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含状态和输入时滞的网络控制系统镇定

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摘 要: 研究含有更广泛被控对象的网络控制系统镇定问题. 假定被控对象含有时变状态和输入时滞,采用 Lyapunov-Krasovskii 泛函方法分析了系统的稳定性. 所提出的方法可转化为线性矩阵不等式的形式,因而可较为容易地求得控制器和广义最大允许时延. 仿真结果说明了所提出方法的有效性.

关键词: 网络控制系统; 时滞; 线性矩阵不等式; Lyapunov-Krasovskii 泛函
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Stabilization of networked control systems with state and input delays

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Abstract: The stabilization problem for networked control systems (NCSs) with a more general plant is studied. The plant in an NCS is a class of systems with time-varying state and input delays. The stability of such NCSs is studied by using Lyapunov-Krasovskii functional approach. The proposed method is formulated in terms of linear matrix inequalities (LMIs) so that the controller and the generalized maximum allowable delay bound (MADB) are easily obtained. Simulation results show the effectiveness of the proposed method.

Key words: Networked control system; Time-delay; Linear matrix inequality; Lyapunov-Krasovskii functional

1 引 言

网络控制系统(NCS)具有布线少、诊断和维护方便以及结构灵活等优点,已经成为研究者关注的热点问题. 网络中不可避免地存在网络诱导时滞和数据包丢包,因而对 NCS 的研究较传统的闭环系统复杂. 文献[1-5]研究了网络控制系统的稳定性,得到了使系统稳定的最大允许时延(MADB).

文献[1-5]基于连续时间模型,将 NCS 看成具有输入时滞的系统. 时滞和丢包的影响相当于一个分段连续的输入时滞,可应用已有的时滞系统的研究方法来研究 NCS. 研究时滞系统常采用两种方法: Razumikhin 方法和 Lyapunov-Krasovskii 泛函方法. 对于时滞导数无任何限制的时滞系统,通常采用 Razumikhin 方法[6],但结果比较保守. Lyapunov-Krasovskii 泛函方法主要用来处理时滞导数小于 1 的慢变时滞系统[7]. 文献[1]采用 Razumikhin 方法研究了 NCS 的控制问题,文献[8,9]采用 Lyapunov-Krasovskii 泛函方法研究了快变时滞系统的控制问题,文献[4,5]将 Lyapunov-Krasovskii 泛函方法应用于 NCS. 然而,以往文献大都未考虑 NCS 被控对象包含时滞项的情况. 被控对象含状态或输入时滞的情况在实际中经常遇到,为此,本文考虑的 NCS 被控对象具有较已往文献中被控对象更广泛的模型: 被控对象含有时变状态和输入时滞,且未限制时滞属于慢变时滞. 本文采用 Lyapunov-Krasovskii 泛函方法分析了系统的稳定性,得到了可保证系统稳定的广义最大允许时延.

2 网络控制系统模型

NCS 含有两类由网络引起的时滞: 由传感器到控制器的时滞 τ_{sc}; 由控制器到执行器的时滞 τ_{ca}. 闭环系统由一个含状态和输入时滞的被控对象

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{n} A_i x(t - h_{1i}) +$$

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$$Bu(t) + \sum_{j=1}^{m} B_j u(t - h_{2j}) \qquad (1)$$

和一个具有零阶保持器的控制器

$$u(t) = K\bar{x}(t - \tau_{ca}),\ t \in [t_k, t_{k+1}),$$
$$k = 1, 2, \cdots \qquad (2)$$

组成. 其中: $x(t) \in R^n$ 为状态向量; $u(t) \in R^m$ 为控制向量; K 为反馈增益矩阵; $\bar{x}(t)$ 为网络输出; t_k 为采样时刻; h_{1i}, h_{2j} 分别为时变状态和输入时滞,假定满足 $t > 0$ 时, $0 \le h_{1i}(t) \le \bar{h}_{1i}$, $0 \le h_{2j}(t) \le \bar{h}_{2j}$; $\bar{h}_{1i}$, $\bar{h}_{2j}$ 分别为状态时滞和输入时滞的上界; $A, A_i(i = 1, 2, \cdots, n)$ 和 $B, B_j(j = 1, 2, \cdots, m)$ 为具有相应维数的系统矩阵和输入矩阵.

模型(1)描述了较已往文献中被控对象 $\dot{x}(t) = Ax(t) + Bu(t)$ 更广泛的系统,考虑了被控对象本身的时滞项. 具有网络诱导时滞和数据包丢包的网络控制系统(NCS)如图 1 所示. 开关关闭时,数据包传输,控制器采用新的数据;开关断开时,数据包丢失,控制器采用旧的数据. 这里认为采样时间 h 是固定的. 在 $d(k)$ 个数据包丢失的情况下,控制信号可表示为

$$\begin{aligned} u(t) &= K\bar{x}(t - \tau_{ca}) = \\ &Kx(t_k - \tau_{ca} - \tau_{sc} - d(k)h) = \\ &Kx(t - \tau(t)),\ t \in [t_k, t_{k+1}). \end{aligned} \qquad (3)$$

其中: $\tau(t) = t - t_k + \tau_{ca} + \tau_{sc} + d(k)h$, $0 \le \tau(t) \le h + \tau_{ca} + \tau_{sc} + d(k)h$, $t \in [t_k, t_{k+1})$. 整个系统可表示为

$$\begin{aligned} \dot{x}(t) =& \sum_{i=0}^{n} A_i x(t - h_{1i}) + \\ & \sum_{j=0}^{m} B_j Kx(t - \tau(t) - h_{2j}). \end{aligned} \qquad (4)$$

其中: $A_0 = A$, $B_0 = B$, $h_{10} = h_{20} = 0$. 本文将使系统稳定的 $\tau(t)$ 的最大值称作广义最大允许时延,这是因为考虑了丢包的因素.

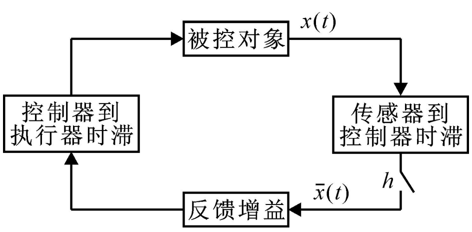

图 1　网络控制系统

3　网络控制系统的镇定

引理 1[10]　假定 $a(\cdot) \in R^{na}$, $b(\cdot) \in R^{nb}$, $N(\cdot) \in R^{na \times nb}$ 定义在区间 Ω. 对于任意矩阵 $X \in R^{na \times na}$, $Y \in R^{na \times nb}$ 和 $Z \in R^{nb \times nb}$,下式成立:

$$-2\int_{\Omega} a^{\mathrm{T}}(\alpha) N b(\alpha)\, \mathrm{d}\alpha \le$$
$$\int_{\Omega} \begin{bmatrix} a(\alpha) \\ b(\alpha) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} X & Y - N \\ Y^{\mathrm{T}} - N^{\mathrm{T}} & Z \end{bmatrix} \times \begin{bmatrix} a(\alpha) \\ b(\alpha) \end{bmatrix} \mathrm{d}\alpha,$$

其中 $\begin{bmatrix} X & Y \\ Y^{\mathrm{T}} & Z \end{bmatrix} \ge 0$.

引理 2　令 $\omega(t) = \int_{a(t)}^{b(t)} \int_{t-\theta}^{t} f(s)\, \mathrm{d}s \mathrm{d}\theta$,则有下式成立:

$$\begin{aligned} \dot{\omega}(t) =& \\ & (b - a) f(t) - (1 + \dot{b}) \int_{t-a}^{t-b} f(s)\, \mathrm{d}s + \\ & (\dot{b} - \dot{a}) \int_{t-a}^{t} f(s)\, \mathrm{d}s. \end{aligned}$$

定理 1　给定标量 $\bar{\tau} > 0$ 和反馈增益矩阵 K,对于任意 $\tau(t) \le \bar{\tau}$,系统(4)是渐近稳定的. 如果存在矩阵 $P_1 > 0$, P_2, P_3, Z_{1il}, Z_{2jl}, $l = 1, 2, 3$, 则 $R_{1i} = R_{1i}^{\mathrm{T}} > 0$ 和 $R_{2j} = R_{2j}^{\mathrm{T}} > 0$ 满足如下线性矩阵不等式:

$$\begin{aligned} & P^{\mathrm{T}} \begin{bmatrix} 0 & I \\ \bar{A} & -I \end{bmatrix} + \begin{bmatrix} 0 & \bar{A}^{\mathrm{T}} \\ I & -I \end{bmatrix} P + \\ & \sum_{i=1}^{n} \bar{h}_i Z_{1i} + \sum_{j=0}^{m} (\bar{\tau} + \bar{h}_{2j}) Z_{2j} + \\ & \begin{bmatrix} 0 & 0 \\ 0 & \sum_{i=1}^{n} \bar{h}_i R_{1i} + \sum_{j=0}^{m} (\bar{\tau} + \bar{h}_{2j}) R_{2j} \end{bmatrix} < 0; \end{aligned} \qquad (5)$$

$$\begin{bmatrix} R_{1i} & [0 \quad A_i^{\mathrm{T}}] P \\ * & Z_{1i} \end{bmatrix} \ge 0, \qquad (6a)$$

$$\begin{bmatrix} R_{2j} & [0 \quad K^{\mathrm{T}} B_j^{\mathrm{T}}] P \\ * & Z_{2j} \end{bmatrix} \ge 0. \qquad (6b)$$

其中

$$P = \begin{bmatrix} P_1 & 0 \\ P_2 & P_3 \end{bmatrix},$$

$$Z_{1i} = Z_{1i}^{\mathrm{T}} = \begin{bmatrix} Z_{1i1} & Z_{1i2} \\ Z_{1i2}^{\mathrm{T}} & Z_{1i3} \end{bmatrix},$$

$$Z_{2j} = Z_{2j}^{\mathrm{T}} = \begin{bmatrix} Z_{2j1} & Z_{2j2} \\ Z_{2j2}^{\mathrm{T}} & Z_{2j3} \end{bmatrix},$$

$$\bar{A} = \sum_{i=0}^{n} A_i + \Big(\sum_{j=0}^{m} B_j \Big) K,$$

“ * ”表示由矩阵对称性得到的矩阵块.

证明　将式(4)写成如下等价系统[8,9]的形式:

$$\begin{aligned} \dot{x}(t) &= y(t), \\ 0 &= -y(t) + \sum_{i=0}^{n} A_i x(t - h_{1i}) + \\ & \sum_{j=0}^{m} B_j Kx(t - \tau - h_{2j}). \end{aligned} \qquad (7)$$

取如下的 Lyapunov-Krasovskii 泛函:

$$V = V_1 + V_2 + V_3. \qquad (8)$$

其中

$$V_1 = S^{\mathrm{T}} EPS,$$

$$V_2 = \sum_{i=1}^{m}\int_{-\bar h_{1i}}^{0}\int_{t+\theta}^{t}\dot x^{\mathrm T}(s)R_{1i}\dot x(s)\,\mathrm{d}s\mathrm{d}\theta,$$

$$V_3 = \sum_{j=0}^{n}\int_{-\bar\tau-\bar h_{2j}}^{0}\int_{t+\theta}^{t}\dot x^{\mathrm T}(s)R_{2j}\dot x(s)\,\mathrm{d}s\mathrm{d}\theta,$$

$$S(t) = \begin{bmatrix} x(t)\\ y(t)\end{bmatrix},\quad E = \begin{bmatrix} I_n & 0\\ 0 & 0\end{bmatrix}. \tag{9}$$

由式(7) 及 Newton-Leibniz 公式得

$$\dot V_1 = S^{\mathrm T}\Delta S + \sum_{i=1}^{n}\phi_i + \sum_{j=0}^{m}\varphi_j. \tag{10}$$

其中

$$\Delta = P^{\mathrm T}\begin{bmatrix} 0 & I\\ \bar A & -I\end{bmatrix} + \begin{bmatrix} I & \bar A^{\mathrm T}\\ I & -I\end{bmatrix}P,$$

$$\phi_i = -2S^{\mathrm T}P^{\mathrm T}\begin{bmatrix} 0\\ A_i\end{bmatrix}\int_{t-h_{1i}}^{t}\dot x(\theta)\,\mathrm{d}\theta,$$

$$\varphi_j = -2S^{\mathrm T}P^{\mathrm T}\begin{bmatrix} 0\\ B_jK\end{bmatrix}\int_{t-\tau-h_{2j}}^{t}\dot x(\theta)\,\mathrm{d}\theta,$$

由引理 1 可得

$$\phi_i \le \bar h_{1i}S^{\mathrm T}Z_{1i}S + \int_{t-h_{1i}}^{t}\dot x^{\mathrm T}(\theta)R_{1i}\dot x(\theta)\,\mathrm{d}\theta,$$

$$\varphi_j \le (\bar\tau + \bar h_{2j})S^{\mathrm T}Z_{2j}S + \int_{t-\tau-h_{2j}}^{t}\dot x^{\mathrm T}(\theta)R_{2j}\dot x(\theta)\,\mathrm{d}\theta. \tag{11}$$

其中

$$\begin{bmatrix} R_{1i} & Y_{1i}\\ Y_{1i}^{\mathrm T} & Z_{1i}\end{bmatrix} \ge 0,\ Y_{1i} = [0\quad A_i^{\mathrm T}]P,$$

$$\begin{bmatrix} R_{2j} & Y_{2j}\\ Y_{2j}^{\mathrm T} & Z_{2j}\end{bmatrix} \ge 0,\ Y_{2j} = [0\quad K^{\mathrm T}B_j^{\mathrm T}]P.$$

由引理 2 得

$$\dot V_2 = \sum_{i=1}^{n}\Big(\bar h_{1i}\dot x^{\mathrm T}R_{1i}\dot x - \int_{t-\bar h_{1i}}^{t}\dot x^{\mathrm T}(\theta)R_{1i}\dot x(\theta)\,\mathrm{d}\theta\Big), \tag{12}$$

$$\dot V_3 = \sum_{j=0}^{m}(\bar\tau + \bar h_{2j})\dot x^{\mathrm T}R_{2j}\dot x - \int_{t-\bar\tau-\bar h_{2j}}^{t}\dot x^{\mathrm T}(\theta)R_{2j}\dot x(\theta)\,\mathrm{d}\theta. \tag{13}$$

由式(10) ～ (13) 可知 $\dot V \le S^{\mathrm T}\Omega S$，其中

$$\Omega = \Delta + \sum_{i=1}^{n}\bar h_i Z_{1i} + \sum_{j=0}^{m}(\bar\tau + \bar h_{2j})Z_{2j} + \begin{bmatrix} 0 & 0\\ 0 & \sum_{i=1}^{n}\bar h_i R_{1i} + \sum_{j=0}^{m}(\bar\tau + \bar h_{2j})R_{2j}\end{bmatrix}.$$

由此可见，如果 $\Omega < 0$ 且式(6) 成立，则 $\dot V < 0$，系统(4) 渐近稳定. □

注 1　若定理 1 中的 K 不是给定的，则不等式(5) 和(6) 是非线性的.

下面给出线性矩阵不等式形式的稳定判据，进而可用来设计静态反馈控制器.

定理 2　给定标量 $\bar\tau > 0$，如果存在 $\bar R_{1i} = \bar R_{1i}^{\mathrm T} > 0$，$\bar R_{2j} = \bar R_{2j}^{\mathrm T} > 0$，$Q_1 > 0$，$Q_2$，$Q_3$，$\tilde Z_{1i} = \tilde Z_{1i}^{\mathrm T}$，$\tilde Z_{2j} = \tilde Z_{2j}^{\mathrm T}$，$Y$ 满足下面的线性矩阵不等式:

$$\begin{bmatrix}
\Lambda & \bar h_{11}Q' & \cdots & \bar h_{1n}Q' & \bar h_{21}'Q' & \cdots & \bar h_{2m}'Q'\\
* & -\bar h_{11}\bar R_{11} & 0 & 0 & 0 & \cdots & 0\\
* & * & \ddots & 0 & 0 & \cdots & 0\\
* & * & \ddots & -\bar h_{1n}\bar R_{1n} & 0 & \cdots & 0\\
* & * & \ddots & * & -\bar h_{21}'\bar R_{21} & \ddots & \cdots\\
\cdots & \cdots & \ddots & \cdots & \ddots & \ddots & 0\\
* & * & \cdots & * & * & * & -\bar h_{2m}'\bar R_{2m}
\end{bmatrix} < 0, \tag{14}$$

$$\begin{bmatrix} Q_1 + Q_1^{\mathrm T} - \bar R_{1i} & 0 & Q_1^{\mathrm T}A_i\\ * & \tilde Z_{1i1} & \tilde Z_{1i2}\\ * & * & \tilde Z_{1i3}\end{bmatrix} \ge 0, \tag{15a}$$

$$\begin{bmatrix} Q_1 + Q_1^{\mathrm T} - \bar R_{2j} & 0 & Y^{\mathrm T}B_j\\ * & \tilde Z_{2j1} & \tilde Z_{2j2}\\ * & * & \tilde Z_{2j3}\end{bmatrix} \ge 0. \tag{15b}$$

其中

$$\Lambda = \begin{bmatrix} & Q_2 & & Q_3\\ \sum_{i=0}^{n}A_iQ_1 + \sum_{j=0}^{m}B_jY - Q_2 & & & -Q_3\end{bmatrix} + \begin{bmatrix} Q_2^{\mathrm T} & \Big(\sum_{i=0}^{n}A_iQ_1 + \sum_{j=0}^{m}B_jY\Big)^{\mathrm T} - Q_2^{\mathrm T}\\ Q_3^{\mathrm T} & -Q_3^{\mathrm T}\end{bmatrix} + \sum_{i=1}^{n}\bar h_{1i}\begin{bmatrix} \tilde Z_{1i1} & \tilde Z_{1i2}\\ * & \tilde Z_{1i3}\end{bmatrix} + \sum_{j=0}^{m}(\bar\tau + \bar h_{2j})\begin{bmatrix} \tilde Z_{2j1} & \tilde Z_{2j2}\\ * & \tilde Z_{2j3}\end{bmatrix},$$

$$Q' = [Q_2\quad Q_3]^{\mathrm T},\ \bar h_{2i}' = \bar\tau + \bar h_{2i},$$

$$\tilde Z_{1i} = \begin{bmatrix} \tilde Z_{1i1} & \tilde Z_{1i2}\\ * & \tilde Z_{1i3}\end{bmatrix},\ \tilde Z_{2j} = \begin{bmatrix} \tilde Z_{2j1} & \tilde Z_{2j2}\\ * & \tilde Z_{2j3}\end{bmatrix}.$$

则含被控对象(1) 且反馈增益为 $K = YQ_1^{-1}$ 的 NCS 对所有 $h + \tau_{sc} + \tau_{ca} + d(k)h \le \bar\tau$ 渐近稳定. 可保证上述 LMIs 有解的 $\bar\tau$ 的最大值为广义最大允许时延.

证明　定义

$$Q = P^{-1} = \begin{bmatrix} Q_1 & 0 \\ Q_2 & Q_3 \end{bmatrix},$$

$$\overline{R}_{1i} = R_{1i}^{-1},\ \overline{R}_{2j} = R_{2j}^{-1},$$

$$\widetilde{Z}_{1i} = Q^{\mathrm{T}} Z_{1i} Q = \begin{bmatrix} \widetilde{Z}_{1i1} & \widetilde{Z}_{1i2} \\ * & \widetilde{Z}_{1i3} \end{bmatrix},$$

$$\widetilde{Z}_{2j} = Q^{\mathrm{T}} Z_{2j} Q = \begin{bmatrix} \widetilde{Z}_{2j1} & \widetilde{Z}_{2j2} \\ * & \widetilde{Z}_{2j3} \end{bmatrix},$$

$$Y = KQ_1.$$

对式(5)左右两边分别乘以 Q^{T} 和 Q,得

$$\begin{bmatrix} Q_2 & Q_3 \\ \sum_{i=0}^{n} A_i Q_1 + \sum_{j=0}^{m} B_j Y - Q_2 & -Q_3 \end{bmatrix} + \begin{bmatrix} Q_2^{\mathrm{T}} & \Big(\sum_{i=0}^{n} A_i Q_1 + \sum_{j=0}^{m} B_j Y\Big)^{\mathrm{T}} - Q_2^{\mathrm{T}} \\ Q_3^{\mathrm{T}} & -Q_3^{\mathrm{T}} \end{bmatrix} +$$

$$\sum_{i=1}^{n} \overline{h}_i \widetilde{Z}_{1i} + \sum_{j=0}^{m} (\overline{\tau} + \overline{h}_{2j}) \widetilde{Z}_{2j} +$$

$$\begin{bmatrix} Q_2^{\mathrm{T}} \\ Q_3^{\mathrm{T}} \end{bmatrix} \Big(\sum_{i=1}^{n} \overline{h}_i R_{1i} + \sum_{j=0}^{m} ((\overline{\tau} + \overline{h}_{2j}) R_{2j}) (Q_2 \quad Q_3) \Big) < 0. \qquad (16)$$

由 Schur 补引理,式(16)等价于(14). 式(6)两边分别乘以 $\mathrm{diag}\{Q_1^{\mathrm{T}}, Q^{\mathrm{T}}\}$ 和 $\mathrm{diag}\{Q_1, Q\}$,得

$$\begin{bmatrix} Q_1^{\mathrm{T}} \overline{R}_{1i}^{-1} Q_1 & 0 & Q_1^{\mathrm{T}} A_i \\ * & \widetilde{Z}_{1i1} & \widetilde{Z}_{1i2} \\ * & * & \widetilde{Z}_{1i3} \end{bmatrix} \geq 0, \qquad (17a)$$

$$\begin{bmatrix} Q_1^{\mathrm{T}} \overline{R}_{2j}^{-1} Q_1 & 0 & Y^{\mathrm{T}} B_j \\ * & \widetilde{Z}_{2j1} & \widetilde{Z}_{2j2} \\ * & * & \widetilde{Z}_{2j3} \end{bmatrix} \geq 0. \qquad (17b)$$

因为 $\overline{R}_{1i}^{-1} > 0$,所以 $(Q_1 - \overline{R}_{1i})^{\mathrm{T}} \overline{R}_{1i}^{-1} (Q_1 - \overline{R}_{1i}) = Q_1^{\mathrm{T}} \overline{R}_{1i}^{-1} Q_1 - (Q_1 + Q_1^{\mathrm{T}} - \overline{R}_{1i}) > 0$. 由此可知

$$Q_1^{\mathrm{T}} \overline{R}_{1i}^{-1} Q_1 > Q_1 + Q_1^{\mathrm{T}} - \overline{R}_{1i}. \qquad (18a)$$

同理

$$Q_1^{\mathrm{T}} \overline{R}_{2j}^{-1} Q_1 > Q_1 + Q_1^{\mathrm{T}} - \overline{R}_{2j}. \qquad (18b)$$

可见式(15)是(17)的充分条件. □

注 2 如果时滞 h_{1i} 和 h_{2j} 是常数,则本文结果同样适用,只需将结论中的 $\overline{h}_{1i}, \overline{h}_{2j}$ 替换为 h_{1i}, h_{2j} 即可.

注 3 本文结论不需知道时滞的导数,因而可处理时滞导数未知的情况. 本文结论也无需限制时变时滞属于慢时变时滞.

4 数值仿真

取如下含状态和输入时滞的被控对象:

$$\dot{x}(t) = Ax(t) + A_1 x(t - h_1) + Bu(t) + B_1 u(t - h_2).$$

令

$$A = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix},\ A_1 = \begin{bmatrix} -1 & -1 \\ 0 & -0.9 \end{bmatrix},$$

$$B = \begin{bmatrix} 1 \\ 1 \end{bmatrix},\ B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$0 \leq h_1,\ h_2 \leq 0.5,$$

则 NCS 可表示为

$$\dot{x}(t) = Ax(t) + A_1 x(t - h_1) + Bu(t - \tau) + B_1 u(t - \tau - h_2),\ t \in [t_k, t_{k+1}),$$

其中 $\tau(t) = t - t_k + \tau_{ca} + \tau_{sc} + d(k)h$. 解

$$\begin{cases} \text{minimize } 1/\overline{\tau}, \\ \text{subject to 式(14) 和(15)}, \end{cases}$$

得广义最大允许时延为 0.42. 当 $\tau(t) = 0.42$, $K = (0.093\,4, -0.292\,2)$ 时,状态响应如图 2 所示.

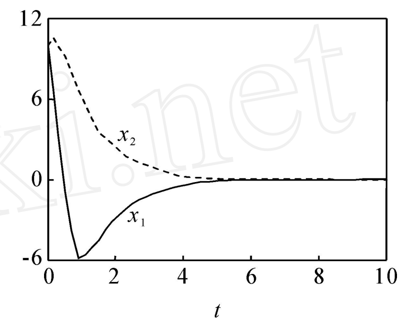

图 2 网络控制系统状态响应

5 结 语

本文研究了一类被控对象含状态和输入时滞的网络控制系统的镇定问题. 利用 Lyapunov-Krasovskii 泛函方法,求出了系统可稳定的充分条件,并转换为线性矩阵不等式的形式. 该方法与采用 Razumkhin 方法相比,减小了保守性,适用于时滞导数大于 1 或时滞导数未知的情况.

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