ACTIVE CONTROLLER DESIGN FOR GLOBAL CHAOS ANTI-SYNCHRONIZATION OF LI AND TIGAN CHAOTIC SYSTEMS

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ABSTRACT

This paper discusses the design of active controllers for achieving global chaos anti-synchronization of identical Li systems (2009), Tigan systems (2008) and non-identical Li and Tigan systems. Lyapunov stability theory has been deployed for establishing the anti-synchronization results derived in this paper for Li and Tigan chaotic systems. Since the Lyapunov exponents are not required for these calculations, the active nonlinear control method is very effective and suitable to achieve anti-synchronization of identical and non-identical Li and Tigan chaotic systems. Numerical simulations have been presented to illustrate the anti-synchronization results for the chaotic systems addressed in this paper.

KEYWORDS

Active Control, Anti-Synchronization, Chaotic Systems, Li System, Tigan System, Nonlinear Control.

1. INTRODUCTION

Chaotic systems are nonlinear dynamical systems which are highly sensitive to initial conditions. This sensitivity of chaotic systems is usually called as the *butterfly effect* [1].

Chaos synchronization problem received great attention in the literature when Pecora and Carroll [2] published their results on chaos synchronization in 1990. From then on, chaos synchronization has been extensively and intensively studied in the last three decades [3-25]. Chaos theory has been explored in a variety of fields including physical systems [3], chemical systems [4], ecological systems [5], secure communications [6-7], etc.

Synchronization of chaotic systems is a phenomenon that may occur when a chaotic oscillator drives another chaotic oscillator. Because of the butterfly effect which causes the exponential divergence of the trajectories of two identical chaotic systems started with nearly the same initial conditions, synchronizing two chaotic systems is seemingly a very challenging problem.

In most of the chaos synchronization approaches, the master-slave or drive-response formalism is used. If a particular chaotic system is called the *master* or *drive* system and another chaotic system is called the *slave* or *response* system, then the idea of anti-synchronization is to use the output of the master system to control the slave system so that the states of the slave system have the same amplitude but opposite signs as the states of the master system asymptotically. In other words, the sum of the states of the master and slave systems are designed to converge to zero asymptotically, when anti-synchronization appears.

In the recent years, various schemes have been deployed for chaos synchronization such as PC method [2], OGY method [8], active control [9-12], adaptive control [13-15], backstepping design [16], sampled-data feedback [17], sliding mode control [18-20], etc. Recently, active control method has been applied to achieve anti-synchronization of two identical chaotic systems [21-22].

In this paper, we use active control to derive new results for the global chaos anti-synchronization of identical Li systems ([23], 2009), identical Tigan systems ([24], 2008) and non-identical Li and Tigan systems.

This paper is organized as follows. In Section 2, we describe the problem statement and our methodology using Lyapunov stability theory. In Section 3, we give a description of the chaotic systems addressed in this paper, viz. Li system (2009) and Tigan system (2008). In Section 4, we derive results for the anti-synchronization of identical Li systems (2009) using active nonlinear control. In Section 5, we derive results for the anti-synchronization of identical Tigan systems (2008) using active nonlinear control. In Section 6, we derive results for the anti-synchronization of Li and Tigan systems using active nonlinear control. In Section 7, we summarize the main results obtained in this paper.

2. PROBLEM STATEMENT AND OUR METHODOLOGY

As the *master* or *drive* system, we consider the chaotic system described by

$$\dot{x} = Ax + f(x), \tag{1}$$

where $x \in R^n$ is the state vector, A is the $n \times n$ matrix of system parameters and $f : R^n \to R^n$ is the nonlinear part of the system.

As the *slave* or *response* system, we consider the following chaotic system described by

$$\dot{y} = By + g(y) + u, \tag{2}$$

where $y \in R^n$ is the state of the slave system, B is the $n \times n$ matrix of system parameters, $g : R^n \to R^n$ is the nonlinear part of the system and u is the active controller to be designed.

If $A = B$ and $f = g$, then x and y are the states of two identical chaotic systems. If $A \neq B$ or $f \neq g$, then x and y are the states of two different chaotic systems.

For the anti-synchronization of the chaotic systems (1) and (2) using active control, we design a state feedback controller u, which anti-synchronizes the states of the master system (1) and the slave system (2) for all initial conditions $x(0), y(0) \in R^n$.

If we define the anti-synchronization error as

$$e = y + x, \tag{3}$$

then the error dynamics is obtained as

$$\dot{e} = By + Ax + g(y) + f(x) + u \tag{4}$$

Thus, the global anti-synchronization problem is essentially to find a feedback controller (active controller) u so as to stabilize the error dynamics (4) for all initial conditions, *i.e.*

$$\lim_{t\to\infty} \|e(t)\| = 0, \quad \text{for all } e(0)\in R^n \tag{5}$$

We use the Lyapunov stability theory as our methodology. We take as a candidate Lyapunov function

$$V(e) = e^T Pe, \tag{6}$$

where P is a positive definite matrix. Note that $V : R^n \to R$ is a positive definite function by construction.

If we find a feedback controller u so that

$$\dot{V}(e) = -e^T Qe, \tag{7}$$

where Q is a positive definite matrix, then $\dot{V} : R^n \to R$ is a negative definite function.

Thus, by Lyapunov stability theory [25], the error dynamics (4) is globally exponentially stable.

3. SYSTEMS DESCRIPTION

The Li system ([23], 2009) is described by the dynamics

$$\begin{aligned} \dot{x}_1 &= a(x_2 - x_1) \\ \dot{x}_2 &= x_1 x_3 - x_2 \\ \dot{x}_3 &= b - x_1 x_2 - c x_3 \end{aligned} \tag{8}$$

where x_1, x_2, x_3 are the state variables and a, b, c are constant, positive parameters of the system.

The Li dynamics (8) is chaotic when the parameter values are taken as $a = 5,\ b = 16$ and $c = 1$. Figure 1 describes the state portrait of the Li system (8).

The Tigan system ([24], 2008) is described by the dynamics

$$\begin{aligned} \dot{x}_1 &= \alpha(x_2 - x_1) \\ \dot{x}_2 &= (\gamma - \alpha) x_1 - \alpha x_1 x_3 \\ \dot{x}_3 &= -\beta x_3 + x_1 x_2 \end{aligned} \tag{9}$$

where x_1, x_2, x_3 are the state variables and α, β, γ are constant, positive parameters of the system.

The Tigan dynamics (9) is chaotic when the parameter values are taken as $\alpha = 2.1,\ \beta = 0.6$ and $\gamma = 30$. Figure 2 describes the state portrait of the Tigan system (9).

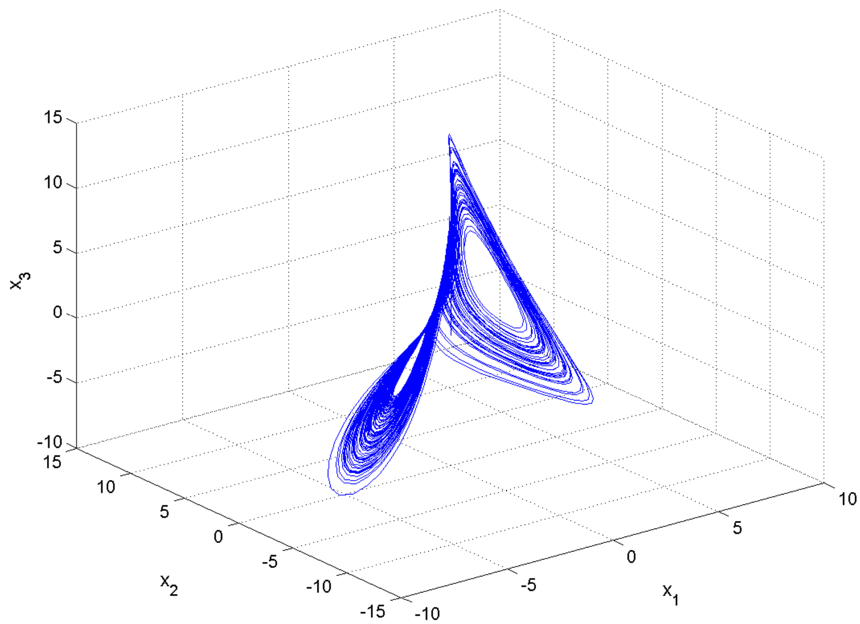

Figure 1. State Orbits of the Li System

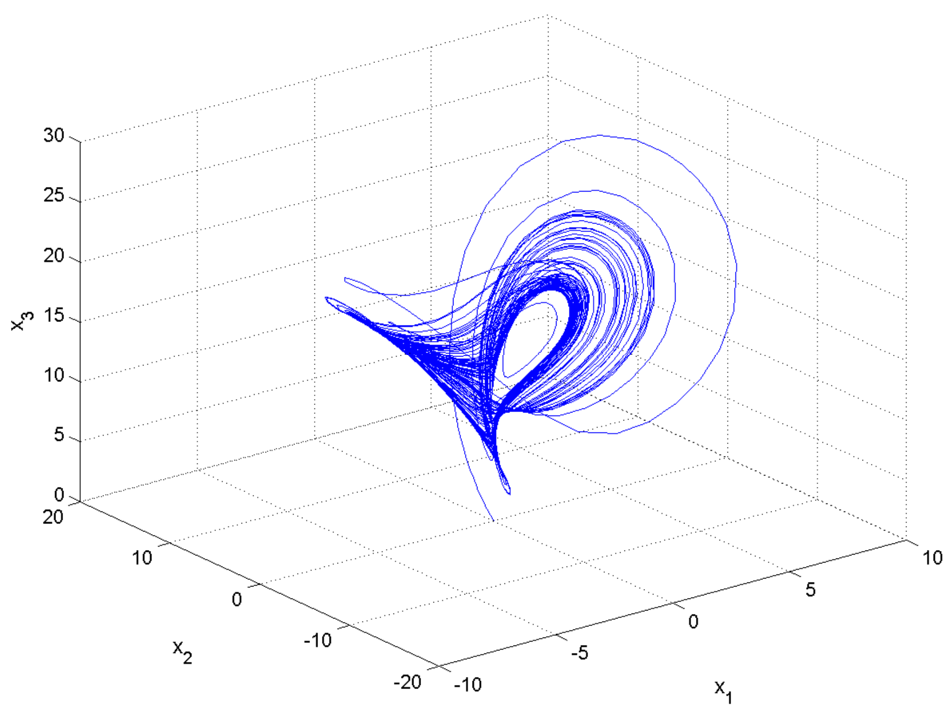

Figure 2. State Orbits of the Tigan System

4. ANTI-SYNCHRONIZATION OF IDENTICAL LI SYSTEMS

In this section, we consider the anti-synchronization of identical Li systems ([23], 2009).

As the master system, we consider the Li dynamics described by

$$\begin{aligned} \dot{x}_1 &= a(x_2 - x_1) \\ \dot{x}_2 &= x_1 x_3 - x_2 \\ \dot{x}_3 &= b - x_1 x_2 - c x_3 \end{aligned} \tag{10}$$

where x_1, x_2, x_3 are the state variables and a, b, c are positive constants.

As the slave system, we consider the controlled Li dynamics described by

$$\begin{aligned} \dot{y}_1 &= a(y_2 - y_1) + u_1 \\ \dot{y}_2 &= y_1 y_3 - y_2 + u_2 \\ \dot{y}_3 &= b - y_1 y_2 - c y_3 + u_3 \end{aligned} \tag{11}$$

where y_1, y_2, y_3 are the state variables and u_1, u_2, u_3 are the active controls.

The anti-synchronization error is defined as

$$\begin{aligned} e_1 &= y_1 + x_1 \\ e_2 &= y_2 + x_2 \\ e_3 &= y_3 + x_3 \end{aligned} \tag{12}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= a(e_2 - e_1) + u_1 \\ \dot{e}_2 &= -e_2 + y_1 y_3 + x_1 x_3 + u_2 \\ \dot{e}_3 &= -c e_3 + 2b - y_1 y_2 - x_1 x_2 + u_3 \end{aligned} \tag{13}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -a e_2 \\ u_2 &= -y_1 y_3 - x_1 x_3 \\ u_3 &= -2b + y_1 y_2 + x_1 x_2 \end{aligned} \tag{14}$$

Substitution of (14) into (13) yields the linear error dynamics

$$\begin{aligned} \dot{e}_1 &= -a e_1 \\ \dot{e}_2 &= -e_2 \\ \dot{e}_3 &= -c e_3 \end{aligned} \tag{15}$$

We consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2}e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2\right), \tag{16}$$

which is a positive definite function on R^3.

Differentiating (16) along the trajectories of the error system (15), we get

$$\dot{V}(e) = -ae_1^2 - e_2^2 - ce_3^2, \tag{17}$$

which is a negative definite function on R^3 since a and c are positive constants.

Thus, by Lyapunov stability theory [25], the error dynamics (15) is globally exponentially stable. Hence, we obtain the following result.

Theorem 1. The identical Li systems (10) and (11) are globally and exponentially anti-synchronized with the active nonlinear controller (14). ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-6}$ is used to solve the two systems of differential equations (10) and (11) with the nonlinear controller (14).

The Li chaotic system (2009) is one of the important paradigms of three-dimensional chaotic systems.

The parameters of the identical Li systems (10) and (11) are selected as

$$a = 5,\ b = 16,\ c = 1$$

so that the systems (10) and (11) exhibit chaotic behaviour.

The initial values for the master system (10) are taken as

$$x_1(0) = 12,\ \ x_2(0) = 8,\ \ x_3(0) = 25$$

and the initial values for the slave system (11) are taken as

$$y_1(0) = 4,\ \ y_2(0) = 16,\ \ y_3(0) = 26$$

Figure 3 depicts the anti-synchronization of the identical Li chaotic systems (10) and (11).

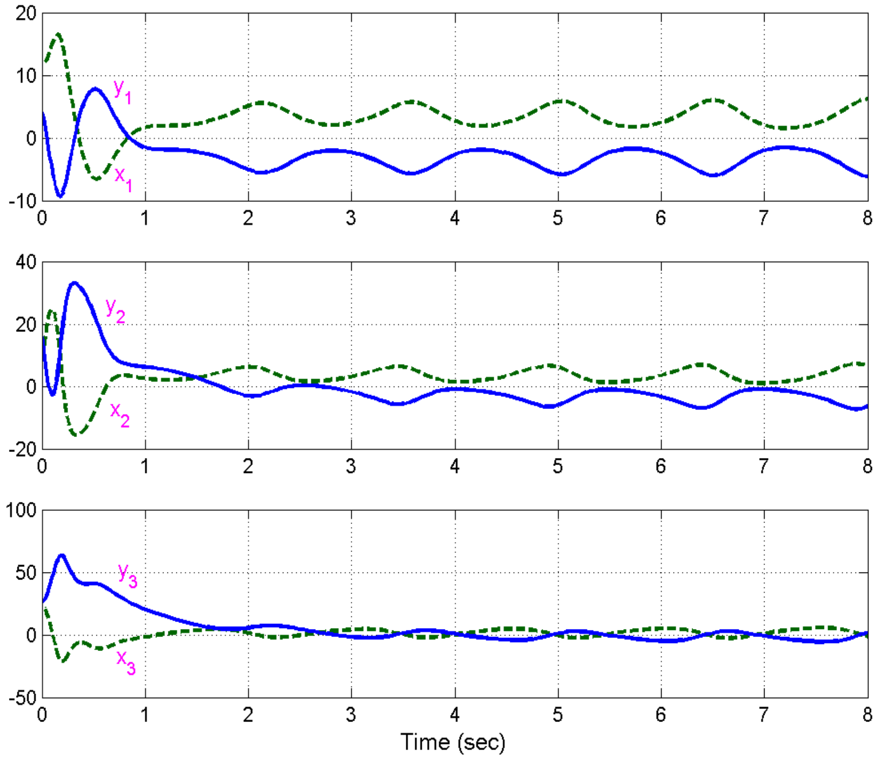

Figure 3. Anti-Synchronization of Identical Li Systems

5. ANTI-SYNCHRONIZATION OF IDENTICAL TIGAN SYSTEMS

In this section, we consider the anti-synchronization of identical Tigan systems ([24], 2008).

As the master system, we consider the Tigan dynamics described by

$$\begin{aligned} \dot{x}_1 &= \alpha(x_2 - x_1) \\ \dot{x}_2 &= (\gamma - \alpha)x_1 - \alpha x_1 x_3 \\ \dot{x}_3 &= -\beta x_3 + x_1 x_2 \end{aligned} \tag{18}$$

where x_1, x_2, x_3 are the state variables and α, β, γ are positive constants.

As the slave system, we consider the controlled Tigan dynamics described by

$$\begin{aligned} \dot{y}_1 &= \alpha(y_2 - y_1) + u_1 \\ \dot{y}_2 &= (\gamma - \alpha)y_1 - \alpha y_1 y_3 + u_2 \\ \dot{y}_3 &= -\beta y_3 + y_1 y_2 + u_3 \end{aligned} \tag{19}$$

where y_1, y_2, y_3 are the state variables and u_1, u_2, u_3 are the active controls.

The anti-synchronization error is defined as

$$\begin{aligned} e_1 &= y_1 + x_1 \\ e_2 &= y_2 + x_2 \\ e_3 &= y_3 + x_3 \end{aligned} \tag{20}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= \alpha(e_2 - e_1) + u_1 \\ \dot{e}_2 &= (\gamma - \alpha)e_1 - \alpha(y_1 y_3 + x_1 x_3) + u_2 \\ \dot{e}_3 &= -\beta e_3 + y_1 y_2 + x_1 x_2 + u_3 \end{aligned} \tag{21}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -\alpha e_2 \\ u_2 &= -(\gamma - \alpha)e_1 - e_2 + \alpha(y_1 y_3 + x_1 x_3) \\ u_3 &= -\beta e_3 - y_1 y_2 - x_1 x_2 \end{aligned} \tag{22}$$

Substitution of (22) into (21) yields the linear error dynamics

$$\begin{aligned} \dot{e}_1 &= -\alpha e_1 \\ \dot{e}_2 &= -e_2 \\ \dot{e}_3 &= -2\beta e_3 \end{aligned} \tag{23}$$

We consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2} e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2\right), \tag{24}$$

which is a positive definite function on R^3.

Differentiating (24) along the trajectories of the system (23), we get

$$\dot{V}(e) = -\alpha e_1^2 - e_2^2 - 2\beta e_3^2, \tag{25}$$

which is a negative definite function on R^3 since α and β are positive constants.

Thus, by Lyapunov stability theory [25], the error dynamics (23) is globally exponentially stable. Hence, we obtain the following result.

Theorem 2. The identical Tigan systems (18) and (19) are globally and exponentially anti-synchronized with the active nonlinear controller (22). ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-6}$ is used to solve the two systems of differential equations (18) and (19) with the nonlinear controller (22).

The Tigan chaotic system (2008) is one of the important paradigms of three-dimensional chaotic systems.

The parameters of the identical Tigan systems (18) and (19) are selected as

$$\alpha = 2.1, \ \beta = 0.6, \ \gamma = 30$$

The initial values for the master system (18) are taken as

$$x_1(0) = 6, \ \ x_2(0) = 17, \ \ x_3(0) = 10$$

and the initial values for the slave system (19) are taken as

$$y_1(0) = 22, \ \ y_2(0) = 30, \ \ y_3(0) = 18$$

Figure 4 depicts the anti-synchronization of the identical Tigan chaotic systems (18) and (19).

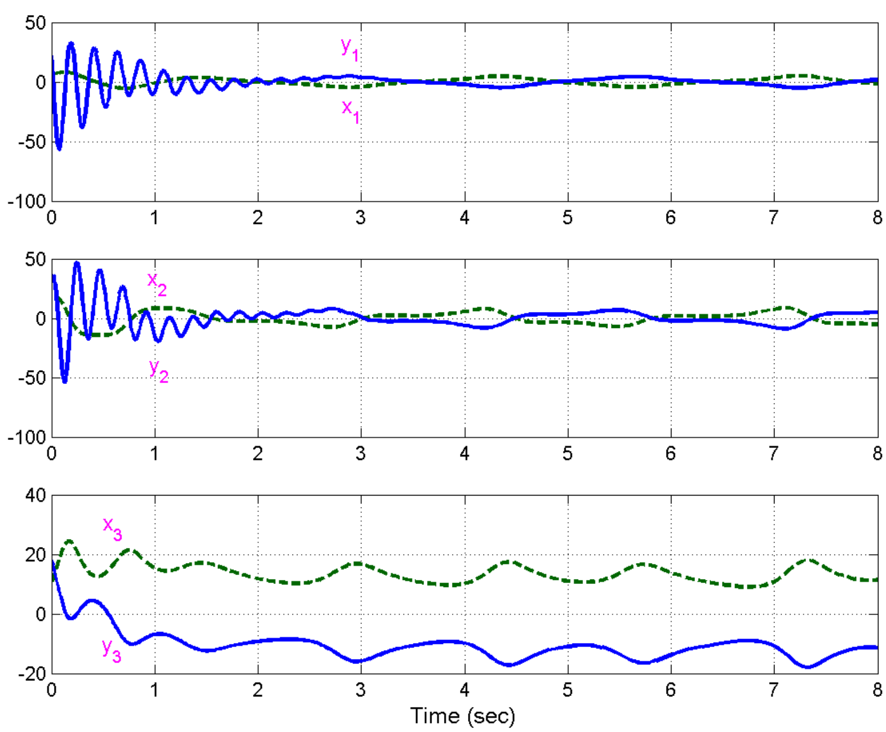

Figure 4. Anti-Synchronization of Identical Tigan Systems

6. ANTI-SYNCHRONIZATION OF LI AND TIGAN SYSTEMS

In this section, we consider the anti-synchronization of Li and Tigan chaotic systems.

As the master system, we consider the Li dynamics described by

$$\begin{aligned} \dot{x}_1 &= a(x_2 - x_1) \\ \dot{x}_2 &= x_1 x_3 - x_2 \\ \dot{x}_3 &= b - x_1 x_2 - c x_3 \end{aligned} \tag{26}$$

where x_1, x_2, x_3 are the state variables and a, b, c are positive constants.

As the slave system, we consider the controlled Tigan dynamics described by

$$\begin{aligned} \dot{y}_1 &= \alpha(y_2 - y_1) + u_1 \\ \dot{y}_2 &= (\gamma - \alpha) y_1 - \alpha y_1 y_3 + u_2 \\ \dot{y}_3 &= -\beta y_3 + y_1 y_2 + u_3 \end{aligned} \tag{27}$$

where y_1, y_2, y_3 are the state variables, α, β, γ are positive constants and u_1, u_2, u_3 are the active controls.

The anti-synchronization error is defined as

$$\begin{aligned} e_1 &= y_1 + x_1 \\ e_2 &= y_2 + x_2 \\ e_3 &= y_3 + x_3 \end{aligned} \tag{28}$$

A simple calculation gives the error dynamics

$$\begin{aligned} \dot{e}_1 &= \alpha(e_2 - e_1) + (a - \alpha)(x_2 - x_1) + u_1 \\ \dot{e}_2 &= -e_2 + (\gamma - \alpha) y_1 + y_2 - \alpha y_1 y_3 + x_1 x_3 + u_2 \\ \dot{e}_3 &= -\beta e_3 + (\beta - c) x_3 + b + y_1 y_2 - x_1 x_2 + u_3 \end{aligned} \tag{29}$$

We consider the active nonlinear controller defined by

$$\begin{aligned} u_1 &= -\alpha e_2 - (a - \alpha)(x_2 - x_1) \\ u_2 &= -(\gamma - \alpha) y_1 - y_2 + \alpha y_1 y_3 - x_1 x_3 \\ u_3 &= -\beta e_3 - (\beta - c) x_3 - b - y_1 y_2 + x_1 x_2 \end{aligned} \tag{30}$$

Substitution of (30) into (29) yields the linear error dynamics

$$\begin{aligned} \dot{e}_1 &= -\alpha e_1 \\ \dot{e}_2 &= -e_2 \\ \dot{e}_3 &= -2\beta e_3 \end{aligned} \tag{31}$$

We consider the quadratic Lyapunov function defined by

$$V(e) = \frac{1}{2}e^T e = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2\right), \tag{32}$$

which is a positive definite function on R^3.

Differentiating (32) along the trajectories of the system (31), we get

$$\dot{V}(e) = -\alpha e_1^2 - e_2^2 - 2\beta e_3^2, \tag{33}$$

which is a negative definite function on R^3 since α and β are positive constants.

Thus, by Lyapunov stability theory [25], the error dynamics (31) is globally exponentially stable. Hence, we obtain the following result.

Theorem 3. The non-identical Li system (26) and Tigan system (27) are globally and exponentially anti-synchronized with the active nonlinear controller (30). ■

Numerical Simulations

For the numerical simulations, the fourth order Runge-Kutta method with initial time-step $h = 10^{-6}$ is used to solve the two systems of differential equations (26) and (27) with the nonlinear controller (30).

The Li chaotic system (2009) is one of the important paradigms of three-dimensional chaotic systems.

The Tigan chaotic system (2008) is also one of the important paradigms of three-dimensional chaotic systems.

The parameters of the Li system (26) are selected as

$$a = 5,\ b = 16,\ c = 1$$

The parameters of the Tigan system (27) are selected as

$$\alpha = 2.1,\ \beta = 0.6,\ \gamma = 30$$

The initial values for the master system (26) are taken as

$$x_1(0) = 10,\ \ x_2(0) = 25,\ \ x_3(0) = 9$$

and the initial values for the slave system (27) are taken as

$$y_1(0) = 26,\ \ y_2(0) = 4,\ \ y_3(0) = 17$$

Figure 5 depicts the anti-synchronization of the non-identical Li and Tigan chaotic systems.

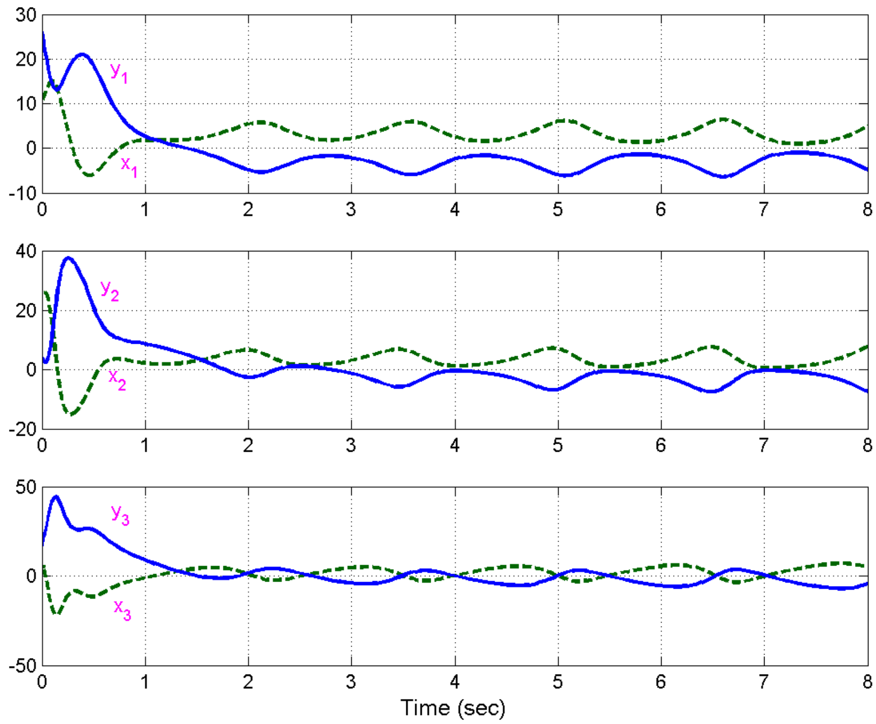

Figure 5. Anti-Synchronization of Li and Tigan Systems

7. CONCLUSIONS

In this paper, using the active control method, new results have been derived for the anti-synchronization for the identical Li systems (2009), identical Tigan systems (2008) and non-identical Li and Tigan systems. The anti-synchronization results derived in this paper have been established using Lyapunov stability theory. Since the Lyapunov exponents are not required for these calculations, the active control method is very convenient and efficient for the anti-synchronization of identical and non-identical Li and Tigan systems. Numerical simulation results have been presented to illustrate the anti-synchronization results derived in this paper.

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