一类带有多源异质干扰的随机系统的精细抗干扰控制

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摘要：本文考虑了一类带有多源异质干扰的随机系统的精细抗干扰控制问题，其中干扰包括带有未知光滑非线性函数的非谐波干扰和白噪声. 采用模糊逻辑系统对光滑未知非线性函数进行逼近，在逼近值的基础上构造自适应干扰观测器来估计干扰. 通过结合干扰观测器跟模糊控制，提出了一种精细抗干扰控制策略以保证复合系统达到依均方渐近有界. 最后，通过仿真验证了所提方案的有效性.

关键词：自适应干扰观测器；精细抗干扰控制；多源异质干扰；模糊逻辑系统

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在复杂环境中，系统的干扰来自于很多方面，如测量噪声、外部环境干扰、系统结构变化及建模误差等. 由于不同类型的干扰会影响系统的控制精度，因此系统带有多源干扰的问题一直是一个研究热点[1—3]. 大多数的抗干扰控制方法是将多源干扰整合成一个等效的系统干扰来处理[4—5]，但是这种方法没有充分利用不同干扰的影响机理和特性. 目前，复合分层抗干扰控制方法被用于处理多源干扰[6—7]，这种方法可以抵消内环干扰同时抑制外环干扰，这在很大程度上提高了系统的抗干扰性能[8—9]. 文献[8—9]将多源干扰分为两种类型：一种是由外源系统生成的部分信息已知的干扰，另一种是 H_2 范数有界干扰和随机模型. 考虑到不同类型干扰具有不同的建模方式，精细抗干扰控制方法可以充分利用干扰信息来达到更高的抗干扰控制精度，而上述提到的复合分层抗干扰控制方法只是精细抗扰控制方法的一种特例.

在上述研究中，部分信息已知的干扰被认为是谐波、常值或中立稳定干扰，可以由线性外源系统来描述. 实际上，还有许多非谐波干扰可以由非线性外源系统来描述[10—11]. 此外，由非线性外源系统生成的非谐波干扰中的非线性动态被认为是已知的[12—13]. 文献[12]构造了一个随机非线性干扰观测器来估计带有已知非线性函数的非谐波干扰. 然而，在大多数实际工程应用中，很难得到非谐波干扰中精确的非线性信息. 因此，有必要考虑带有未知非线性函数的非谐波干扰. 值得注意的是，文献[12]中所提出的方法在估计这种非谐波干扰时是相对保守的. 由于不需要系统精确的数学模型，模糊逻辑系统已经成为解决不确定性控制问题的一种有效途径[14—15].

近几年，模糊逻辑系统已经成功用于逼近随机系统中未知非线性函数[16—18]. 文献[16]考虑一类非线性随机系统，包括未知非线性不确定性、输入饱和、未建模动力学和未测量状态. 文献[18]针对随机扰动和输入饱和问题，提出了一种基于命令滤波的自适应模糊控制方法. 由于干扰的来源和渠道不同，上述方法不能直接扩展到多源异质干扰的处理. 因此，带有多源异质干扰的随机系统的研究具有一定的挑战性.

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1 问题描述

具有多源异质干扰的随机系统可以描述为:

$$\dot{x}(t) = Ax(t) + B_0[u(t) + D(t)] + B_1 x(t)\xi(t), \tag{1}$$

式中: $x \in \mathbf{R}^n$, $u \in \mathbf{R}^m (m < n)$ 分别是系统的状态和控制输入; 乘性噪声 $\xi_1(t) \in \mathbf{R}$ 是有限带宽白噪声; $A \in \mathbf{R}^{n\times n}$, $B_0 \in \mathbf{R}^{n\times m}$, $B_1 \in \mathbf{R}^{n\times m}$ 和 $B_2 \in \mathbf{R}^n$ 是已知的实数矩阵, $D(t) \in \mathbf{R}^m$ 表示一类带有未知光滑非线性函数的非谐波干扰,可由下列非线性外源系统生成:

$$\begin{cases}\dot{z}(t) = Wz(t) + Ff(z(t)), \\ D_0(t) = Vz(t),\end{cases} \tag{2}$$

这里, $z(t) \in \mathbf{R}^{2r}$ 是外源系统的状态向量, W, F 和 V 是已知的实数矩阵, $f(z(t)) \in \mathbf{R}$ 是一个连续未知非线性函数,可以用一个模糊逻辑系统来近似,其规则为 If - Then[14]:

R^l: If z_1 is F_1^l and $\cdots$ and z_n is F_n^l, then y is G^l, $l = 1, 2, \cdots, N$.

这里, $z = [z_1, \cdots, z_N]^{\mathrm{T}}$ 和 y 分别是模糊逻辑系统的输入和输出, $F_i^l (i = 1, 2, \cdots, n)$ 和 G^l 是分别与隶属度函数 $\mu_{F_i^l}(z_i)$ 和 $\mu_{G^l}(y)$ 相关的模糊集.

模糊逻辑逼近系统可以表示为:

$$y(z) = \frac{\sum_{l=1}^{N} \bar{y}_l \prod_{i=1}^{n} \mu_{F_i^l}(z_i)}{\sum_{l=1}^{N} [\prod_{i=1}^{n} \mu_{F_i^l}(z_i)]},$$

其中, $\bar{y}_l = \max_{y \in \mathbf{R}} \mu G^l(y)$, 定义模糊基函数为:

$$\varphi_l(z) = \frac{\prod_{i=1}^{n} \mu_{F_i^l}(z_i)}{\sum_{l=1}^{N} [\prod_{i=1}^{n} \mu_{F_i^l}(z_i)]}.$$

令 $\theta = [\bar{y}_1, \bar{y}_2, \cdots, \bar{y}_n]^{\mathrm{T}} = [\theta_1, \theta_2, \cdots, \theta_N]^{\mathrm{T}}$ 和 $\varphi(z) = [\varphi_1(z), \varphi_2(z), \cdots, \varphi_N(z)]^{\mathrm{T}}$, 则模糊逻辑系统可表示为:

$$y(z) = \theta^{\mathrm{T}} \varphi(z). \tag{3}$$

未知非线性 $f(z)$ 可以用模糊逻辑系统 $y(z) = \hat{f}(z \mid \theta)$ 来逼近:

$$\hat{f}(z \mid \theta) = \theta^{\mathrm{T}} \varphi(z). \tag{4}$$

定义模糊参数向量 θ^* 为

$$\theta^* = \arg\min_{\theta \in \Omega_1} [\sup_{x \in \Omega_z} \| \hat{f}(z \mid \theta) - f(z \mid \theta) \|], \tag{5}$$

式中: Ω_1, Ω_z 分别是关于 θ, z 的紧集. 规定模糊最优逼近误差为

$$\varepsilon(z) = f(z) - \hat{f}(z \mid \theta^*), \tag{6}$$

基于式(3) ~ (6), 干扰(2)可表示为

$$\begin{aligned}\dot{z}(t) &= Wz(t) + F[\hat{f}(z \mid \theta) + (\hat{f}(z \mid \theta^*) - \hat{f}(z \mid \theta)) + (f(z) - \hat{f}(z \mid \theta^*))] = \\ &Wz(t) + F\theta^{\mathrm{T}}\varphi(z) + F\tilde{\theta}^{\mathrm{T}}\varphi(z) + F\varepsilon(z),\end{aligned} \tag{7}$$

其中 $\tilde{\theta} = \theta^* - \theta$. 由此干扰模型(2)可以描述为:

$$\begin{cases}\dot{z}(t) = Wz(t) + F\theta^{\mathrm{T}}\varphi(z) + F\tilde{\theta}^{\mathrm{T}}\varphi(z) + F\varepsilon(z), \\ D_0(t) = Vz(t).\end{cases} \tag{8}$$

注 1: 实际上,干扰模型(2)可以代表工程上的一大类干扰. 当 $F = 0$ 时, $D_0(t)$ 表示未知常数,未知相位和振幅的谐波干扰; 当 $F \neq 0$ 时, $D_0(t)$ 可表示一类由非线性外源系统产生的非谐波干扰.

用 $\frac{\mathrm{d}W_1(t)}{\mathrm{d}t}$ 代替 $\xi_1(t)$, 那么式(1)和(8)可重新表示为:

$$\begin{cases} \mathrm{d}x(t) = Ax(t)\mathrm{d}t + B_0D_0(t) + B_0u(t)\mathrm{d}t + B_1x(t)\mathrm{d}W_1(t), \\ \mathrm{d}z(t) = Wz(t)\mathrm{d}t + F\theta^{\mathrm{T}}\varphi(z)\mathrm{d}t + F\tilde{\theta}^{\mathrm{T}}\varphi(z)\mathrm{d}t + F\varepsilon(z)\mathrm{d}t, \\ D_0(t) = Vz(t). \end{cases} \tag{9}$$

假设 1　(W,B_0V) 是能观的,(A,B_0) 是能控的.

考虑以下非线性随机微分方程:

$$\mathrm{d}x(t) = f(x(t),t)\mathrm{d}t + g(x(t),t)\mathrm{d}B(t), t \geqslant t_0(t_0 \geqslant 0), \tag{10}$$

其中:f: $\mathbf{R}^n \times \mathbf{R}_+ \to \mathbf{R}^n$,$g$: $\mathbf{R}^n \times \mathbf{R}_+ \to \mathbf{R}^{n\times m}$ 满足局部 Lipschitz 条件,且 $x(t) \in \mathbf{R}^n$,$f(0,t) = 0$,$g(0,t) = 0$. $B(t)$,$t \geqslant 0$ 是一个 m 维的独立维纳过程.

引理 1[18]　假设存在函数 $V \in C^{2,1}(\mathbf{R}^n \times \mathbf{R}_+)$ 和 $\kappa \in \kappa_\nu \subset \kappa_\infty$,正常数 p,β,λ,$(x,t) \in \mathbf{R}^n \times \mathbf{R}_+$,使得

$$\kappa(|x|^p) \leqslant V(x,t), LV(x,t) \leqslant -\lambda V(x,t) + \beta; \tag{11}$$

对所有 $(x,t) \in \mathbf{R}^n \times \mathbf{R}_+$,有

$$\lim_{t\to\infty} \sup E|x(t;t_0,x_0)|^p \leqslant \kappa^{-1}\left(\frac{\beta}{\lambda}\right), \tag{12}$$

那么系统(10)是依 p - 阶矩渐近稳定.

2　自适应干扰观测器

本节在未知光滑非线性函数逼近值的基础上构造了一个新的自适应干扰观测器,并设计了一个精细抗干扰控制器.

自适应干扰观测器构造如下:

$$\begin{cases} \hat{D}(t) = V\hat{z}(t), \hat{z}(t) = v(t) - Lx(t), \\ \mathrm{d}V(t) = (W + LB_0V)\hat{z}(t)\mathrm{d}t + L(Ax(t) + B_0u(t))\mathrm{d}t + F\theta^{\mathrm{T}}\hat{\varphi}(z)\mathrm{d}t, \end{cases} \tag{13}$$

式中:$v(t)$ 是辅助变量,表示自适应观测器的状态;L 是观测增益. 定义干扰误差为 $e_z(t) = z(t) - \hat{z}(t)$,由式(9)和(13),可推得误差系统为:

$$\mathrm{d}e_z(t) = (W+LB_0V)e_z(t)\mathrm{d}t + F\tilde{\theta}^{\mathrm{T}}\hat{\varphi}(z)\mathrm{d}t + F\varepsilon(z)\mathrm{d}t + LB_1x(t)\mathrm{d}W_1(t) + F\theta^{\mathrm{T}}\varphi(z)\mathrm{d}t - F\theta^{\mathrm{T}}\hat{\varphi}(z)\mathrm{d}t. \tag{14}$$

令 $\bar{\varepsilon}(z) = \theta^T\tilde{\varphi}(z) + \varepsilon(z)$,其中 $\tilde{\varphi}(z) = \varphi(z) - \hat{\varphi}(z)$,则式(14)可表示为

$$\mathrm{d}e_z(t) = (W + LB_0V)e_z(t)\mathrm{d}t + F\tilde{\theta}^{\mathrm{T}}\hat{\varphi}(z)\mathrm{d}t + F\bar{\varepsilon}(z)\mathrm{d}t + LB_1x(t)\mathrm{d}W_1(t). \tag{15}$$

由于 (W,B_0V) 是能观的,因此式(15)中 $\mathrm{d}e_z(t) = (W + LB_0V)e_z(t)\mathrm{d}t$ 的极点可被配置到左半平面. 通过调节 L 可以满足自适应干扰观测器的性能要求.

在自适应观测器的基础上,精细抗干扰控制器可设计为:

$$u(t) = -\hat{D}(t) + Kx(t), \tag{16}$$

这里,K 是控制增益可以通过线性矩阵不等式求解.

将式(16)代入式(9)中,可得到闭环系统:

$$\mathrm{d}x(t) = Ax(t)\mathrm{d}t + B_0Vz(t)\mathrm{d}t + B_0Kx(t)\mathrm{d}t + B_1x(t)\mathrm{d}W_1(t). \tag{17}$$

将式(15)、(17)结合,得到复合系统:

$$\begin{bmatrix} \mathrm{d}x(t) \\ \mathrm{d}e_z(t) \end{bmatrix} = \begin{bmatrix} A + B_0K & B_0V \\ 0 & W + LB_0V \end{bmatrix}\begin{bmatrix} x(t) \\ e_z(t) \end{bmatrix}\mathrm{d}t + \begin{bmatrix} 0 \\ F \end{bmatrix}\tilde{\theta}^{\mathrm{T}}\hat{\varphi}(z)\mathrm{d}t + \begin{bmatrix} B_1 & 0 \\ LB_1 & 0 \end{bmatrix}x(t)\mathrm{d}W_1(t) + \begin{bmatrix} 0 \\ F \end{bmatrix}\bar{\varepsilon}(z)\mathrm{d}t. \tag{18}$$

复合系统可以写成如下形式:

$$\begin{cases} \mathrm{d}(\bar{x}(t)) = \bar{A}\bar{x}(t)\,\mathrm{d}t + \bar{B}_1\bar{x}(t)\,\mathrm{d}W_1(t) + \bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z)\,\mathrm{d}t + \bar{F}_2\bar{\varepsilon}(z)\,\mathrm{d}t, \\ h(t) = C\bar{x}(t), \end{cases} \tag{19}$$

式中:

$$\bar{x}(t) = \begin{bmatrix} x(t) \\ e_z(t) \end{bmatrix}, \bar{A} = \begin{bmatrix} A + B_0K & B_0V \\ 0 & W + LB_0V \end{bmatrix}, \bar{B}_1 = \begin{bmatrix} B_1 & 0 \\ LB_1 & 0 \end{bmatrix}, \bar{F}_1 = \begin{bmatrix} 0 \\ F \end{bmatrix}, \bar{F}_2 = \begin{bmatrix} 0 \\ F \end{bmatrix}. \tag{20}$$

在式(19)中,$h(t) = C\bar{x}(t)$ 是参考输出,$C = [C_1 \quad C_2]$是权重矩阵可以调节系统的性能.

3 精细抗干扰控制

本节的目的是设计一个精细抗干扰控制方案,使得复合系统达到期望的动态性能,可以得到预期的结果.

定理 1 对于带有干扰(2)的随机系统(1),在满足假设 1 的条件下,对于给定参数 $\alpha > 0$,存在对称矩阵 $Q_1 = P_1^{-1} > 0$,$Q_2 = P_2^{-1} > 0$ 和矩阵 R,满足下列线性矩阵不等式:

$$\Omega = \begin{bmatrix} \Theta_1 & B_0VQ_2 & Q_1B_1^{\mathrm{T}} & Q_1B_1^{\mathrm{T}}L^{\mathrm{T}} & Q_1C_1^{\mathrm{T}} & 0 \\ * & \Theta_2 & 0 & 0 & Q_2C_2^{\mathrm{T}} & F \\ * & * & -Q_1 & 0 & 0 & 0 \\ * & * & * & -Q_2 & 0 & 0 \\ * & * & * & * & -I & 0 \\ * & * & * & * & * & -\alpha^2 I \end{bmatrix} < 0, \tag{21}$$

式中:

$$\Theta_1 = AQ_1 + Q_1^{\mathrm{T}}A^{\mathrm{T}} + B_0R + R^{\mathrm{T}}B_0^{\mathrm{T}},\ \Theta_2 = Q_2W + W^{\mathrm{T}}Q_2^{\mathrm{T}} + LB_0VQ_2 + Q_2V^{\mathrm{T}}B_0^{\mathrm{T}}L^{\mathrm{T}}.$$

通过设计精细抗干扰控制器(17)中的控制增益 $K = RQ_1^{-1}$,自适应律选为:

$$\dot{\theta} = \Gamma^{-1}\hat{\varphi}(z)\tilde{x}^{\mathrm{T}}(t)P\bar{F}_1, \tag{22}$$

这里对称矩阵 $\Gamma > 0$,$\tilde{x}^{\mathrm{T}}(t) = [x(t) \quad \hat{z}(t)]$,那么复合系统(18)在 $\bar{\varepsilon}(z) = 0$ 的情况下是依均方渐近有界的,在 $\bar{\varepsilon}(z) \neq 0$ 的情况下满足 $\| h(t) \|_2 < \alpha \| \varepsilon(z) \|_2$.

证明 对于复合系统(19),考虑下列 Lyapunov 函数:

$$V(\bar{x}(t), t) = \bar{x}^{\mathrm{T}}(t)P\bar{x}(t) + \mathrm{Tr}(\tilde{\theta}^{\mathrm{T}}\Gamma\tilde{\theta}). \tag{23}$$

选取

$$P = \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} = \begin{bmatrix} Q_1^{-1} & 0 \\ 0 & Q_2^{-1} \end{bmatrix} > 0. \tag{24}$$

系统(19)在 $\bar{\varepsilon}(z) = 0$ 的情况下,有:

$$\begin{aligned} LV(\bar{x}(t), t) &= \frac{\partial V}{\partial x}(\bar{A}\bar{x}(t) + \bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z)) + \mathrm{Tr}(\bar{x}^{\mathrm{T}}(t)\bar{B}_1^{\mathrm{T}}P\bar{B}_1\bar{x}(t)) - 2\tilde{\theta}^{\mathrm{T}}\Gamma\dot{\theta} \leqslant \\ &\bar{x}^{\mathrm{T}}(t)(P\bar{A} + \bar{A}^{\mathrm{T}}P + \bar{B}_1^{\mathrm{T}}P\bar{B}_1)\bar{x}(t) + 2(\bar{x}^{\mathrm{T}}(t)P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z)) - 2\tilde{\theta}^{\mathrm{T}}\Gamma\dot{\theta} = \\ &\bar{x}^{\mathrm{T}}(t)(P\bar{A} + \bar{A}^{\mathrm{T}}P + \bar{B}_1^{\mathrm{T}}P\bar{B}_1)\bar{x}(t) + 2[I_1\bar{x}(t) + I_2\bar{x}(t)]^{\mathrm{T}}P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z) - 2\tilde{\theta}^{\mathrm{T}}\Gamma\dot{\theta} = \\ &\bar{x}^{\mathrm{T}}(t)(P\bar{A} + \bar{A}^{\mathrm{T}}P + \bar{B}_1^{\mathrm{T}}P\bar{B}_1)\bar{x}(t) + 2[x(t) \quad \hat{z}(t)]P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z) - 2\tilde{\theta}^{\mathrm{T}}\Gamma\dot{\theta} + 2[0 \quad z(t)]P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z), \end{aligned}$$

这里

$$I_1 = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}, I_2 = \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix}, \tilde{x}(t) = \begin{bmatrix} x(t) \\ \hat{z}(t) \end{bmatrix}. \tag{25}$$

令 $\Omega_0 = P\bar{A} + \bar{A}^{\mathrm{T}}P + \bar{B}_1^{\mathrm{T}}P\bar{B}_1$,$\gamma(t) = 2[0 \quad z(t)]P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\hat{\varphi}(z)$,定义 $\tilde{x}^{\mathrm{T}}(t)P\bar{F}_1\tilde{\theta}^{\mathrm{T}}\varphi(z) = \tilde{\theta}^{\mathrm{T}}\Gamma\dot{\theta}$. 由此,自适应律可以设计为:$\dot{\theta} = \Gamma^{-1}\hat{\varphi}(z)\tilde{x}^{\mathrm{T}}(t)P\bar{F}_1$.

考虑 $z(t)$,$\tilde{\theta}^{\mathrm{T}}$ 和 $\hat{\varphi}(z)$ 为有界矩阵,则一定存在一个常数 $\beta > 0$,使得 $0 \leqslant \gamma(t) \leqslant \beta$,由此得:

$$LV(\bar{x}(t),t) \leqslant \bar{x}^{\mathrm{T}}(t)(P\bar{A}+\bar{A}^{\mathrm{T}}P+\bar{B}_1^{\mathrm{T}}P\bar{B}_1)\bar{x}(t)+\gamma(t) \leqslant \bar{x}^{\mathrm{T}}(t)\Omega_0\bar{x}(t)+\beta. \tag{26}$$

如果 $\Omega_0<0$ 成立，那么存在一个常数 $\alpha>0$ 有:

$$\Omega_0<0 \Rightarrow \Omega_0+\alpha I<0. \tag{27}$$

基于式(23)、(24)、(26)和(27)，选取函数 $\kappa=\lambda_{\min}(P)\,|\bar{x}|^p$，正常数 $p=2$ 和 $\mu=\dfrac{\alpha}{\lambda_{\min}(P)}$，使得

$$\kappa(|\bar{x}|^p)=\lambda_{\min}(P)\,|\bar{x}|^2 \leqslant \bar{x}^{\mathrm{T}}P\bar{x}=V(\bar{x},t), \tag{28}$$

$$LV(\bar{x}(t),t) \leqslant -\mu V(\bar{x}(t),t)+\alpha. \tag{29}$$

基于引理 1，有:

$$\lim_{t\to\infty}\sup E\,|x(t;t_0,x_0)|^p \leqslant \kappa^{-1}\left(\frac{\alpha}{\mu}\right). \tag{30}$$

因此，复合系统(19)在缺少 $\bar{\varepsilon}(z)$ 的情况下是依均方渐近有界的.

下一步证明复合系统(19)在 $\bar{\varepsilon}(z)\in L_2[0,\infty)$ 的情况下满足 $\|h(t)\|_2<\alpha\|\bar{\varepsilon}(z)\|_2$. 考虑到 H_∞ 的性能要求，建立干扰衰减指标 $\alpha>0$，考虑下列辅助函数:

$$\begin{aligned}J(t)&=E\int_0^t[h^{\mathrm{T}}(s)h(s)-\alpha^2\bar{\varepsilon}^{\mathrm{T}}(s)\bar{\varepsilon}(s)]\mathrm{d}t=\\ &E\int_0^t[h^{\mathrm{T}}(s)h(s)-\alpha^2\bar{\varepsilon}^{\mathrm{T}}(s)\bar{\varepsilon}(s)+LV(\bar{x}(t),t)]\mathrm{d}t-EV(\bar{x}(t),t)\leqslant\\ &E\int_0^t[h^{\mathrm{T}}(s)h(s)-\alpha^2\bar{\varepsilon}^{\mathrm{T}}(s)\bar{\varepsilon}(s)+LV(\bar{x}(t),t)]\mathrm{d}t=E\int_0^t\begin{bmatrix}\bar{x}(s)\\ \bar{\varepsilon}(s)\end{bmatrix}^{\mathrm{T}}\Omega_1\begin{bmatrix}\bar{x}(s)\\ \bar{\varepsilon}(s)\end{bmatrix}\mathrm{d}t,\end{aligned} \tag{31}$$

这里

$$\Omega_1=\begin{bmatrix}\Omega_0+C^{\mathrm{T}}C & P\bar{F}_2\\ \bar{F}_2^{\mathrm{T}}P & -\alpha^2 I\end{bmatrix}. \tag{32}$$

进一步证明: $\Omega<0 \Leftrightarrow \Omega_1<0$.

1) 证明 $\Omega_1<0 \Leftrightarrow \Omega_2<0$. 在式(20)、(32)和舒尔补引理的基础上，$\Omega_1<0$ 等价于 $\Omega_2<0$，这里

$$\Omega_2=\begin{bmatrix}\Pi_{11} & P_1B_0V & B_1^{\mathrm{T}}P_1 & B_1^{\mathrm{T}}L^{\mathrm{T}}P_2 & C_1^{\mathrm{T}} & 0\\ * & \Pi_{22} & 0 & 0 & C_2^{\mathrm{T}} & P_2F\\ * & * & -P_1 & 0 & 0 & 0\\ * & * & * & -P_2 & 0 & 0\\ * & * & * & * & -I & 0\\ * & * & * & * & * & -\alpha^2 I\end{bmatrix}<0, \tag{33}$$

$$\Pi_{11}=P_1A+A^{\mathrm{T}}P_1^{\mathrm{T}}+P_1B_0K+K^{\mathrm{T}}B_0^{\mathrm{T}}P_1,\ \Pi_{22}=P_2W+W^{\mathrm{T}}P^2+P_2LB_0V+V^{\mathrm{T}}B_0^{\mathrm{T}}L^{\mathrm{T}}P_2.$$

2) 证明 $\Omega_2<0 \Leftrightarrow \Omega_3<0$. $\Omega_2<0$，两边同乘 $\mathrm{diag}\{Q_1\quad Q_2\quad Q_1\quad Q_2\quad I\quad I\}$，可得 $\Omega_2<0 \Leftrightarrow \Omega_3<0$.

$$\Omega=\begin{bmatrix}\Theta_1 & B_0VQ_2 & Q_1B_1^{\mathrm{T}} & Q_1B_1^{\mathrm{T}}L^{\mathrm{T}} & Q_1C_1^{\mathrm{T}} & 0\\ * & \Theta_2 & 0 & 0 & Q_2C_2^{\mathrm{T}} & F\\ * & * & -Q_1 & 0 & 0 & 0\\ * & * & * & -Q_2 & 0 & 0\\ * & * & * & * & -I & 0\\ * & * & * & * & * & -\alpha^2 I\end{bmatrix}<0, \tag{34}$$

$$\Theta_1=AQ_1+Q_1^{\mathrm{T}}A^{\mathrm{T}}+B_0R+R^{\mathrm{T}}B_0^{\mathrm{T}},\ \Theta_2=Q_2W+W^{\mathrm{T}}Q_2^{\mathrm{T}}+LB_0VQ_2+Q_2V^{\mathrm{T}}B_0^{\mathrm{T}}L^{\mathrm{T}}.$$

3) 证明 $\Omega_3<0 \Leftrightarrow \Omega<0$. 令 $K=RQ_1^{-1}$，可得 $\Omega_3<0 \Leftrightarrow \Omega<0$.

综上所述，$\Omega<0 \Leftrightarrow \Omega_3<0 \Leftrightarrow \Omega_2<0 \Leftrightarrow \Omega_1<0 \Leftrightarrow \Omega_0<0$. 显然，如果 $\Omega_1<0$ 则 $J(t)<0$，从而 $\|h(t)\|_2<\alpha\|\varepsilon(z)\|_2$. 因此，复合系统(19)在 $\bar{\varepsilon}(z)=0$ 时是依均方渐近有界的，在 $\bar{\varepsilon}(z)\neq 0$ 时满足 $\|h(t)\|_2<\alpha\|\varepsilon(z)\|_2$.

4 仿真案例

为验证所提方法的有效性,给定一个数值仿真算例. 考虑带有如下系统参数:

$$A=\begin{bmatrix}1 & 32.37 & 32.2\\ -0.2 & 0.5 & 0\\ 3 & 4.72 & 0\end{bmatrix},\ B_0=\begin{bmatrix}3\\1\\2\end{bmatrix},\ B_1=\begin{bmatrix}-0.1 & -2.65 & 0.1\\ 0 & -1 & 0.62\\ 2.13 & -0.65 & 2\end{bmatrix},$$

$$W=\begin{bmatrix}-1 & 5\\ -5 & -4\end{bmatrix},\ V=[5\quad 0],\ F=\begin{bmatrix}-1.72\\ 0.59\end{bmatrix},\ C_1=[-5\quad 0\quad 1],\ C_2=[1\quad 1].$$

假设$f(z)=2\sin(z_1)z_2^2$,定义模糊隶属度函数

$$\mu_{F_i^1}(z_i)=\exp\left[\frac{-0.5(z_i+1)^2}{4}\right],\ \mu_{F_i^2}(z_i)=\exp\left[\frac{-0.5(z_i+0.5)^2}{4}\right],\ \mu_{F_i^3}(z_i)=\exp\left[\frac{-0.5z_i^2}{4}\right],$$

$$\mu_{F_i^4}(z_i)=\exp\left[\frac{-0.5(z_i-0.5)^2}{4}\right],\ \mu_{F_i^5}(z_i)=\exp\left[\frac{-0.5(z_i-1)^2}{4}\right],\ i=1,\cdots,4.$$

系统初始状态假设为$x(0)=[2,2,-1]^{\mathrm{T}}$,通过将极点配置到$[-6\quad -4.2]$,求得:

$$L=\begin{bmatrix}-0.2229 & -0.0743 & -0.1486\\ 0.2109 & 0.0703 & 0.1406\end{bmatrix}.$$

根据定理1,可得

$$K=[-6.2493\quad -1.2056\quad -8.1723],\ R=[-18.0888\quad -7.6857\quad -3.3239],$$

$$Q_1=\begin{bmatrix}3.7992 & 1.7532 & -0.9504\\ 1.7532 & 1.5178 & -0.6241\\ -0.9504 & -0.6241 & 1.2256\end{bmatrix},Q_2=\begin{bmatrix}1.0308 & -0.3776\\ -0.3776 & 1.3584\end{bmatrix}.$$

仿真结果见图1~4.

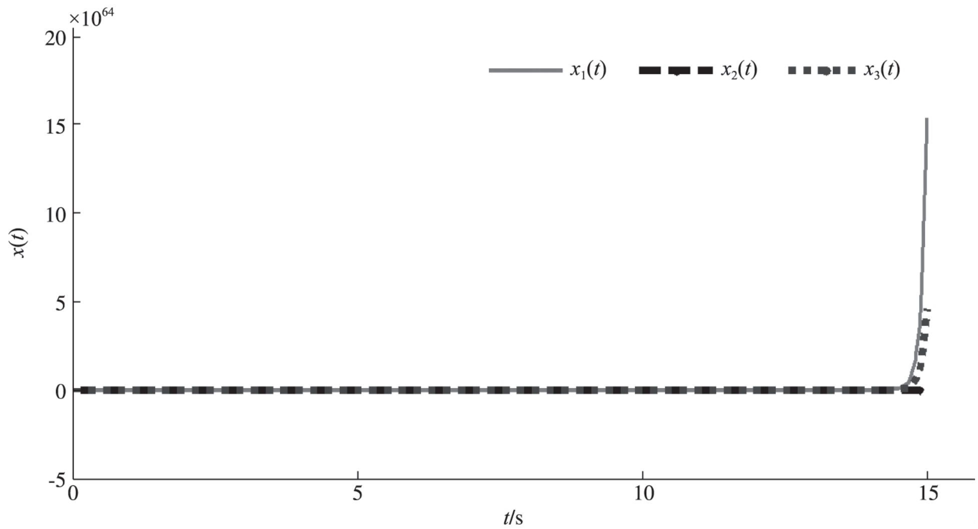

图1 无控状态下系统响应曲线

Fig. 1 The response of system states without control

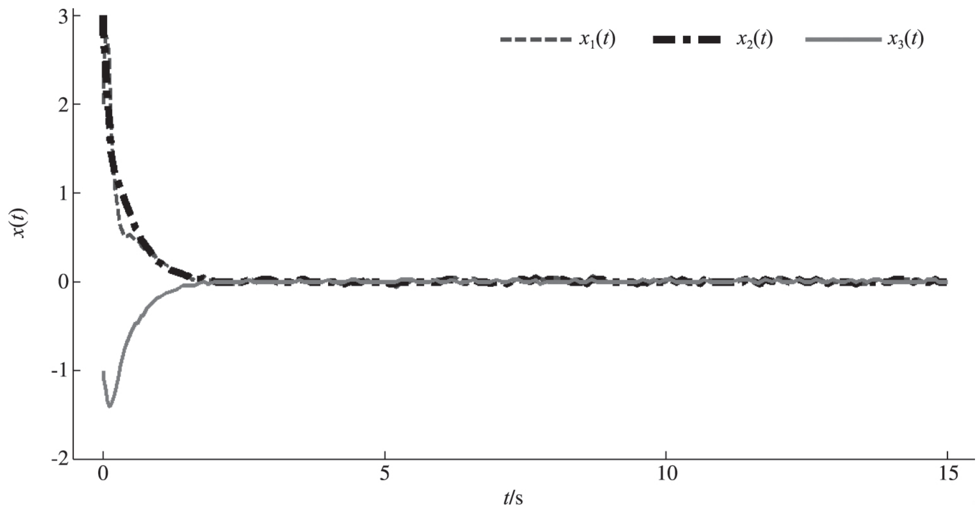

图 2　系统状态在加入控制器后的响应曲线

Fig. 2 The response of system states under EADC

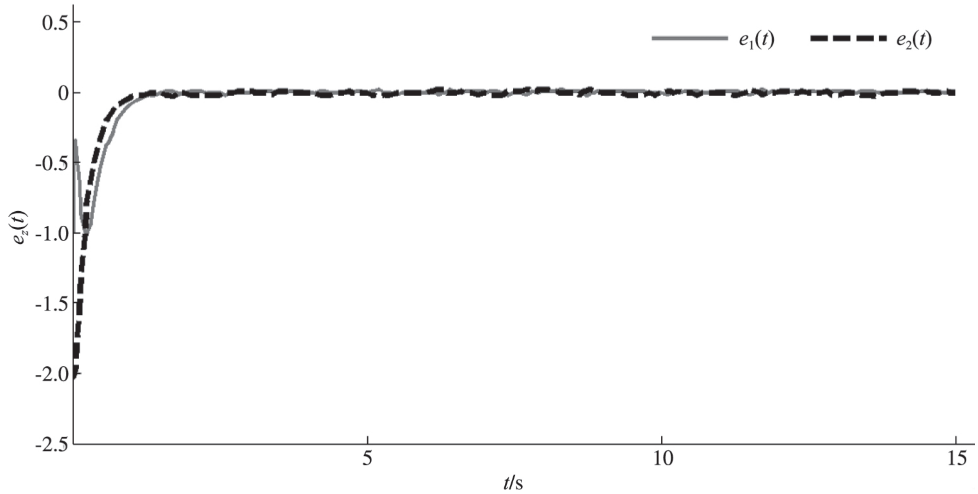

图 3　干扰误差估计

Fig. 3 The response of the disturbance estimation error

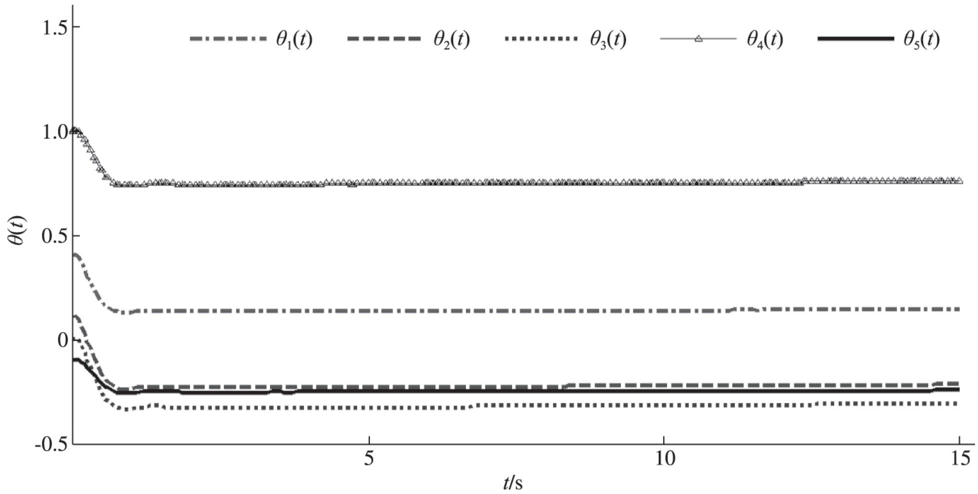

图 4　自适应参数轨迹曲线

Fig. 4 The trajectory of parameters θ

5 结语

本文研究了一类带有多源异质干扰的随机系统的抗干扰问题.构造了一个自适应干扰观测器来估计带有未知非线性函数的非谐波干扰,并采用模糊逻辑系统来逼近未知非线性函数.在自适应干扰观测器的基础上,提出了一个精细抗干扰控制方案使得复合系统达到依均方渐近有界.进一步的研究工作将考虑随机系统带有未知频率、未知幅度和未知相位的扰动.

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Fine-grained Expression Recognition of Attention Bilinear Pooling Based on Feature Fusion

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Abstract: The subtle differences in facial expressions can convey very different emotions, making facial recognition a challenging task. In this paper, a feature fusion attention bilinear pooling model (FFABP) has been proposed to capture and fuse second-order local features and first-order global features, which realizes the combining of the coarse-grained and fine-grained features. Attention is used by bilinear pooling model. The high-dimensional space representation of the bilinear pooling model is used to capture the subtle local differences between expressions, and the attention is used to highlight the role of important spatial positions in the feature maps. Self-attention is used in FFABP to learn the relationship between different regional features, which can obtain the global geometric features of images. Experiments show that the model can obtain competitive performance and robustness on FER2013 and CK + datasets compared with other existing models.

Keywords: feature fusion; attention; subtle facial expression recognition

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Elegant Anti – disturbance Control for Stochastic Systems with Multiple Heterogeneous Disturbances Based on Fuzzy Logic Systems

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Abstract: The problem of elegant anti – disturbance control for a class of stochastic systems with multiple heterogeneous disturbances was considered in this paper. The disturbances include white noise and non – harmonic disturbances with unknown smooth nonlinear functions, which can be approximated by fuzzy logic systems. Based on the approximation of the unknown nonlinear function, an adaptive disturbance observer was constructed. Combining disturbance observer – based control with fuzzy control, an elegant anti – disturbance control (EADC) scheme was proposed such that the composite system achieves asymptotically bounded in mean square. Finally, the effectiveness of the proposed scheme was verified by simulation.

Keywords: adaptive disturbance observer; elegant anti – disturbance control; multiple heterogeneous disturbances; fuzzy logic systems

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