馈控制器

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第一作者简介: 王晓静(1994—),女,山东烟台人,硕士研究生,研究方向为应用概率统计. E-mail: 1191024763@qq.com

通信作者简介: 刘晓华(1959—),男,山东烟台人,教授,硕士研究生导师,博士,研究方向为系统控制与优化. E-mail: xhliu@ldu.edu.cn

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$$u_k = Lx_k + \sum_{i=1}^{d} L_i u_{k-i}, \tag{2}$$

其中: $L, L_i, i = 1, 2, \cdots, d$ 是常数矩阵,使得闭环系统满足

$$\lim_{k\to\infty} E(\| x_k \|^2) = 0.$$

问题 1　寻找系统(1)在如(2)所示的控制器控制下可镇定的条件,如果该条件满足,给出显式的 RHC 镇定控制器.

2　输入时滞系统的 RHC 镇定控制

本节研究系统(1)基于 RHC 的镇定问题,首先给出 RHC 的解.

2.1　滚动时域控制

为了解决问题 1,引入如下的性能指标

$$J_{k-1}(x_k, k) = E_{k-1}\Big\{ \sum_{i=0}^{N} [x_{k+i}^{\mathrm{T}} (E_0^{k+i})^{\mathrm{T}} Q E_0^{k+i} x_{k+i} + u_{k+i}^{\mathrm{T}} R u_{k+i}] + x_{k+N+1}^{\mathrm{T}} (E_0^{k+N+1})^{\mathrm{T}} F_1 E_0^{k+N+1} x_{k+N+1} + \sum_{i=N+1-d}^{N} u_{k+i}^{\mathrm{T}} F_2 u_{k+i} \Big\}, \tag{3}$$

其中: k 为初始时刻,$Q > 0, R > 0, F_1 > 0, F_2 > 0, N$ 为时域长度,$E_{k-1}[\cdot]$ 表示 $[\cdot]$ 关于测度 F_{k-1} 的条件期望.

下面解决系统(1)的线性二次最优控制问题,即寻找 F_{k-1} - 可测的控制 u_k,使得性能指标(3)最小. 为了进一步的研究,给出如下假设:

假设 1　对广义随机系统(1),有 $E_0 A_i = A_i E_0$ 和 $E_0 \bar{A}_i = \bar{A}_i E_0$ 成立.

假设 2　对 (E_0, A_i) 是容许的,即 $\deg(\det(zE_0 - A_i)) = \mathrm{rank}(E_0)$.

本文的研究是在假设 1 和假设 2 满足的前提下进行.

为了得到 RHC 镇定控制器,需求解在系统(1)的约束下,最小化性能指标(3)的最优控制问题. 由极值原理,可得

$$\lambda_{k+N} = F_1 E_0^{k+N+1} x_{k+N+1}, \tag{4}$$

$$\lambda_{i-1} = E_{i-1}[A^{\mathrm{T}} \lambda_i] + Q E_0^i x_i, i = k, k+1, \cdots, k+N, \tag{5}$$

$$0 = (R + F_2) u_i + E_{i-1}[B_0^{\mathrm{T}} (E_0^i)^{\mathrm{T}} \lambda_i], i = k+N-d+1, k+N-d+2, \cdots, k+N, \tag{6}$$

$$0 = R u_i + E_{i-1}[B_0^{\mathrm{T}} (E_0^i)^{\mathrm{T}} \lambda_i + B_d^{\mathrm{T}} (E_0^{i+d})^{\mathrm{T}} \lambda_{i+d}], i = k, k+1, \cdots, k+N-d, \tag{7}$$

其中: λ_i 为协态,且 $\lambda_i = 0, i > k+N$.

引理 1　在系统(1)的约束下,最小化性能指标(3)的最优控制器为

$$u_s = -R_s^{-1} T_s E_0^s x_s - R_s^{-1} \sum_{j=0}^{d-1} T_s^j u_{j+s-d}, s = k, k+1, \cdots, k+N, \tag{8}$$

其中: $R_s, T_s, T_s^j, P_s, P_s^j, j = 0, 1, \cdots, d-1$ 满足如下的倒向随机差分方程:

$$P_s = A^{\mathrm{T}} P_{s+1} A - T_s^{\mathrm{T}} R_s^{-1} T_s + Q, \tag{9}$$

$$T_s = B_0^{\mathrm{T}} (E_0^s)^{\mathrm{T}} P_{s+1} A + (P_{s+1}^{d-1})^{\mathrm{T}} A, \tag{10}$$

$$R_s = R + B_0^{\mathrm{T}} (E_0^s)^{\mathrm{T}} P_{s+1} E_0^s B_0 + B_d^{\mathrm{T}} (E_0^{s+d})^{\mathrm{T}} P_{s+d+1} E_0^{s+d} B_d + B_0^{\mathrm{T}} (E_0^s)^{\mathrm{T}} P_{s+1}^{d-1} + (P_{s+1}^{d-1})^{\mathrm{T}} E_0^s B_0 - \sum_{i=1}^{d} (T_{s+i}^{d-i})^{\mathrm{T}} R_{s+i}^{-1} T_{s+i}^{d-i}, k \leqslant s \leqslant k+N-d, \tag{11}$$

$$R_s = (R + F_2) + B_0^{\mathrm{T}} (E_0^s)^{\mathrm{T}} P_{s+1} E_0^s B_0 + B_d^{\mathrm{T}} (E_0^{s+d})^{\mathrm{T}} P_{s+d+1} E_0^{s+d} B_d + B_0^{\mathrm{T}} (E_0^s)^{\mathrm{T}} P_{s+1}^{d-1} + (P_{s+1}^{d-1})^{\mathrm{T}} E_0^s B_0 - \sum_{i=1}^{d} (T_{s+i}^{d-i})^{\mathrm{T}} R_{s+i}^{-1} T_{s+i}^{d-i}, k+N-d < s \leqslant k+N, \tag{12}$$

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$$T_s^0 = B_0^{\mathrm{T}}(E_0^s)^{\mathrm{T}}P_{s+1}E_0^sB_d + (P_{s+1}^{d-1})^{\mathrm{T}}E_0^sB_d, \tag{13}$$

$$T_s^j = B_0^{\mathrm{T}}(E_0^s)^{\mathrm{T}}P_{s+1}^{j-1} + (P_{s+j+1}^{d-j-1})^{\mathrm{T}}E_0^jB_d - \sum_{i=1}^{j}(T_{s+i}^{d-i})^{\mathrm{T}}R_{s+i}^{-1}T_{s+i}^{j-i}, \tag{14}$$

$$P_s^0 = A^{\mathrm{T}}P_{s+1}E_0^sB_d - T_s^{\mathrm{T}}R_s^{-1}T_s^0, \tag{15}$$

$$P_s^j = A^{\mathrm{T}}P_{s+1}^{j-1} - T_s^{\mathrm{T}}R_s^{-1}T_s^j,\ j = 1,2,\cdots,d-1. \tag{16}$$

终端值为: $P_{k+N+1} = F_1, P_{k+N+1+i} = 0, P_{k+N+i}^j = 0, T_{k+N+i}^j = 0, R_{k+N+i} = I, i \geqslant 1, j = 0,1,\cdots,d-1.$

此外,最优协态 λ_i 和状态 x_k 满足如下关系:

$$\lambda_{k-1} = P_kE_0^kx_k + \sum_{j=0}^{d-1}P_k^ju_{j+k-d}.$$

2.2 RHC 镇定

本文需要解决的另一个问题是系统(1)的镇定问题,输入时滞系统的 RHC 镇定条件将在这一部分给出. 首先研究性能指标(3)的性质.

引理2 假设对给定的矩阵 H_1 和 H_2,性能指标(3)中的矩阵 F_1 和 F_2 满足下列的矩阵不等式

$$\begin{bmatrix} \Pi_{11} & \Pi_{12} \\ \Pi_{12}^{\mathrm{T}} & \Pi_{22} \end{bmatrix} \leqslant 0, \tag{17}$$

其中:

$$\Pi_{11} = Q + H_1^{\mathrm{T}}(F_2 + R)H_1 + (A + B_0H_1)^{\mathrm{T}}F_1(A + B_0H_1) - F_1,$$
$$\Pi_{12} = H_1^{\mathrm{T}}(F_2 + R)H_2 + (A + B_0H_1)^{\mathrm{T}}F_1(B_0H_2 + B_d),$$
$$\Pi_{22} = H_2^{\mathrm{T}}(F_2 + R)H_2 + (B_0H_2 + B_d)^{\mathrm{T}}F_1(B_0H_2 + B_d) - F_2.$$

则有

$$E_{k-1}[J_k^*(x_{k+1},k+1)] - J_{k-1}^*(x_k,k) \leqslant 0 \tag{18}$$

成立. 其中,$J_{k-1}^*(x_k,k)$ 是系统初始状态为 x_k,且最优控制序列为(8)时的性能指标(3)的值.

证明 由性能指标(3),可得

$$E_{k-1}[J_k^*(x_{k+1},k+1)] - J_{k-1}^*(x_k,k) =$$
$$E_{k-1}\{E_k[\sum_{i=0}^{N}\bar{x}_{k+i+1}^{\mathrm{T}}(E_0^{k+i+1})^{\mathrm{T}}QE_0^{k+i+1}\bar{x}_{k+i+1} + \sum_{i=0}^{N}\bar{u}_{k+i+1}^{\mathrm{T}}R\bar{u}_{k+i+1}] +$$
$$\bar{x}_{k+N+2}^{\mathrm{T}}(E_0^{k+N+2})^{\mathrm{T}}F_1E_0^{k+N+2}\bar{x}_{k+N+2} + \sum_{i=N+1-d}^{N}\bar{u}_{k+i+1}^{\mathrm{T}}F_2\bar{u}_{k+i+1}\} -$$
$$E_{k-1}\{\sum_{i=0}^{N}[\tilde{x}_{k+i}^{\mathrm{T}}(E_0^{k+i})^{\mathrm{T}}QE_0^{k+i}\tilde{x}_{k+i} + \tilde{u}_{k+i}^{\mathrm{T}}R\tilde{u}_{k+i}] + \tilde{x}_{k+N+1}^{\mathrm{T}}(E_0^{k+N+1})^{\mathrm{T}}F_1E_0^{k+N+1}\tilde{x}_{k+N+1} + \sum_{i=N+1-d}^{N}\tilde{u}_{k+i}^{\mathrm{T}}F_2\tilde{u}_{k+i}\}, \tag{19}$$

其中: $\bar{u}_{k+i+1}$ 和 $\tilde{u}_{k+i}, i = 1,2,\cdots,N$ 分别是以 x_{k+1} 和 x_k 为初始状态时,最小化性能指标(3)所得的最优控制序列; $\bar{x}_{k+i+1}$ 和 $\tilde{x}_{k+i}$ 是系统(1)分别在控制序列 $\bar{u}_{k+i+1}$ 和 $\tilde{u}_{k+i}$, $i = 0,1,\cdots,N$ 控制下的最优状态. 令

$$\bar{u}_{k+i+1} = \begin{cases} \tilde{u}_{k+i+1}, & i = 1,2,\cdots,N-1, \\ H_1E_0^{k+N+1}\tilde{x}_{k+N+1} + H_2\tilde{u}_{k+N+1-d}, & i = N. \end{cases} \tag{20}$$

考虑到系统(1)和式(20),由式(19)可得

$$E_{k-1}[J_k^*(x_{k+1},k+1)] - J_{k-1}^*(x_k,k) \leqslant$$
$$E_{k-1}\{\tilde{x}_{k+N+1}^{\mathrm{T}}(E_0^{k+N+1})^{\mathrm{T}}QE_0^{k+N+1}\tilde{x}_{k+N+1} + (H_1E_0^{k+N+1}\tilde{x}_{k+N+1} + H_2\tilde{u}_{k+N+1-d})^{\mathrm{T}}(F_2+R)(H_1E_0^{k+N+1}\tilde{x}_{k+N+1} + H_2\tilde{u}_{k+N+1-d}) +$$
$$[A(k+N+1)\tilde{x}_{k+N+1} + B_0(k+N+1)(H_1E_0^{k+N+1}\tilde{x}_{k+N+1} + H_2\tilde{u}_{k+N+1-d}) + B_d(k+N+1)\tilde{u}_{k+N+1-d}]^{\mathrm{T}} \times$$
$$(E_0^{k+N+1})^{\mathrm{T}}F_1E_0^{k+N+1}[A(k+N+1)\tilde{x}_{k+N+1} + B_0(k+N+1)(H_1E_0^{k+N+1}\tilde{x}_{k+N+1} + H_2\tilde{u}_{k+N+1-d}) +$$
$$B_d(k+N+1)\tilde{u}_{k+N+1-d}] - \tilde{x}_k^{\mathrm{T}}(E_0^k)^{\mathrm{T}}QE_0^k\tilde{x}_k - \tilde{u}_k^{\mathrm{T}}R\tilde{u}_k - \tilde{x}_{k+N+1}^{\mathrm{T}}(E_0^{k+N+1})^{\mathrm{T}}F_1E_0^{k+N+1}\tilde{x}_{k+N+1} - \tilde{u}_{k+N+1-d}^{\mathrm{T}}F_2\tilde{u}_{k+N+1-d}\} =$$

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$$E_{k-1}\left\{\begin{bmatrix} E_0^{k+N+1}\tilde{x}_{k+N+1} \\ \tilde{u}_{k+N+1-d}\end{bmatrix}^{\mathrm{T}} \Pi \begin{bmatrix} E_0^{k+N+1}\tilde{x}_{k+N+1} \\ \tilde{u}_{k+N+1-d}\end{bmatrix} - \tilde{x}_k^{\mathrm{T}}(E_0^k)^{\mathrm{T}} Q E_0^k \tilde{x}_k - \tilde{u}_k^{\mathrm{T}} R \tilde{u}_k\right\}, \tag{21}$$

其中 Π 为(17)中的矩阵. 显然,若 $\Pi \leqslant 0$,则有式(18)成立. 证毕.

下面的定理将矩阵不等式(17)转化为线性矩阵不等式进行求解.

定理 1　若存在 $X>0, S>0, Y_1, Y_2$,使得

$$\begin{bmatrix} -X & 0 & XQ^{\frac{1}{2}} & Y_1R^{\frac{1}{2}} & Y_1 & XA^{\mathrm{T}}+Y_1B_0^{\mathrm{T}} \\ * & -S & 0 & Y_2R^{\frac{1}{2}} & Y_2 & Y_2B_0^{\mathrm{T}}+SB_d^{\mathrm{T}} \\ * & * & -I & 0 & 0 & 0 \\ * & * & * & -I & 0 & 0 \\ * & * & * & * & -S & 0 \\ * & * & * & * & * & -X \end{bmatrix} \leqslant 0, \tag{22}$$

则矩阵不等式(17)的解为 $F_1 = X^{-1}, F_2 = S^{-1}, H_1 = Y_1^{\mathrm{T}}F_1, H_2 = Y_2^{\mathrm{T}}F_2$.

证明　不等式(17)等价于

$$\begin{bmatrix} \Pi_{11} & \Pi_{12} \\ \Pi_{12}^{\mathrm{T}} & \Pi_{22}\end{bmatrix} = \begin{bmatrix} -F_1 & 0 \\ 0 & -F_2\end{bmatrix} +$$

$$\begin{bmatrix} Q+H_1^{\mathrm{T}}(F_2+R)H_1+(A+B_0H_1)^{\mathrm{T}}F_1(A+B_0H_1) & H_1^{\mathrm{T}}(F_2+R)H_2+(A+B_0H_1)^{\mathrm{T}}F_1(B_0H_2+B_d) \\ * & H_2^{\mathrm{T}}(F_2+R)H_2+(B_0H_2+B_d)^{\mathrm{T}}F_1(B_0H_2+B_d)\end{bmatrix} =$$

$$\begin{bmatrix} -F_1 & 0 \\ 0 & -F_2\end{bmatrix} + \begin{bmatrix} Q^{\frac{1}{2}} & H_1^{\mathrm{T}}R^{\frac{1}{2}} & H_1^{\mathrm{T}} & (A+B_0H_1)^{\mathrm{T}} \\ 0 & H_2^{\mathrm{T}}R^{\frac{1}{2}} & H_2^{\mathrm{T}} & (B_0H_2+B_d)^{\mathrm{T}}\end{bmatrix} \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & F_2 & 0 \\ 0 & 0 & 0 & F_1\end{bmatrix} \begin{bmatrix} Q^{\frac{1}{2}} & 0 \\ R^{\frac{1}{2}}H_1 & R^{\frac{1}{2}}H_2 \\ H_1 & H_2 \\ A+B_0H_1 & B_0H_2+B_d\end{bmatrix} =$$

$$\begin{bmatrix} -F_1 & 0 \\ 0 & -F_2\end{bmatrix} - \begin{bmatrix} Q^{\frac{1}{2}} & H_1^{\mathrm{T}}R^{\frac{1}{2}} & H_1^{\mathrm{T}} & (A+B_0H_1)^{\mathrm{T}} \\ 0 & H_2^{\mathrm{T}}R^{\frac{1}{2}} & H_2^{\mathrm{T}} & (B_0H_2+B_d)^{\mathrm{T}}\end{bmatrix} \times$$

$$\begin{bmatrix} -I & 0 & 0 & 0 \\ 0 & -I & 0 & 0 \\ 0 & 0 & -F_2^{-1} & 0 \\ 0 & 0 & 0 & -F_1^{-1}\end{bmatrix}^{-1} \begin{bmatrix} Q^{\frac{1}{2}} & 0 \\ R^{\frac{1}{2}}H_1 & R^{\frac{1}{2}}H_2 \\ H_1 & H_2 \\ A+B_0H_1 & B_0H_2+B_d\end{bmatrix} \leqslant 0. \tag{23}$$

通过引入变量变换 $X = F_1^{-1}, S = F_2^{-1}, Y_1 = F_1^{-1}H_1^{\mathrm{T}}, Y_2 = F_2^{-1}H_2^{\mathrm{T}}$,以及 Schur 补引理,则矩阵不等式(23)等价于线性矩阵不等式(22).

定理 2　给定 $Q>0, R>0$,若存在 $F_1>0, F_2>0$ 和矩阵 H_1, H_2,使得矩阵不等式(17)成立,则系统(1)在滚动时域控制下是渐近均方稳定的.

证明　由引理 2,存在 $F_1>0, F_2>0$ 和 H_1, H_2 满足式(17),则有

$$E_{k-1}[J_k^*(x_{k+1}, k+1)] - J_{k-1}^*(x_k, k) \leqslant 0$$

成立. 由于

$$E\{E_{k-1}[J_k^*(x_{k+1}, k+1)] - J_{k-1}^*(x_k, k)\} = E[J_k^*(x_{k+1}, k+1)] - E[J_{k-1}^*(x_k, k)],$$

因此,$E[J_{k-1}^*(x_k, k)]$ 是单调不增的. 又因为 $E[J_{k-1}^*(x_k, k)] \geqslant 0$,所以 $\lim\limits_{k\to\infty} E[J_{k-1}^*(x_k, k)]$ 存在,且

$$\lim_{k\to\infty} E[J_k^*(x_{k+1}, k+1) - J_{k-1}^*(x_k, k)] = 0.$$

由式(21)可得,$\lim\limits_{k\to\infty} E(\|\tilde{x}_k\|^2) = 0$.

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3 仿真算例

本节通过一个仿真算例来检验RHC方法的有效性.

考虑具有输入时滞的离散时间广义系统(1)和性能指标(3),其中

$$E_0 = \begin{bmatrix} 0.1 & 0 \\ 0.1 & 0 \end{bmatrix}, A = \begin{bmatrix} -0.5 & 1 \\ 0.5 & -2 \end{bmatrix}, B_0 = \begin{bmatrix} -2 \\ -1 \end{bmatrix}, B_2 = \begin{bmatrix} -0.5 \\ -0.2 \end{bmatrix}, Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

及 $R = 1, d = 2, N = 2$.

通过求解LMI(22),可得矩阵 F_1, F_2, H_1, H_2. 由式(9) ~ (16)可计算出 u_k 的增益矩阵

$$K = \begin{bmatrix} -R_0^{-1}T_0 & -R_0^{-1}T_0^1 & -R_0^{-1}T_0^0 \end{bmatrix}.$$

仿真中取系统(1)的初始值为 $x_0 = \begin{bmatrix} 1 & -1 \end{bmatrix}^{\mathrm{T}}$, $u_0 = 1$, $u_{-1} = -1$,图1给出了RHC控制闭环系统的状态轨迹,从图1中可以看出系统状态是渐近稳定的.

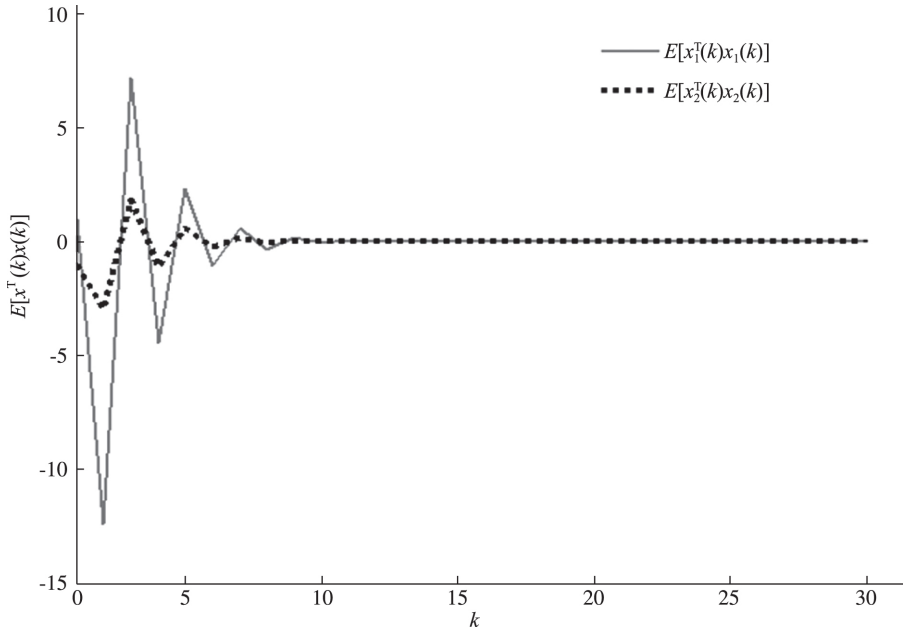

图1 闭环系统的状态轨迹

Fig. 1 The state trajectory of the closed loop system

4 结语

本文研究了具有输入时滞的离散时间广义系统的RHC镇定问题. 构造了一个包含两个终端加权矩阵的性能指标,在满足正则化和无脉冲条件下,通过求解一组耦合的差分方程,得到显式的RHC镇定控制器. 同时提出基于终端加权矩阵LMI形式的RHC镇定的充分条件,该条件保证系统的最优代价是单调递减的,从而保证了系统的闭环状态轨迹渐近稳定. 仿真结果验证该方法的有效性.

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RHC Stabilization Control for Discrete-time Singular Systems with Input Delay

WANG Xiaojing, LIU Xiaohua

(School of Mathematics and Statistics Science,Ludong University,Yantai 264039,China)

Abstract: The RHC stabilization problem for discrete-time singular systems with input delay is studied. A cost function containing two terminal weighted matrixes was constructed,and a sufficient condition for the stabilization of the system was obtained by monotonically decreasing the cost function,which could be solved by LMI. Under the condition of stabilization,the explicit RHC controller was obtained by the LQR method.

Keywords: input delay; receding horizon control; singular system; stabilization

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