

具有双通道数据包丢失的 Delta 算子系统故障检测

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摘要

研究同时存在双通道数据包丢失和时变时延的 Delta 算子网络控制系统(NCSs)故障检测问题. 假定数据包丢失发生在控制器到执行器、传感器至控制器的数据传输过程中, 并且利用两个相互独立的伯努利随机变量描述是否发生丢包. 将上述的 NCSs 建模为网络切换系统, 提出任意切换律下故障检测滤波器的设计方法. 利用线性矩阵不等式(LMIs)方法、Lyapunov-Krasovskii 泛函和平均驻留时间等得出所考虑的网络切换系统具备指数均方稳定性的充分条件. 证明了所用的网络切换系统满足 H_∞ 性能, 并推导出了滤波器参数的显式表达. 数值仿真结果验证了所提方法的有效性.

关键词

网络控制系统
故障检测
数据包丢失
时变时延
Delta 算子
中图法分类号: TP273
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Fault Detection for Delta Operator Systems with Two-channel Packet Losses

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Abstract

The problem of fault detection for delta operators networked control systems (NCSs) with two-channel packet losses and time-varying delays is investigated. Here, it is assumed that packet losses occur during data transfer from controller-to-actuator and sensor-to-controller and that two independent Bernoulli random variables are used to indicate whether packet loss has occurred. The above NCSs are modeled as networked switched systems, and the design method of fault detection filter under an arbitrary switching law is given. The sufficient conditions of the exponential mean-square stability of the considered networked switched system are obtained using linear matrix inequalities (LMIs) approach, Lyapunov-Krasovskii functional, and average dwell time. It is proved that the system satisfies the H_∞ performance. The explicit expression of the desired filter parameters is derived. A numerical example is presented to verify the effectiveness of the proposed method.

Keywords

networked control systems (NCSs);
fault detection;
packet losses;
time-varying delays;
Delta operator

0 引言

网络控制系统(NCSs)是将传感器、控制器和执行器通过一个共用的通信网络连接起来的反馈控制系统^[1]. 相较于传统的点对点控制系统, NCSs 具备信息资源共享、布线简单、成本低等优点, 从而引起人们广泛关注^[2-4]. 由于 NCSs 中引入了通信网络, 数据传输的过程中不可避免出现一些新的问题, 如数据包丢失、时延、通信受限等^[5-6]. 这些缺陷使得 NCSs 的参数乃至整个系统的结构瞬间发生改变, 进而展现出不同时间或空间上的多模态特性, 这种特性无法使用单一模态的传统连续时间或离散时间系统模

型进行描述. 然而, 使用任意时间切换的切换系统^[7]模型可以很好地解决上述问题. 因此, 使用切换系统理论对 NCSs 进行分析研究是十分必要的^[8].

此外, NCSs 的故障检测研究也取得了一些新的进展. 文[9]探讨了通信受限和丢包下不确定 Delta 算子离散系统故障检测问题, 其系统模型为单一模态的离散模型, 且丢包为单通道丢包; 文[10]讨论了网络切换系统存在时变时延和丢包的故障检测和控制协同设计问题, 但所得故障检测滤波器的参数没有显式表示; 文[11]给出了连续丢包情形下正切换系统的故障检测问题, 其丢包仅发生在传感器至滤波器的数据传输过程中, 且没有考虑时延对系统

的影响, 其离散系统模型为移位算子模型; 文[12]则采用神经网络预测控制器对系统输出进行预测, 从而补偿丢包对系统的影响, 并给出 NCSs 故障判定的准则.

另一方面, 在高速采样时移位算子离散化方法得到的系统模型与之前的连续系统存在一定差距, 且采样后系统极点位于稳定环的边界, 使得离散化后的系统趋向不稳定. 然而, Delta 算子可以很好地解决这些困扰, 而且系统的采样周期出现在离散化后的系统模型中, 便于观察采样周期对系统性能的影响^[13]. 将 Delta 算子、NCSs 和切换系统分析方法三者结合起来研究一个系统的成果尚不多见. 文[14]仅仅考虑了时变时延对系统建模的影响, 文[15]则进一步考虑了系统中存在时延和参数不确定性时, 如何设计故障检测滤波器和分析系统鲁棒稳定性的问题. 关于多约束条件下的 Delta 算子网络切换系统故障检测的研究目前尚处于起步阶段.

本文研究同时存在双通道丢包和时变时延的 Delta 算子网络切换系统的故障检测问题, 给出任意切换律下故障检测滤波器的参数表示, 将故障检测滤波器作为残差生成器, 使得残差和故障之间的差值尽可能小; 借助 LMIs 给出系统指数均方稳定的充分条件, 并得到了最小的扰动抑制水平 γ . 数值仿真结果验证了所提方法的有效性.

1 问题描述

Delta 算子定义^[13]如下:

$$\delta \mathbf{x}(t) = \begin{cases} \frac{d\mathbf{x}(t)}{dt}, & h=0 \\ \frac{\mathbf{x}(t+h) - \mathbf{x}(t)}{h}, & h \neq 0 \end{cases}$$

其中, h 代表采样周期.

考虑下面带有时变时延的 Delta 算子网络切换系统^[16]:

$$\delta \mathbf{x}(k) = \mathbf{A}_{\sigma(k)} \mathbf{x}(k) + \mathbf{A}_{\tau\sigma(k)} \mathbf{x}(k - \tau(k)) + \mathbf{B}_{\sigma(k)} \mathbf{u}(k) + \mathbf{D}_{\sigma(k)} \mathbf{d}(k) + \mathbf{F}_{\sigma(k)} \mathbf{f}(k) \quad (1)$$

其中, $\mathbf{x}(k) \in \mathbb{R}^n$ 代表系统的状态向量; $\tau(k)$ 是时变时延且是正整数, 满足 $\tau_m \leq \tau(k) \leq \tau_M$, τ_m 、 τ_M 分别是时延的下界和上界; $\mathbf{u}(k) \in \mathbb{R}^p$ 为控制输入; $\mathbf{d}(k) \in \mathbb{R}^q$ 是已知的干扰信号, 且满足 $l_2[0, +\infty)$; $\mathbf{f}(k) \in \mathbb{R}^m$ 是待检测的故障信号, 可为过程故障或执行器故障^[17]; $\sigma(k) \rightarrow \mathbb{N} = \{1, 2, 3, \dots, n\}$ 代表切换信号. 系统的初始时刻记为 k_0 , 令 k_1, k_2, \dots, k_v 表示系统在间隔 $[k_0, k)$ 内的切换点, 且 $k_0 < k_1 < \dots < k_v < k$, $v \geq 1$. 当 $\sigma(k) = i \in \mathbb{N}$ 时, 表示第 i 个子系统被激活, 在子系统 i 上停留的时间称为驻留时间; $\mathbf{A}_i, \mathbf{A}_{\tau i}, \mathbf{B}_i, \mathbf{D}_i, \mathbf{F}_i$ 是具有适当维数的矩阵.

传感器至控制器的数据传输可表示为

$$\hat{\mathbf{y}}(k) = \boldsymbol{\alpha}(k) \mathbf{C}_i \mathbf{x}(k) + \mathbf{E}_i \mathbf{d}(k) \quad (2)$$

其中, $\hat{\mathbf{y}}(k) \in \mathbb{R}^l$ 表示测量输出, \mathbf{C}_i 和 \mathbf{E}_i 是已知的常数矩阵, 随机变量 $\boldsymbol{\alpha}(k)$ 满足:

$$\begin{cases} \text{Prob}\{\boldsymbol{\alpha}(k) = 1\} = \bar{\alpha} \\ \text{Prob}\{\boldsymbol{\alpha}(k) = 0\} = 1 - \bar{\alpha} \\ \text{var}\{\boldsymbol{\alpha}(k)\} = E\{(\boldsymbol{\alpha}(k) - \bar{\alpha})^2\} = \sigma_1^2 \end{cases} \quad (3)$$

这里, $\boldsymbol{\alpha}(k) = 1$ 代表传感器至控制器的数据传输正常,

$\boldsymbol{\alpha}(k) = 0$ 则表示数据包丢失; $\text{Prob}\{\cdot\}$ 表示概率; $\text{var}\{\cdot\}$ 表示方差; $E\{\cdot\}$ 表示数学期望.

设计如下基于观测器的故障检测滤波器^[10]:

$$\begin{cases} \delta \hat{\mathbf{x}}(k) = \mathbf{A}_i \hat{\mathbf{x}}(k) + \mathbf{A}_{\tau i} \hat{\mathbf{x}}(k - \tau(k)) + \mathbf{B}_i \bar{\mathbf{u}}(k) + \mathbf{L}_i (\hat{\mathbf{y}}(k) - \bar{\boldsymbol{\alpha}} \mathbf{C}_i \hat{\mathbf{x}}(k)) \\ \bar{\mathbf{u}}(k) = \bar{\boldsymbol{\beta}} \hat{\mathbf{u}}(k) \\ \mathbf{r}(k) = \mathbf{V}_i (\hat{\mathbf{y}}(k) - \bar{\boldsymbol{\alpha}} \mathbf{C}_i \hat{\mathbf{x}}(k)) \end{cases} \quad (4)$$

$$\begin{cases} \hat{\mathbf{u}}(k) = \mathbf{K}_i \hat{\mathbf{x}}(k) \\ \mathbf{u}(k) = \boldsymbol{\beta}(k) \hat{\mathbf{u}}(k) \end{cases} \quad (5)$$

式中: $\hat{\mathbf{x}}(k) \in \mathbb{R}^n$ 是状态估计向量; $\bar{\mathbf{u}}(k) \in \mathbb{R}^p$ 是观测器的控制输入; $\hat{\mathbf{u}}(k) \in \mathbb{R}^p$ 代表没有数据包丢失时观测器的控制输入; $\mathbf{r}(k) \in \mathbb{R}^m$ 是产生的残差信号; $\mathbf{K}_i \in \mathbb{R}^{p \times n}$ 是控制器增益矩阵, $\mathbf{L}_i \in \mathbb{R}^{n \times l}$ 是滤波器增益矩阵, $\mathbf{V}_i \in \mathbb{R}^{m \times l}$ 是残差发生器增益矩阵, 随机变量 $\boldsymbol{\beta}(k)$ 表示从控制器到执行器的数据包丢失信息, 且满足:

$$\begin{cases} \text{Prob}\{\boldsymbol{\beta}(k) = 1\} = \bar{\boldsymbol{\beta}} \\ \text{Prob}\{\boldsymbol{\beta}(k) = 0\} = 1 - \bar{\boldsymbol{\beta}} \\ \text{var}\{\boldsymbol{\beta}(k)\} = E\{(\boldsymbol{\beta}(k) - \bar{\boldsymbol{\beta}})^2\} = \sigma_2^2 \end{cases} \quad (6)$$

这里, $\boldsymbol{\beta}(k) = 1$ 代表控制器到执行器的数据传输成功, 而 $\boldsymbol{\beta}(k) = 0$ 则表示数据丢失. 式(2)中的 $\boldsymbol{\alpha}(k)$ 和式(6)中的 $\boldsymbol{\beta}(k)$ 是相互独立的伯努利白噪声序列. 令:

$$\begin{cases} \mathbf{e}(k) = \mathbf{x}(k) - \hat{\mathbf{x}}(k) \\ \tilde{\mathbf{r}}(k) = \mathbf{r}(k) - \mathbf{f}(k) \end{cases} \quad (7)$$

其中, $\mathbf{e}(k)$ 代表状态估计误差, $\tilde{\mathbf{r}}(k)$ 表示残差误差. 为了检测系统是否发生故障, 选择如下的评价函数和阈值:

$$J(\tilde{\mathbf{r}}) = \tilde{\mathbf{r}}(k)_{2, M} = \left[\sum_{k_0}^M \tilde{\mathbf{r}}^T(k) \tilde{\mathbf{r}}(k) \right]^{1/2}$$

$$J_{th} = \sup_{w \in l_2, f=0} \tilde{\mathbf{r}}(k)_{2, M} = \left[\sum_{k_0}^M \tilde{\mathbf{r}}^T(k) \tilde{\mathbf{r}}(k) \right]^{1/2}$$

式中, M 是仿真步长, T 为转置运算, 根据下面评价标准判断是否发生故障: 当 $J(\tilde{\mathbf{r}}) > J_{th}$, 发生故障; 而 $J(\tilde{\mathbf{r}}) \leq J_{th}$ 则表示系统正常, 未发生故障. 记:

$$\begin{aligned} \boldsymbol{\varphi}(k) &= \begin{bmatrix} \mathbf{x}(k) \\ \mathbf{e}(k) \end{bmatrix} \\ \boldsymbol{\omega}(k) &= \begin{bmatrix} \mathbf{d}(k) \\ \mathbf{f}(k) \end{bmatrix} \end{aligned}$$

则可以得到如下 Delta 算子网络切换系统的表达式:

$$\begin{cases} \delta \boldsymbol{\varphi}(k) = \bar{\mathbf{A}}_i \boldsymbol{\varphi}(k) + \bar{\mathbf{A}}_{\tau i} \boldsymbol{\varphi}(k - \tau(k)) + \bar{\mathbf{B}}_{1i} \boldsymbol{\omega}(k) + (\boldsymbol{\alpha}(k) - \bar{\boldsymbol{\alpha}}) \bar{\mathbf{A}}_{1i} \boldsymbol{\varphi}(k) + (\boldsymbol{\beta}(k) - \bar{\boldsymbol{\beta}}) \bar{\mathbf{A}}_{2i} \boldsymbol{\varphi}(k) \\ \tilde{\mathbf{r}}(k) = \bar{\mathbf{C}}_i \boldsymbol{\varphi}(k) + (\boldsymbol{\alpha}(k) - \bar{\boldsymbol{\alpha}}) \bar{\mathbf{C}}_{1i} \boldsymbol{\varphi}(k) + \bar{\mathbf{B}}_{2i} \boldsymbol{\omega}(k) \end{cases} \quad (8)$$

式中,

$$\bar{\mathbf{A}}_i = \begin{bmatrix} \mathbf{A}_i + \bar{\boldsymbol{\beta}} \mathbf{B}_i \mathbf{K}_i & -\bar{\boldsymbol{\beta}} \mathbf{B}_i \mathbf{K}_i \\ 0 & \mathbf{A}_i - \bar{\boldsymbol{\alpha}} \mathbf{L}_i \mathbf{C}_i \end{bmatrix}, \bar{\mathbf{A}}_{\tau i} = \begin{bmatrix} \mathbf{A}_{\tau i} & 0 \\ 0 & \mathbf{A}_{\tau i} \end{bmatrix}$$

$$\bar{\mathbf{B}}_{1i} = \begin{bmatrix} \mathbf{D}_i & \mathbf{F}_i \\ \mathbf{D}_i - \mathbf{L}_i \mathbf{E}_i & \mathbf{F}_i \end{bmatrix}, \bar{\mathbf{A}}_{1i} = \begin{bmatrix} 0 & 0 \\ -\mathbf{L}_i \mathbf{C}_i & 0 \end{bmatrix}$$

$$\bar{\mathbf{A}}_{2i} = \begin{bmatrix} \mathbf{B}_i \mathbf{K}_i & -\mathbf{B}_i \mathbf{K}_i \\ \mathbf{B}_i \mathbf{K}_i & -\mathbf{B}_i \mathbf{K}_i \end{bmatrix}, \bar{\mathbf{C}}_i = [0 \quad \bar{\boldsymbol{\alpha}} \mathbf{V}_i \mathbf{C}_i]$$

$$\bar{\mathbf{C}}_{1i} = [\mathbf{V}_i \mathbf{C}_i \quad 0], \bar{\mathbf{B}}_{2i} = [\mathbf{V}_i \mathbf{E}_i \quad -\mathbf{I}]$$

I 为单位矩阵.

定义 1^[18] 给定标量 $0 < \lambda < 1$, 零初始条件下, 对非零的 $\omega(k) \in l_2[0, \infty)$, 如果系统(8)是指数均方稳定的且满足:

$$E \left\{ \sum_{s=k_0}^{\infty} (1-\lambda)^s \tilde{r}^T(s) \tilde{r}(s) \right\} \leq E \left\{ \sum_{s=k_0}^{\infty} \gamma^2 \omega^T(s) \omega(s) \right\} \quad (9)$$

则网络化切换时延系统(8)是指数均方稳定的, 并且具有 H_{∞} 性能 γ .

定义 2^[18] 如果存在标量 $\theta > 0$ 和 $0 < \chi < 1$, 当 $\omega(k) = 0$ 时, $E \left\{ \left\| \int \varphi(k) \right\|^2 \right\} < \theta \chi^{(k-k_0)} E \left\{ \left\| \int \phi_l \right\|^2 \right\}$, $k \geq k_0$, 则离散切换时延系统(8)在切换信号 $\sigma(\tau)$ 作用下是指数均方稳定的, 其中, $\left\| \int \phi_l \right\| = \sup_{k_0-h_M < \theta < k_0} \left\| \int \phi_{\theta} \right\|$, χ 称为衰减率.

定义 3^[19] 对于任意 $k \geq k_0$, 给定切换信号 $\sigma(\tau)$, $k_0 \leq \tau \leq k$, 令 N_{σ} 表示切换信号 $\sigma(\tau)$ 在 $[k_0, k]$ 上的切换次数. 给定 $N_0 \geq 0$ 和 $T_a > 0$, 则 $N_{\sigma}(k_0, k) \leq N_0 + \frac{k-k_0}{T_a}$, T_a 和 N_0 分别表示平均驻留时间和抖动界.

不失一般性, 本文假设 $N_0 = 0$.

2 主要结果

本节给出了系统(8)是指数均方稳定的, 且具有 H_{∞} 性能 γ 的充分条件. 定理 1 和定理 2 证明了系统(8)是指数均方稳定的, 且具有 H_{∞} 性能 γ . 定理 3 则基于定理 2 给出了所设计故障检测滤波器中 K_i 和 L_i 的表达式.

定理 1 给定标量 $0 < \lambda < 1$, $\mu > 1$, 任意带有平均驻留时间的切换信号 $\sigma(k)$ 满足 $T_a > T_a^* = (-\ln \mu) / \ln(1-\lambda)$, 如果存在正定矩阵 P_i 、 Q_i 、 R_{1i} 、 R_{2i} , $i = 1, 2, \dots, n$, 对于任意的 $i, j \in \mathbb{N}$, 使得式(10)、(11)成立, 则闭环网络切换系统(8)是指数均方稳定的, 且满足 H_{∞} 性能指标 γ .

$$\begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ * & \Sigma_{22} \end{bmatrix} < 0 \quad (10)$$

$$\begin{cases} P_i \leq \mu P_j \\ Q_i \leq \mu Q_j \\ R_{1i} \leq \mu R_{1j} \\ R_{2i} \leq \mu R_{2j} \end{cases} \quad (11)$$

式中:

$$\Sigma_{11} = \text{diag} \left\{ -\frac{1}{h}(1-\lambda)P_i + \frac{1}{h}(\tau_M - \tau_m + 1)Q_i + \frac{1}{h}R_{1i} + \right.$$

$$\left. \frac{1}{h}R_{2i}, -\frac{1}{h}(1-\lambda)^{\tau_m}R_{1i}, -\frac{1}{h}(1-\lambda)^{\tau_m}Q_i, \right.$$

$$\left. -\frac{1}{h}(1-\lambda)^{\tau_M}R_{2i}, -\frac{1}{h}\gamma^2 I \right\}$$

$$\Sigma_{12} = \begin{bmatrix} \bar{\Sigma}_{11} & \sqrt{h}\sigma_1 \bar{A}_{1i}^T & \sqrt{h}\sigma_2 \bar{A}_{2i}^T & \sqrt{\frac{1}{h}}\sigma_1 \bar{C}_i^T & \sqrt{\frac{1}{h}}\sigma_1 \bar{C}_{1i}^T \\ 0 & 0 & 0 & 0 & 0 \\ \sqrt{h}\bar{A}_{\tau i}^T & 0 & 0 & 0 & 0 \\ \sqrt{h}\bar{B}_{1i}^T & 0 & 0 & \sqrt{\frac{1}{h}}\bar{B}_{2i}^T & 0 \end{bmatrix}$$

$$\bar{\Sigma}_{11} = \sqrt{\frac{1}{h}}(h\bar{A} + I)^T$$

$$\Sigma_{22} = \text{diag} \{-P_i^{-1}, -P_i^{-1}, -P_i^{-1}, -I, -I\}$$

证明 对于第 i 个子系统, 定义如下的李亚普诺夫函数:

$$V_i(k) = V_{1i}(k) + V_{2i}(k) + V_{3i}(k)$$

其中:

$$V_{1i}(k) = \varphi^T(k) P_i \varphi(k)$$

$$V_{2i}(k) = \sum_{s=k-\tau_m}^{k-1} (1-\lambda)^{k-s-1} \varphi^T(s) R_{1i} \varphi(s) + \sum_{s=k-\tau(k)}^{k-1} (1-\lambda)^{k-s-1} \cdot$$

$$\varphi^T(s) Q_i \varphi(s) + \sum_{s=k-\tau_M}^{k-1} (1-\lambda)^{k-s-1} \varphi^T(s) R_{2i} \varphi(s)$$

$$V_{3i}(k) = \sum_{j=k-\tau_M+1}^{k-\tau_m} \sum_{s=j}^{k-1} (1-\lambda)^{k-s-1} \varphi^T(s) Q_i \varphi(s)$$

根据文[18]中的方法, 则有:

$$E \{ h \delta V_i(k) + \lambda V_i(k) + \tilde{r}^T(k) \tilde{r}(k) - \gamma^2 \omega^T(k) \omega(k) \} \leq h \xi^T(k) \Phi \xi(k)$$

其中:

$$\xi^T(k) = [\varphi^T(k) \quad \varphi^T(k-\tau_m) \quad \varphi^T(k-\tau(k)) \quad \varphi^T(k-\tau_M) \quad \omega^T(k)]$$

$$\Phi = \begin{bmatrix} \Phi_{11} & 0 & (h\bar{A}_i + I)^T P_i \bar{A}_{\tau i} & 0 & \Phi_{15} \\ * & \Phi_{22} & 0 & 0 & 0 \\ * & * & \frac{1}{h} \Phi_{33} & 0 & h\bar{A}_{\tau i}^T P_i \bar{B}_{1i} \\ * & * & * & \Phi_{44} & 0 \\ * & * & * & * & \Phi_{55} \end{bmatrix} \quad (12)$$

$$\Phi_{11} = \frac{1}{h}(h\bar{A}_i + I)^T P_i (h\bar{A}_i + I) + h\sigma_1^2 \bar{A}_{1i}^T P_i \bar{A}_{1i} +$$

$$h\sigma_2^2 \bar{A}_{2i}^T P_i \bar{A}_{2i} - \frac{1}{h}(1-\lambda)P_i + \frac{1}{h}(\tau_M - \tau_m + 1)Q_i +$$

$$\frac{1}{h}R_{1i} + \frac{1}{h}R_{2i} + \frac{1}{h}\bar{C}_i^T \bar{C}_i + \frac{1}{h}\sigma_1^2 \bar{C}_{1i}^T \bar{C}_{1i}$$

$$\Phi_{15} = \frac{1}{h}\bar{C}_i^T \bar{B}_{2i} + (h\bar{A}_i + I)^T P_i B_{1i}$$

$$\Phi_{22} = -\frac{1}{h}(1-\lambda)^{\tau_m} R_{1i}$$

$$\Phi_{33} = -(1-\lambda)^{\tau_m} Q_i + h\bar{A}_{\tau i}^T P_i \bar{A}_{\tau i}$$

$$\Phi_{44} = -\frac{1}{h}(1-\lambda)^{\tau_M} R_{2i}$$

$$\Phi_{55} = h\bar{B}_{1i}^T P_i \bar{B}_{1i} + \frac{1}{h}\bar{B}_{2i}^T \bar{B}_{2i} - \frac{1}{h}\gamma^2 I$$

根据式(10), 由 Schur 补引理^[20]知:

$$\Sigma_{11} - \Sigma_{12} \Sigma_{22}^{-1} \Sigma_{12}^T = \Phi < 0$$

所以有:

$$E \{ V_i(k+1) - V_i(k) + \lambda V_i(k) + \tilde{r}^T(k) \tilde{r}(k) - \gamma^2 \omega^T(k) \omega(k) \} < 0 \quad (13)$$

令 $\omega(k) = 0$, 由式(10)可知:

$$E \left\{ \delta V_i(k) + \frac{1}{h} \lambda V_i(k) \right\} < 0$$

则有:

$$E \{ V_{\sigma(k)}(k) \} \leq (1-\lambda)^{k-k_l} V_{\sigma(k)}(k_l) \quad (14)$$

根据式(11)和式(13)可得到:

$$\begin{aligned}
 E\{V_{\sigma(k)}(k)\} &\leq (1-\lambda)^{k-k_l} V_{\sigma(k)}(k_l) \\
 &\leq (1-\lambda)^{k-k_l} \mu \cdot V_{\sigma(k_l-1)}(k_l) \\
 &\leq \mu(1-\lambda)^{k-k_l} (1-\lambda)^{k-k_l-1} V_{\sigma(k_l-1)}(k_l-1) \\
 &\leq \dots \\
 &\leq (1-\lambda)^{(k-k_0)} \mu^{(k-k_0)/T_a} V_{\sigma(k_0)}(k_0) \\
 &= ((1-\lambda)\mu^{1/T_a})^{(k-k_0)} V_{\sigma(k_0)}(k_0)
 \end{aligned}$$

记:

$$\begin{aligned}
 \kappa_1 &= \frac{1}{h} \min_{\Psi_i \in N} \lambda_{\min}(P_i) \\
 \kappa_2 &= \frac{1}{h} \max_{\Psi_i \in N} \lambda_{\max}(P_i) + \frac{1}{h} \max_{\Psi_i \in N} \lambda_{\max}(R_{1i}) + \\
 &\quad \frac{1}{h} (\tau_M - \tau_m + 1) \max_{\Psi_i \in N} \lambda_{\max}(Q_i) + \frac{1}{h} \max_{\Psi_i \in N} \lambda_{\max}(R_{2i})
 \end{aligned}$$

经过简单计算, 可以得到:

$$\begin{aligned}
 \kappa_1 E\left\{\int \varphi(k) \int \varphi(k)\right\} &\leq E\{V_{\sigma(k)}(k)\} \\
 &\leq ((1-\lambda)\mu^{1/T_a})^{k-k_0} \cdot V_{\sigma(k_0)}(k_0) \\
 &\leq ((1-\lambda)\mu^{1/T_a})^{k-k_0} \kappa_2 E\left\{\int \varphi \int \varphi\right\}
 \end{aligned}$$

即: $E\left\{\int \varphi(k) \int \varphi(k)\right\} \leq \frac{\kappa_2}{\kappa_1} \chi^{k-k_0} E\left\{\int \varphi \int \varphi\right\}, \chi = (1-\lambda)\mu^{1/T_a}.$

由 $T_a > \bar{T}_a = \frac{-\ln \mu}{\ln(1-\lambda)}$, 因此有 $\chi < 1$, χ 称为衰减率.

从而根据定义 2 可知系统(8)是指数均方稳定的.

当 $\omega(k) \neq 0$, 需要考虑系统(8)的 H_∞ 性能. 令:

$$\begin{aligned}
 \Gamma(k) &= -\tilde{r}^T(k) \tilde{r}(k) + \gamma^2 \omega^T(k) \omega(k) \\
 \Delta V(k)_i &= V_i(k+1) - V_i(k)
 \end{aligned}$$

式(13)可写作:

$$E\{\Delta V(k)_i + \lambda V_i(k) - \Gamma(k)\} < 0 \quad (15)$$

应用递推关系可得:

$$\begin{aligned}
 E\{V_i(k)\} &< (1-\lambda)^{k-k_0} V_i(k_0) + E\left\{\sum_{s=k_0}^{k-1} (1-\lambda)^{k-s-1} \Gamma(s)\right\} \quad (16)
 \end{aligned}$$

为了建立系统(8)的 H_∞ 性能指标, 选择如下的指数函数:

$$J_N = E\left\{\sum_{s=k_0}^{\infty} (1-\lambda)^s \tilde{r}^T(s) \tilde{r}(s) - \gamma^2 \omega^T(s) \omega(s)\right\} \quad (17)$$

根据式(11)、(14)、(16)和文[8]可得:

$$\begin{aligned}
 E\{V_{\sigma(k)}(k)\} &< (1-\lambda)^{k-k_l} V_{\sigma(k)}(k_l) + E\left\{\sum_{s=k_l}^{k-1} (1-\lambda)^{k-s-1} \Gamma(s)\right\} \\
 &\leq \dots \\
 &\leq (1-\lambda)^{k-k_0} \mu^{N(k_0, k)} V_{\sigma(k_0)}(k_0) + \\
 &\quad E\left\{\sum_{s=k_0}^{k-1} \mu^{N(s, k)} (1-\lambda)^{k-s-1} \Gamma(s)\right\} \quad (18)
 \end{aligned}$$

在零初始条件下有:

$$E\left\{\sum_{s=k_0}^{k-1} \mu^{N(s, k)} (1-\lambda)^{k-s-1} \Gamma(s)\right\} \geq 0 \quad (19)$$

即:

$$\begin{aligned}
 &\mu^{-N_{\sigma(0, k)}} E\left\{\sum_{s=k_0}^{k-1} \mu^{N_{\sigma(s, k)}} (1-\lambda)^{k-s-1} \tilde{r}^T(s) \tilde{r}(s)\right\} \\
 &\leq \mu^{-N_{\sigma(0, k)}} E\left\{\sum_{s=k_0}^{k-1} \mu^{N_{\sigma(s, k)}} (1-\lambda)^{k-s-1} \gamma^2 \omega^T(s) \omega(s)\right\} \quad (20)
 \end{aligned}$$

进一步计算可得:

$$\begin{aligned}
 &E\left\{\sum_{s=k_0}^{k-1} \mu^{-N_{\sigma(0, s)}} (1-\lambda)^{k-s-1} \tilde{r}^T(s) \tilde{r}(s)\right\} \\
 &\leq E\left\{\sum_{s=k_0}^{k-1} \mu^{-N_{\sigma(0, s)}} (1-\lambda)^{k-s-1} \omega^T(s) \omega(s)\right\} \quad (21)
 \end{aligned}$$

由定义 3 可知: $N_{\sigma}(0, s) \leq \frac{s}{T_a} \leq \frac{-s \ln(1-\lambda)}{\ln \mu}$, 式

(21)可转化为

$$\begin{aligned}
 &E\left\{\sum_{s=k_0}^{k-1} \mu^{\frac{s \ln(1-\lambda)}{\ln \mu}} (1-\lambda)^{k-s-1} \tilde{r}^T(s) \tilde{r}(s)\right\} \\
 &\leq E\left\{\sum_{s=k_0}^{k-1} \mu^{-N_{\sigma(0, s)}} (1-\lambda)^{k-s-1} \tilde{r}^T(s) \tilde{r}(s)\right\} \\
 &\leq E\left\{\sum_{s=k_0}^{k-1} \mu^{-N_{\sigma(0, s)}} (1-\lambda)^{k-s-1} \tilde{r}^T(s) \tilde{r}(s)\right\} \quad (22)
 \end{aligned}$$

令 $k \rightarrow \infty$, 有 $J_N \leq 0$. 由定义(1)知中系统(8)具有 H_∞ 性能.

定理 2 给定标量 $0 < \bar{\alpha} < 1, 0 < \bar{\beta} < 1, 0 < \lambda < 1$ 和 $\mu > 1$, 如果存在正定矩阵 $P_i, Q_i, R_{1i}, R_{2i}, i=1, 2, \dots, n$, 矩阵 X_i, K_i, L_i, V_i , 使得式(23)成立, 则闭环网络切换系统(8)是指数均方稳定的, 且满足 H_∞ 性能 γ .

$$\left[\begin{array}{cccccc}
 \Omega_{11} & 0 & 0 & 0 & 0 & \sqrt{\frac{1}{h}}(h\bar{A}_i + I)^T X_i & \sqrt{h}\sigma_1 \bar{A}_{1i}^T X_i & \sqrt{h}\sigma_2 \bar{A}_{2i}^T X_i & \sqrt{\frac{1}{h}} \bar{C}_i^T & \sqrt{\frac{1}{h}} \sigma_1 \bar{C}_{1i}^T \\
 * & \Omega_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 * & * & \Omega_{33} & 0 & 0 & \sqrt{h} \bar{A}_{\pi i}^T X_i & 0 & 0 & 0 & 0 \\
 * & * & * & \Omega_{44} & 0 & 0 & 0 & 0 & 0 & 0 \\
 * & * & * & * & -\frac{1}{h} \gamma^2 I & \sqrt{h} \bar{B}_{1i}^T X_i & 0 & 0 & \sqrt{\frac{1}{h}} \bar{B}_{2i}^T & 0 \\
 * & * & * & * & * & \Omega_{66} & 0 & 0 & 0 & 0 \\
 * & * & * & * & * & * & \Omega_{77} & 0 & 0 & 0 \\
 * & * & * & * & * & * & * & \Omega_{88} & 0 & 0 \\
 * & * & * & * & * & * & * & * & -I & 0 \\
 * & * & * & * & * & * & * & * & * & -I
 \end{array} \right] < 0 \quad (23)$$

式中:

$$\begin{aligned} \Omega_{11} &= -\frac{1}{h}(1-\lambda)P_i + \frac{1}{h}(\tau_m - \tau_m + 1)Q_i + \frac{1}{h}R_{1i} + \frac{1}{h}R_{2i} \\ \Omega_{22} &= -\frac{1}{h}(1-\lambda)^{\tau_m}R_{1i}, \quad \Omega_{33} = -\frac{1}{h}(1-\lambda)^{\tau_m}Q_i \\ \Omega_{44} &= -\frac{1}{h}(1-\lambda)^{\tau_m}R_{2i} \end{aligned}$$

$$\Omega_{66} = \Omega_{77} = \Omega_{88} = P_i - (X_i + X_i^T)$$

证明 由式(23)可知: $P_i - (X_i + X_i^T) < 0$, 则有: $(P_i - X_i^T)P_i^{-1}(P_i - X_i) > 0$, 进一步有: $-X_i^T P_i^{-1} X_i < P_i - (X_i + X_i^T)$, 所以式(23)可转化为式(24). 利用 $\text{diag}\{I, I, I, I, I, X_i^{-T}, X_i^{-T}, X_i^{-T}, I, I\}$ 对式(24)进行全等变换, 即可将其转换为式(10), 证明完毕.

$$\begin{bmatrix} \Omega_{11} & 0 & 0 & 0 & 0 & \sqrt{\frac{1}{h}}(h\bar{A}_i + I)^T X_i & \sqrt{h}\sigma_1 \bar{A}_{1i}^T X_i & \sqrt{h}\sigma_2 \bar{A}_{2i}^T X_i & \sqrt{\frac{1}{h}}\bar{C}_i^T & \sqrt{\frac{1}{h}}\sigma_1 \bar{C}_{1i}^T \\ * & \Omega_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & \Omega_{33} & 0 & 0 & \sqrt{h}\bar{A}_{\tau_i}^T X_i & 0 & 0 & 0 & 0 \\ * & * & * & \Omega_{44} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\frac{1}{h}\gamma^2 I & \sqrt{h}\bar{B}_{1i}^T X_i & 0 & 0 & \sqrt{\frac{1}{h}}\bar{B}_{2i}^T & 0 \\ * & * & * & * & * & -X_i^T P_i^{-1} X_i & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -X_i^T P_i^{-1} X_i & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -X_i^T P_i^{-1} X_i & 0 & 0 \\ * & * & * & * & * & * & * & * & -I & 0 \\ * & * & * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \quad (24)$$

定理 3 给定标量 $0 < \bar{\alpha} < 1, 0 < \bar{\beta} < 1, 0 < \lambda < 1$ 和 $\mu > 1$, 如果存在正定矩阵 P_i, Q_i, R_{1i}, R_{2i} , 矩阵 $X_i = \text{diag}\{X_{i1}, X_{i1}\}, K_i, L_i, V_i, M_i, \bar{L}, i=1, 2, \dots, n$, 使得式(25)、式(26)成立, 则闭环网络切换系统(8)是指数均方稳定的, 并满足 H_∞ 性能指标 γ , 且控制器增益 $K_i = (B_i^T)^{-1}(X_{i1}^{-1})^T B_i M_i$,

滤波器增益 $L_i = (X_{i1}^{-1})^T \bar{L}_i^T$.

$$\begin{cases} P_i = \begin{bmatrix} P_{i11} & P_{i12} \\ * & P_{i22} \end{bmatrix} > 0 \\ Q_i = \begin{bmatrix} Q_{i11} & Q_{i12} \\ * & Q_{i22} \end{bmatrix} > 0 \end{cases}, \begin{cases} R_{1i} = \begin{bmatrix} R_{1i11} & R_{1i12} \\ * & R_{1i22} \end{bmatrix} > 0 \\ R_{2i} = \begin{bmatrix} R_{2i11} & R_{2i12} \\ * & R_{2i22} \end{bmatrix} > 0 \end{cases} \quad (25)$$

$$\begin{bmatrix} \Omega_{11} & 0 & 0 & 0 & 0 & \Omega_{16} & \Omega_{17} & \Omega_{18} & \sqrt{\frac{1}{h}}\bar{C}_i^T & \sqrt{\frac{1}{h}}\sigma_1 \bar{C}_{1i}^T \\ * & \Omega_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & \Omega_{33} & 0 & 0 & \Omega_{36} & 0 & 0 & 0 & 0 \\ * & * & * & \Omega_{44} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -\frac{1}{h}\gamma^2 I & \Omega_{56} & 0 & 0 & \sqrt{\frac{1}{h}}\bar{B}_{2i}^T & 0 \\ * & * & * & * & * & \Omega_{66} & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & \Omega_{77} & 0 & 0 & 0 \\ * & * & * & * & * & * & * & \Omega_{88} & 0 & 0 \\ * & * & * & * & * & * & * & * & -I & 0 \\ * & * & * & * & * & * & * & * & * & -I \end{bmatrix} < 0 \quad (26)$$

其中,

$$\begin{aligned} \bar{\Omega}_{16} &= \begin{bmatrix} \sqrt{h}A_i^T X_{i1} + \sqrt{h}\bar{\beta}M_i^T B_i^T + \frac{1}{h}X_{i1} & 0 \\ -\sqrt{h}\bar{\beta}M_i^T B_i^T & \sqrt{h}A_i^T X_{i1} - \sqrt{h}\bar{\alpha}C_i^T \bar{L}_i \end{bmatrix} \\ \bar{\Omega}_{17} &= \begin{bmatrix} 0 & -\sqrt{h}\sigma_1 C_{1i}^T \bar{L}_i \\ 0 & 0 \end{bmatrix}, \quad \bar{\Omega}_{36} = \begin{bmatrix} \sqrt{h}A_{\tau_i}^T X_{i1} & 0 \\ 0 & \sqrt{h}A_{\tau_i}^T X_{i1} \end{bmatrix} \\ \bar{\Omega}_{18} &= \begin{bmatrix} \sqrt{h}\sigma_2 M_i^T B_i^T & \sqrt{h}\sigma_2 M_i^T B_i^T \\ -\sqrt{h}\sigma_2 M_i^T B_i^T & -\sqrt{h}\sigma_2 M_i^T B_i^T \end{bmatrix} \end{aligned}$$

$$\bar{\Omega}_{56} = \begin{bmatrix} \sqrt{h}D_i^T X_{i1} & \sqrt{h}D_i^T X_{i1} - \sqrt{h}E_i^T \bar{L}_i \\ \sqrt{h}F_i^T X_{i1} & \sqrt{h}F_i^T X_{i1} \end{bmatrix}$$

证明 将 $X_i = \text{diag}\{X_{i1}, X_{i1}\}$ 代入式(23), 可将其转化为式(26), 因此系统(8)是指数均方稳定的, 且满足 H_∞ 性能 γ . 将 $X_i = \text{diag}\{X_{i1}, X_{i1}\}$ 代入 Ω_{16} 计算可得: $\Omega_{16} = \begin{bmatrix} \sqrt{h}A_i^T X_{i1} + \sqrt{h}\bar{\beta}\Xi_{11} + \frac{1}{h}X_{i1} & 0 \\ -\sqrt{h}\bar{\beta}\Xi_{11} & \sqrt{h}A_i^T X_{i1} - \sqrt{h}\bar{\alpha}C_i^T \Xi_{12} \end{bmatrix}$, 其中, $\Xi_{11} = K_i^T B_i^T X_{i1}, \Xi_{12} = L_i^T X_{i1}$.

令: $K_i^T B_i^T X_{i1} = M_i^T B_i^T$, $L_i^T X_{i1} = \bar{L}_i$, 则有: $K_i = (B_i^T)^{-T}$, $(X_{i1}^{-1})^T B_i M_i$, $L_i = (X_{i1}^{-1})^T \bar{L}_i$. 证明完毕.

3 算例分析

考虑下面具有两个子系统^[10, 14]的网络化切换系统, 其参数矩阵为

$$A_1 = \begin{bmatrix} -56 & 10 \\ 7 & -5 \end{bmatrix}, A_{r1} = \begin{bmatrix} 14 & -3.8 \\ -12 & -6 \end{bmatrix}, B_1 = \begin{bmatrix} -9 \\ 1 \end{bmatrix}$$

$$D_1 = [2.9 \ 2.9], F_1 = [2.3 \ 4.5]^T$$

$$C_1 = [3.4 \ 0.35], E_1 = -0.5$$

$$A_2 = \begin{bmatrix} -55 & 10 \\ 9 & -50 \end{bmatrix}, A_{r2} = \begin{bmatrix} 10 & -4 \\ -12 & -10 \end{bmatrix}, B_2 = \begin{bmatrix} 9 \\ -7 \end{bmatrix}$$

$$D_2 = [10 \ -6], F_2 = [7 \ 10]^T$$

$$C_2 = [6 \ 7], E_2 = 1.14$$

给定时延 $\tau(k) = 2 + [1 + (-1)^k]/2$, 采样周期 $h = 0.01$, $\lambda = 0.05$, $\mu = 2.4$, 则: $\bar{T}_a = -\ln \mu / \ln(1 - \lambda) = 17.0679$.

这里, 选择不同丢包率验证所提方法的有效性, 在上面参数不变的情况下, 丢包率的选取必须使得式(25)和(26)具有可行解, 才能确保系统(8)是指数均方稳定的, 并且满足 H_∞ 性能.

情况 1 设传感器到控制器丢包率 $\bar{\alpha} = 0.8$, 控制器到执行器丢包率 $\bar{\beta} = 0.9$. 利用 LMI 求解式(25)和(26)可得控制器增益矩阵:

$$K_1 = [3.058 \ 5 \ 0.386 \ 1], K_2 = [-0.348 \ 1 \ 0.848 \ 6]$$

滤波器增益矩阵:

$$L_1 = \begin{bmatrix} -4.504 \ 3 \\ 0.071 \ 3 \end{bmatrix}, L_2 = \begin{bmatrix} -1.459 \ 4 \\ -2.329 \ 7 \end{bmatrix}$$

残差发生器增益矩阵:

$$V_1 = 0.006 \ 0, V_2 = 0.001 \ 8$$

最小的扰动抑制:

$$\gamma_{\min} = 1.006 \ 8$$

情况 2 $\bar{\alpha} = 0.5$, $\bar{\beta} = 0.7$, 利用 LMI 求解式(25)和式(26)可得控制器增益矩阵:

$$K_1 = [2.147 \ 6 \ 0.443 \ 9], K_2 = [-0.386 \ 4 \ 1.002 \ 8]$$

滤波器增益矩阵:

$$L_1 = \begin{bmatrix} -2.394 \ 9 \\ 0.015 \ 0 \end{bmatrix}, L_2 = \begin{bmatrix} -0.308 \ 4 \\ -2.286 \ 1 \end{bmatrix}$$

残差发生器增益矩阵:

$$V_1 = -0.009 \ 7, V_2 = 0.010 \ 2$$

最小的扰动抑制

$$\gamma_{\min} = 1.06$$

在情况 1 中, 保持传感器到控制器的丢包率 $\bar{\alpha} = 0.8$ 不变, 改变控制器到执行器的丢包率 $\bar{\beta}$, 说明丢包率的改变一定程度上影响系统的 H_∞ 性能, 见表 1.

表 1 最小扰动抑制 γ_{\min}

Tab.1 Minimal disturbance attenuation level γ_{\min}

$\bar{\beta}$	0.8	0.7	0.6
γ_{\min}	1.020 5	1.040 3	1.092 8

注 1 一个稳定运行的网络控制系统对数据包丢失具有一定的鲁棒性, 但当丢包率超过系统容许的范围时, 将会对系统的控制性能造成严重的影响, 甚至导致系统失稳. 为了确保增广系统(8)能够稳定运行, 我们需要对控制器到执行器通道、传感器至控制器通道的数据包丢失率做一个预设, 在 Matlab 仿真阶段, 我们首先选取较大的丢包率来验证系统(8)是否满足定理 3 中系统稳定性和 H_∞ 性能的要求, 由于本文所考虑的是双通道数据包丢失, 这就造成传感器至控制器的丢包率 $\bar{\alpha}$ 和控制器到执行器丢包率 $\bar{\beta}$ 是相互制约的, 我们需要经过多次实验来验证丢包率的选取是否恰当, 因为丢包率选取不当, 将会导致系统失去稳定性.

为验证系统故障检测性能, 考虑如下的阶跃突变故障信号:

$$f(k) = \begin{cases} 1, & 64 \leq k \leq 114 \\ 0, & \text{其它} \end{cases}$$

干扰信号 $d(k)$ 幅值小于 0.5, 且服从标准正态分布. 系统(8)的初始状态为 0, 图 1 为网络化切换系统的切换规则; 由图 2 可以得出当系统发生故障时, 残差误差值不再趋近 0; 图 3 是系统的状态响应曲线.

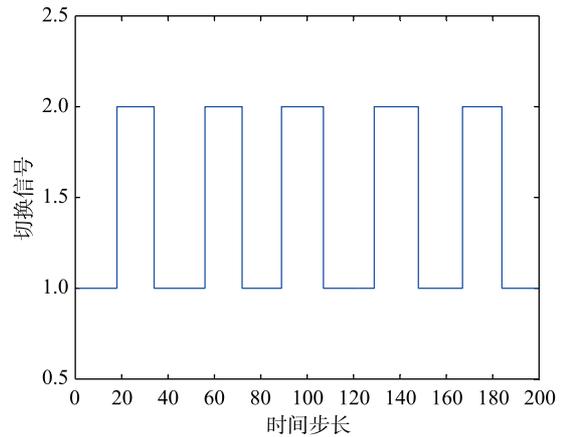


图 1 切换信号

Fig.1 Switched signal

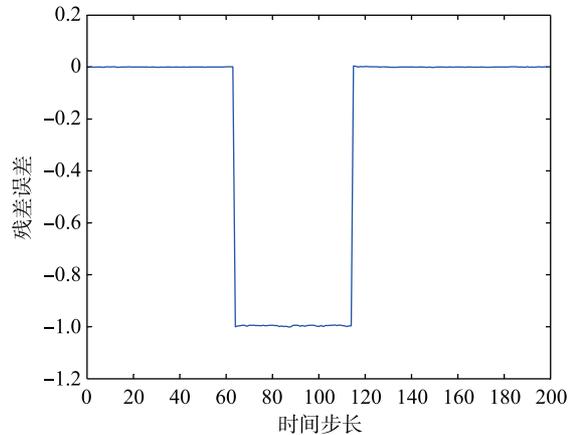


图 2 残差误差

Fig.2 Residual error

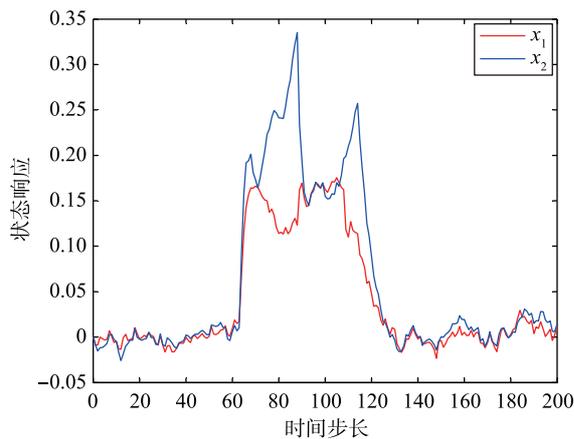


图3 状态响应

Fig.3 State response

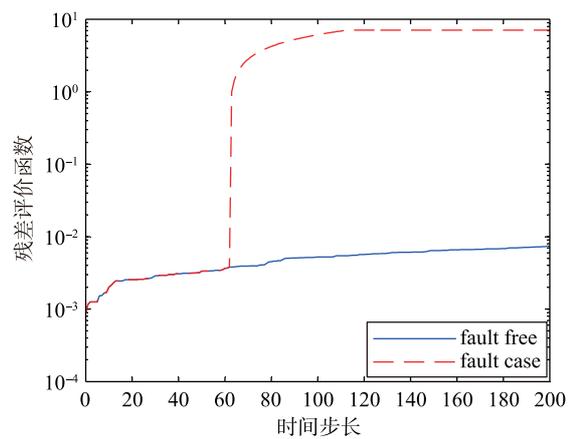


图4 残差评价函数

Fig.4 Residual evaluation function

由图4可知当发生故障时,所选择的残差评价函数的值将不再和阈值相同,而是在故障信号存在期间逐渐增大.当 $k=64$ 时,评价函数 $J(\bar{r})=1.0004$,而阈值的上界为 $J_{th}=0.0074$,因此在故障发生时即可检测出故障,说明本文所设计的故障检测滤波器是有效的.

注2 现有表示离散系统的方法有移位算子方法和Delta算子方法,后者更适合高速采样系统^[13].当用这两种方法表示同一个离散系统时(如文[10]采用移位算子方法,本文采用Delta算子方法),文[10]中的系统参数矩阵并不能保证本文中系统的稳定性.在确保系统稳定的前提下,文[10]中得到的最小扰动抑制 $\gamma_{min}=1.542$,在故障发生1个时间步长后检测出故障,而本文得到的最小扰动抑制 $\gamma_{min}=1.0068$,在故障发生时就能立刻检测出故障,说明

本文所采用的方法抗干扰能力更强,故障检测性能优于文[10].当采用Delta算子方法表示离散系统时,文[16]在故障发生7个时间步长后检测出故障,本文是在故障发生的瞬间就能检测故障信号.

4 结论

本文利用Delta算子方法解决了双通道丢包和时变时延约束下的网络切换系统故障检测问题.构建一个任意切换信号下的故障检测滤波器,利用LMI、平均驻留时间等方法证明了增广系统是指数均方稳定的,并得到了最小的 H_2 性能.仿真结果表明本文所设计的故障检测滤波器的能够快速有效地检测出故障发生的时刻.

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