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一个新混沌系统的自适应反同步控制及实现

摘要

针对所提出的一类新型混沌系统,研究了其驱动与响应系统的反同步控制问题.基于李雅普诺夫稳定性理论,利用自适应控制方法,提出了可以实现混沌系统反同步的控制器的设计方法和参数自适应学习算法.在此基础上,通过Matlab软件进行数值仿真,仿真结果显示所有的参数均可以得到准确地识别,并且可以在较短的时间内使误差系统趋于稳定,说明了控制器与参数自适应律的正确性.最后,基于Multisim电路仿真平台对同步电路进行验证,结果进一步证明了该方法的电路可实现性.

关键词

自适应;混沌系统;反同步控制

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0　引言

混沌也是一个非线性系统,并且动力学特性十分明显,具体表现为其随着时间的变化具有确定性的变化,同时也具有微弱的随机性变化.自从Pecora等[1]利用驱动-响应方法实现了混沌系统的同步控制后,混沌的同步控制理论[2-4]得到迅速发展,其在保密通信[5]、化学反应[6]、信息处理[7]和生物系统[8]等领域得到广泛的应用.混沌同步控制理论日臻完善,如已经提出的驱动-响应同步方法[9]、线性与非线性反馈方法[10-11]、自适应方法[12-13]、主动控制法[14]等.

现在对经典的混沌系统反同步问题已经有了一些理论成果,比如超混沌Chen系统[15-16].文献[17]对不确定参数的Lorenz系统进行了反同步控制,并且将同步的方法应用到了保密通信中,制定出新的混沌保密通信方案.本文在文献[18]的基础上提出了一个新的高维混沌系统,并且通过自适应理论对该系统在参数完全不确定的情况下进行了自适应错位反同步控制.本文基于李雅普诺夫稳定性理论设计了合适的自适应同步控制器以及参数的学习算法,并且通过Matlab以及Mutisim软件对同步方案分别进行了数值与电路仿真.仿真结果说明了本文同步方案的正确性以及可实施性.

1　新混沌系统的自适应反同步控制

1.1　新混沌系统

本文在文献[18]提出的一个新型非线性混沌系统基础上做了改进,除了在原来的数学模型上增加一维变量形成新的四维系统以外,状态变量x_1,x_2,x_4各增加了一个交叉项,x_3增加了一个平方项,由此设计了一类新型的混沌系统,其不确定参数较文献[18]更多.该系统的状态方程如下:

$$\begin{cases}\dot{x}_1 = -a_1x_1 + n_1x_2x_3,\\ \dot{x}_2 = -b_1x_1x_3 + c_1x_2 + d_1,\\ \dot{x}_3 = n_1(x_1^2 + x_2^2) - h_1x_3 - mx_4 - d_1,\\ \dot{x}_4 = -g_1x_1x_2 - l_1x_4 - d_1,\end{cases} \tag{1}$$

x_i为系统的状态变量,$a_1,b_1,c_1,d_1,n_1,l_1,m_1,g_1$是系统参数.将该系统的数学模型简化为下列形式:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{BP}(\boldsymbol{x}) + \boldsymbol{C}, \tag{2}$$

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其中 $\boldsymbol{x}$ 是系统状态变量,且 $\boldsymbol{x} \in \Omega_1 \subset \mathbf{R}^n$,$\boldsymbol{P}(\boldsymbol{x})$ 是系统的非线性项.其中,

$$\boldsymbol{A} = \begin{bmatrix} -a_1 & 0 & 0 & 0 \\ 0 & c_1 & 0 & 0 \\ 0 & 0 & -h_1 & -m_1 \\ 0 & 0 & 0 & -l_1 \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} n_1 & 0 & 0 & 0 \\ 0 & -b_1 & 0 & 0 \\ 0 & 0 & n_1 & 0 \\ 0 & 0 & 0 & -g_1 \end{bmatrix},$$

$$\boldsymbol{C} = \begin{bmatrix} 0 \\ d_1 \\ -d_1 \\ -d_1 \end{bmatrix}, \quad \boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \quad \boldsymbol{P}(\boldsymbol{x}) = \begin{bmatrix} x_2x_3 \\ x_1x_3 \\ x_1^2 + x_2^2 \\ x_1x_2 \end{bmatrix}.$$

当 $a_1 = 20, b_1 = 30, c_1 = 10, d_1 = 30, h_1 = 5, m_1 = 4, n_1 = 2.5, g_1 = 15, l_1 = 35$ 时,系统(1)呈现混沌现象,如图 1 所示.

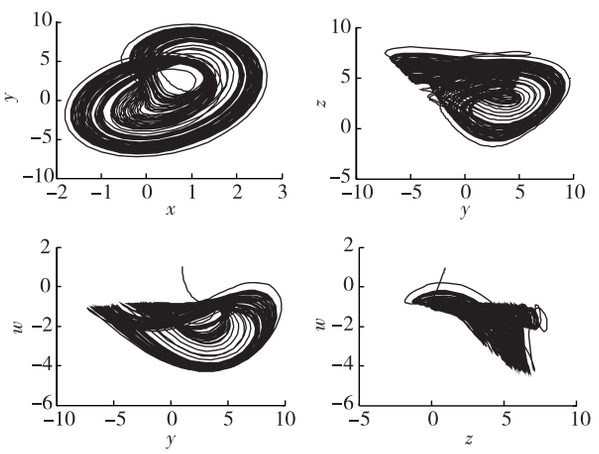


图 1 新混沌系统的相图

Fig. 1 Phase of a new chaotic systems

系统存在一个混沌吸引子,其具有混沌系统的一切特性.比如初值的敏感性、存在正的 Lyapunov 指数等.

1.2 混沌系统的反同步

将方程(1)作为驱动系统,添加相应的自适应控制器 $u_i(i = 1,2,3,4)$,则相应的响应系统表达式为

$$\begin{cases} \dot{y}_1 = -a_2y_1 + n_2y_2y_3 + u_1, \\ \dot{y}_2 = -b_2y_1y_3 + c_2y_2 + d_2 + u_2, \\ \dot{y}_3 = n_2(y_1^2 + y_2^2) - h_2y_3 - m_2y_4 - d_2 + u_3, \\ \dot{y}_4 = -g_2y_1y_2 - l_2y_4 - d_2 + u_4, \end{cases} \tag{3}$$

上述响应系统表达式可归结为

$$\dot{\boldsymbol{y}} = \boldsymbol{D}\boldsymbol{y} + \boldsymbol{E}\boldsymbol{Q}(\boldsymbol{y}) + \boldsymbol{F} + \boldsymbol{U}, \tag{4}$$

其中 $\boldsymbol{y} \in \Omega_2 \subset \mathbf{R}^n$ 是系统的状态变量,$\boldsymbol{U}$ 为系统的自适应反同步控制器,$\boldsymbol{D}$,$\boldsymbol{E}$,$\boldsymbol{F}$ 是系统的不确定参数矩阵,且

$$\boldsymbol{D} = \begin{bmatrix} -a_2 & 0 & 0 & 0 \\ 0 & c_2 & 0 & 0 \\ 0 & 0 & -h_2 & -m_2 \\ 0 & 0 & 0 & -l_2 \end{bmatrix}, \quad \boldsymbol{E} = \begin{bmatrix} n_2 & 0 & 0 & 0 \\ 0 & -b_2 & 0 & 0 \\ 0 & 0 & n_2 & 0 \\ 0 & 0 & 0 & -g_2 \end{bmatrix},$$

$$\boldsymbol{y} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix}, \boldsymbol{F} = \begin{bmatrix} 0 \\ d_2 \\ -d_2 \\ -d_2 \end{bmatrix}, \boldsymbol{U} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}, \boldsymbol{Q}(\boldsymbol{x}) = \begin{bmatrix} y_2y_3 \\ y_1y_3 \\ y_1^2 + y_2^2 \\ y_1y_2 \end{bmatrix}.$$

令驱动系统(1)和响应系统(3)的反同步误差为

$$e_i = x_i + y_j, i \neq j, \tag{5}$$

则误差系统可表示为

$$\dot{\boldsymbol{e}} = \dot{\boldsymbol{x}} + \dot{\boldsymbol{y}} \tag{6}$$

其中

$$\begin{cases} e_1 = y_3 + x_1, \\ e_2 = y_4 + x_2, \\ e_3 = y_2 + x_3, \\ e_4 = y_1 + x_4. \end{cases} \tag{7}$$

将上述驱动系统(1)和响应系统(3)代入(7),计算可得到相应的误差系统为

$$\begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \end{bmatrix} = \begin{bmatrix} -\tilde{a}_1 + \hat{a}_1 & 0 & 0 & 0 \\ 0 & \tilde{c}_1 - \hat{c}_1 & 0 & 0 \\ 0 & 0 & -\tilde{h}_1 + \hat{h}_1 & -\tilde{m}_1 + \hat{m}_1 \\ 0 & 0 & 0 & -\tilde{l}_1 + \hat{l}_1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} +$$

$$\begin{bmatrix} \tilde{n}_1 - \hat{n}_1 & 0 & 0 & 0 \\ 0 & -\tilde{b}_1 + \hat{b}_1 & 0 & 0 \\ 0 & 0 & \tilde{n}_1 - \hat{n}_1 & 0 \\ 0 & 0 & 0 & -\tilde{g}_1 + \hat{g}_1 \end{bmatrix} \cdot \begin{bmatrix} x_2x_3 \\ x_1x_2 \\ x_1^2 + x_2^2 \\ x_1x_2 \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ d_1 \\ -d_1 \\ -d_1 \end{bmatrix} + \begin{bmatrix} 0 & 0 & -\tilde{h}_2 + \hat{h}_2 & -\tilde{m}_2 + \hat{m}_2 \\ 0 & 0 & 0 & -\tilde{l}_2 + \hat{l}_2 \\ -\tilde{a}_2 + \hat{a}_2 & 0 & 0 & 0 \\ 0 & \tilde{c}_2 - \hat{c}_2 & 0 & 0 \end{bmatrix} \cdot$$

$$\begin{bmatrix} y_3 \\ y_4 \\ y_2 \\ y_1 \end{bmatrix} + \begin{bmatrix} \tilde{n}_2 - \hat{n}_2 & 0 & 0 & 0 \\ 0 & -\tilde{g}_2 + \hat{g}_2 & 0 & 0 \\ 0 & 0 & \tilde{n}_2 - \hat{n}_2 & 0 \\ 0 & 0 & 0 & -\tilde{b}_2 + \hat{b}_2 \end{bmatrix} \cdot$$

$$\begin{bmatrix} y_1^2 + y_2^2 \\ y_1y_2 \\ y_2y_3 \\ y_1y_3 \end{bmatrix} + \begin{bmatrix} 0 \\ d_2 \\ -d_2 \\ -d_2 \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix}, \tag{8}$$

其中 $\tilde{a}_i = a_i - \hat{a}_i, \tilde{b}_i = b_i - \hat{b}_i, \tilde{c}_i = c_i - \hat{c}_i, \tilde{d}_i = d_i - \hat{d}_i,$

$\tilde{h}_i = h_i - \hat{h}_i, \tilde{l}_i = l_i - \hat{l}_i, \tilde{m}_i = m_i - \hat{m}_i, \tilde{n}_i = n_i - \hat{n}_i, \tilde{g}_i = g_i - \hat{g}_i, i = 1,2.$

定理 1 针对系统(1)和(3),设计如下所示的自适应控制器:

$$\begin{cases} u_1 = \hat{a}_2 y_1 - \hat{n}_2 y_2 y_3 + \hat{g}_1 x_1 x_2 + \hat{e}_1 x_4 + \hat{d}_1 - K_4 e_4, \\ u_2 = \hat{b}_1 y_1 y_3 - \hat{c}_2 y_2 - \hat{d}_2 - \hat{n}_1 (x_1^2 + x_2^2) + \\ \quad \hat{h}_1 x_3 + \hat{m}_1 x_4 + \hat{d}_1 - K_3 e_3, \\ u_3 = -\hat{n}_2 (y_1^2 + y_2^2) + \hat{d}_2 + \hat{h}_2 y_3 + \hat{m}_2 y_4 + \\ \quad \hat{a}_1 x_1 - \hat{n}_1 x_2 x_3 - K_1 e_1, \\ u_4 = \hat{g}_2 y_1 y_2 + \hat{e}_2 y_4 + \hat{b}_1 x_1 x_3 - \hat{c}_1 x_2 + \hat{d}_2 - K_2 e_2, \end{cases} \tag{9}$$

其中 K_1, K_2, K_3, K_4 为大于0的可调系数,驱动系统和响应参数自适应律设计如下:

$$\begin{cases} \dot{\hat{a}}_1 = e_1 x_1 - k_{11} \tilde{a}_1, \\ \dot{\hat{b}}_1 = e_2 x_1 x_3 - k_{12} \tilde{b}_1, \\ \dot{\hat{c}}_1 = -e_2 x_2 - k_{13} \tilde{c}_1, \\ \dot{\hat{d}}_1 = -e_2 + e_3 + e_4 - k_{14} \tilde{d}_1, \\ \dot{\hat{h}}_1 = e_3 x_3 - k_{15} \tilde{h}_1, \\ \dot{\hat{m}}_1 = e_3 x_4 - k_{16} \tilde{m}_1 \\ \dot{\hat{n}}_1 = -e_1 x_2 x_3 - (x_1^2 + x_2^2) e_3 - k_{17} \tilde{n}_1, \\ \dot{\hat{l}}_1 = x_4 e_4 - k_{18} \tilde{l}_1, \\ \dot{\hat{g}}_1 = e_4 x_1 x_2 - k_{19} \tilde{g}_1, \\ \dot{\hat{a}}_2 = e_4 y_1 - k_{20} \tilde{a}_2, \\ \dot{\hat{b}}_2 = e_3 y_1 y_3 - k_{21} \tilde{b}_2, \\ \dot{\hat{c}}_2 = -e_3 y_2 - k_{22} \tilde{c}_2, \\ \dot{\tilde{d}}_2 = e_1 - e_3 + e_2 - k_{23} \tilde{d}_2, \\ \dot{\hat{h}}_2 = e_1 y_3 - k_{24} \tilde{h}_2, \\ \dot{\hat{m}}_2 = e_1 y_4 - k_{26} \tilde{m}_2, \\ \dot{\hat{g}}_2 = e_2 y_1 y_2 - k_{28} \tilde{g}_2 \\ \dot{\hat{l}}_2 = e_2 y_4 - k_{25} \tilde{l}_2, \\ \dot{\hat{n}}_2 = -e_4 y_2 y_3 - e_1 (y_1^2 + y_2^2) - k_{27} \tilde{n}_2, \end{cases} \tag{10}$$

那么驱动系统(1)和响应系统(3)可以实现反同步控制.其中 $k_{1n}, k_{2n} \geqslant 0 (n = 1,2,3,\cdots,9)$ 且为常数.

证明 构造 Lyapunov 势函数如下:

$$V = \frac{1}{2}(e_1^2 + e_2^2 + e_3^2 + e_4^2 + \tilde{a}_1^2 + \tilde{b}_1^2 + \tilde{c}_1^2 + \tilde{d}_1^2 + \tilde{l}_1^2 + \tilde{n}_1^2 + \tilde{m}_1^2 + \tilde{g}_1^2 + \tilde{a}_2^2 + \tilde{b}_2^2 + \tilde{c}_2^2 + \tilde{d}_2^2 + \tilde{l}_2^2 + \tilde{n}_2^2 + \tilde{m}_2^2 + \tilde{g}_2^2),$$

对 V 求导得:

$$\dot{V} = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 + e_4 \dot{e}_4 + \tilde{a}_1 \dot{\tilde{a}}_1 + \tilde{b}_1 \dot{\tilde{b}}_1 + \tilde{c}_1 \dot{\tilde{c}}_1 + \tilde{d}_1 \dot{\tilde{d}}_1 + \tilde{l}_1 \dot{\tilde{l}}_1 + \tilde{m}_1 \dot{\tilde{m}}_1 + \tilde{n}_1 \dot{\tilde{n}}_1 + \tilde{g}_1 \dot{\tilde{g}}_1 + \tilde{a}_2 \dot{\tilde{a}}_2 + \tilde{b}_2 \dot{\tilde{b}}_2 + \tilde{c}_2 \dot{\tilde{c}}_2 + \tilde{d}_2 \dot{\tilde{d}}_2 + \tilde{l}_2 \dot{\tilde{l}}_2 + \tilde{m}_2 \dot{\tilde{m}}_2 + \tilde{n}_2 \dot{\tilde{n}}_2 + \tilde{g}_2 \dot{\tilde{g}}_2. \tag{11}$$

将式(9)、(10)带入式(11)可得:

$$\dot{V} = -(K_1 e_1^2 + K_2 e_2^2 + K_3 e_3^2 + K_4 e_4^2 - k_{11} \tilde{a}_1^2 - k_{12} \tilde{b}_1^2 - k_{13} \tilde{c}_1^2 - k_{14} \tilde{d}_1^2 - k_{15} \tilde{h}_1^2 - k_{16} \tilde{m}_1^2 - k_{17} \tilde{n}_1^2 - k_{18} \tilde{l}_1^2 - k_{19} \tilde{g}_1^2 - k_{20} \tilde{a}_2^2 - k_{21} \tilde{b}_2^2 - k_{22} \tilde{c}_2^2 - k_{23} \tilde{d}_2^2 - k_{24} \tilde{h}_2^2 - k_{25} \tilde{m}_2^2 - k_{26} \tilde{n}_2^2 - k_{27} \tilde{l}_2^2 - k_{28} \tilde{g}_2^2 < 0,$$

$\lim_{t \to \infty} \dot{V} = 0 \Rightarrow \lim_{t \to \infty} e_i(t) = 0 (i = 1,2,3,4)$,由李雅普诺夫定理得,误差系统稳定,即驱动系统(1)和响应系统(3)实现反同步.定理 1 得证.

2 系统的数值仿真

根据上述驱动响应系统的控制器和参数自适应律,在 Matlab 中通过数值仿真来验证方法的有效性.设系统状态变量初值为 $(x_1(0), x_2(0), x_3(0), x_4(0)) = (1,1,1,1)$,$(y_1(0), y_2(0), y_3(0), y_4(0)) = (0,0,0,0)$,系统的误差为 $(e_1(0), e_2(0), e_3(0), e_4(0)) = (1,1,1,1)$,系统自适应参数设置为 $(a_1, b_1, c_1, d_1, m_1, n_1, g_1, l_1, h_1) = (20,30,10,30,4,2.5,5,35,5)$,响应系统参数设置为 $(a_2, b_2, c_2, d_2, m_2, n_2, g_2, l_2, h_2) = (25,30,10,35,5,3,20,35,5)$,参数估计值的初值全部设置为 0,可调系数设置为 $k_i = 0.1, K_i = 2$.

在仿真实验中,在控制器 U 的作用下,驱动和响应系统很快可以实现反同步,驱动系统和响应系统的状态曲线如图 2 所示.

由图 2 可以看出,随着时间的变化,驱动系统(1)和响应系统(2)的状态变量曲线都相应地实现了反同步,与预期的效果一致.

仿真中时间步长设置为 0.01 s.反同步误差如图 3 所示.

图 3 表明在自适应控制器的作用下,最终系统的误差稳定地趋于 0,实现了混沌系统的反同步.

图 4 和图 5 是系统自适应参数的仿真变化曲线.

由图 4 和图 5 可以看出,自适应参数在 5 s 左右已经基本上达到真实值,在 10 s 内已经可以稳定在最初设定的值.

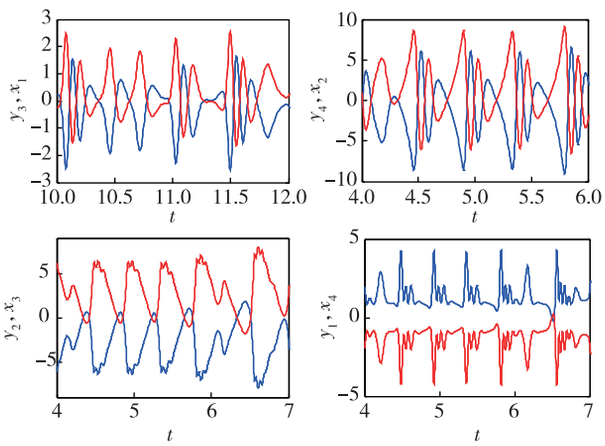


图 2　驱动系统(1)和响应系统(2)反同步变化曲线

Fig. 2　Anti-synchronization curves of the drive system(1) and response system(2)

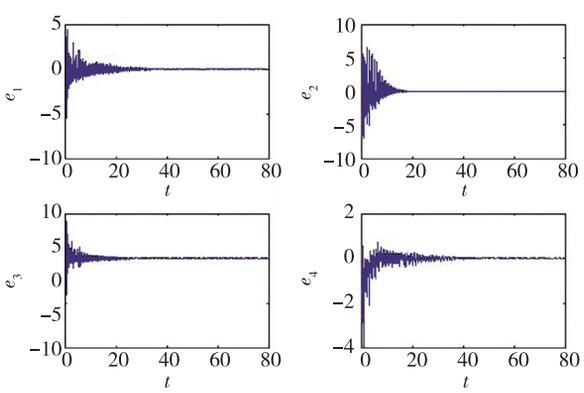


图 3　误差 e_1,e_2,e_3,e_4 的变化曲线

Fig. 3　Changing curves of error e_1,e_2,e_3,e_4

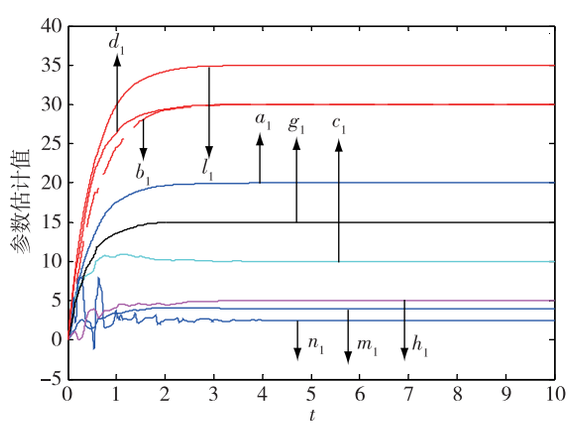


图 4　驱动系统不确定参数估计变化曲线

Fig. 4　Uncertainty parameters estimation curves of drive system

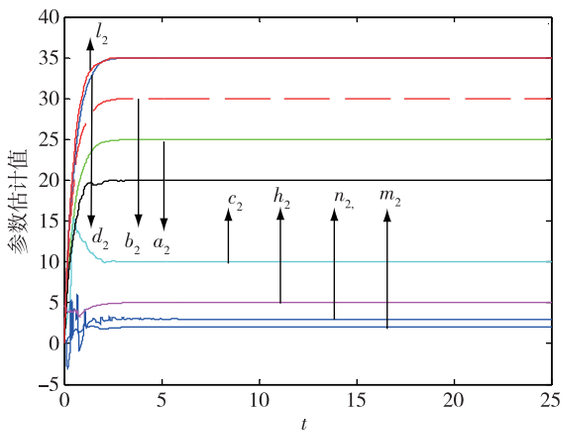


图 5　响应系统不确定参数估计变化曲线

Fig. 5　Uncertainty parameters estimation curves of response system

3　系统的电路仿真

以上通过数值仿真成功地实现了 2 个新混沌系统的自适应错位反同步,下面通过 Multisim 软件对本文的方案进行硬件实现,实验结果如图 6 所示.

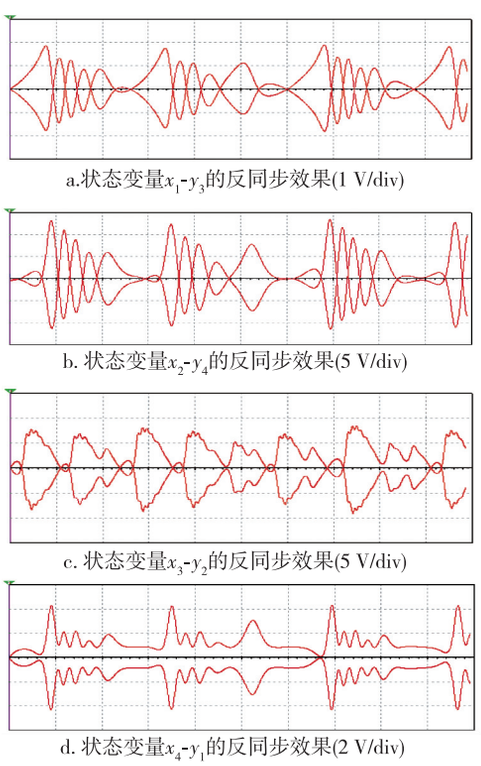


图 6　状态变量的反同步效果

Fig. 6　Anti-synchronization result of state variables

由图 6 可以看出自适应反同步控制的电路仿真达到了预期的效果,说明通过电路仿真也可以实现混沌系统的自适应反同步控制.图 7—9 是部分仿真电路.

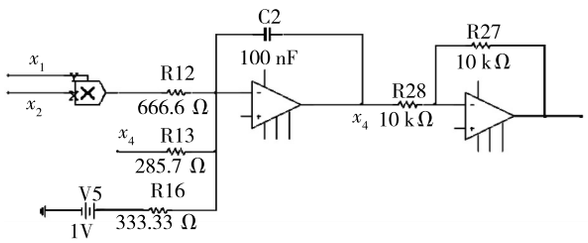


图 7 状态变量 x_4 的设计

Fig. 7 Design of state variable x_4

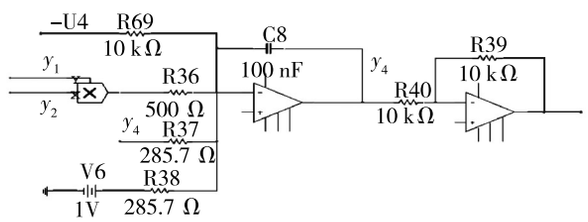


图 8 状态变量 y_4 的设计

Fig. 8 Design of state variable y_4

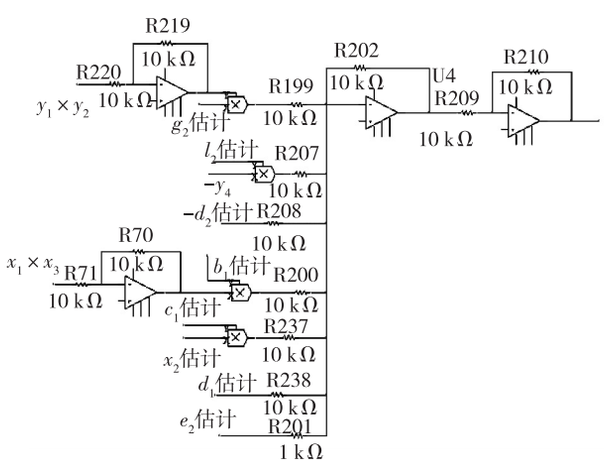


图 9 控制器 U_4 的设计

Fig. 9 Design of controller U_4

4 总结

本文针对一类四维新型混沌系统,设计了自适应反同步控制器和参数自适应律.将该方法通过 Matlab 软件和 Multisim 软件进行仿真,2 种仿真结果一致,都实现了 2 个系统的反同步控制,说明了本文所设计的控制器的有效性.

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Adaptive anti synchronization control of a new chaotic system and its implementation

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Abstract As for a new proposed class of chaotic system, the anti-synchronization control problem is studied between the drive and the response system. Based on Lyapunov stability theory and the adaptive control method, a method of controller design and an adaptive learning algorithm of the parameters are presented for the anti-synchronization of the new chaotic system. On this basis, through the numerical simulation carried out via Matlab software, the simulation results show that all the parameters can be accurately identified, and that it can make error system stable in a relatively short period of time, which certifies the correctness of the controller and the parameter adaptive law. Finally, synchronization circuit results are verified via Multisim simulation platform, which further proves that the circuit can be realized.

Key words adaptive; chaotic system; anti-synchronization control