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Global Chaos Synchronization of Rucklidge Chaotic Systems for Double Convection via Sliding Mode Control

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Abstract: In the recent decades, there is great interest shown in the literature in the finding of chaotic motion and oscillations in nonlinear dynamical systems arising in physics, chemistry, biology, and engineering. Chaotic systems have many important applications in science and engineering. This paper discusses the Rucklidge chaotic system (1992) for nonlinear double convection. When the convection takes place in a fluid layer rotating uniformly about a vertical axis and in the limit of tall thin rolls, convection in an imposed vertical magnetic field and convection in a rotating fluid layer are both modeled by Rucklidge's third-order set of ordinary differential equations which produces chaotic solutions. This paper starts with a detailed analysis of the Rucklidge's nonlinear double convection system and the parameter values for which the Rucklidge system exhibits chaotic behaviour. Next, a sliding mode control law is devised for the global chaos synchronization of the Rucklidge chaotic systems. The main results for the chaos synchronization of Rucklidge chaotic systems are established using Lyapunov stability theory. Next, the sliding mode control results are illustrated with numerical simulations using MATLAB.

1. Introduction

Chaos theory describes the qualitative study of unstable aperiodic behaviour in deterministic nonlinear dynamical systems. For the motion of a dynamical system to be chaotic, the system variables should contain some nonlinear terms and the system must satisfy three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [1-2].

In 1963, Lorenz [3] discovered a 3-D chaotic system when he was studying a 3-D weather model for atmospheric convection. After a decade, Rössler [4] discovered a 3-D chaotic system, which was constructed during the study of a chemical reaction. These classical chaotic systems paved the way to the discovery of many 3-D chaotic systems such as Arneodo system [5], Sprott systems [6], Chen system [7], Lü-Chen system [8], Cai system [9], Tigan system [10], etc. Many new chaotic systems have been also discovered in the recent years like Sundarapandian systems [11, 12], Vaidyanathan systems [13-43], Pehlivan system [44], Pham system [45], etc.

Recently, there is significant result in the chaos literature in the control and synchronization of physical and chemical systems. In the chaos control problem, the design goal is to find a state feedback control law so as to stabilize or regulate the state trajectories of the chaotic system. In the synchronization of chaotic systems, a pair of chaotic systems called master and slave systems are considered for the synchronization process and the design goal is to device a feedback mechanism so that the trajectories of the slave system asymptotically track the trajectories of the master system.

In control theory, active control method is used when the parameters are available for measurement [46-65]. Adaptive control is a popular control technique used for stabilizing systems when the system parameters are unknown [66-79]. There are also other popular methods available for control and synchronization of systems such as backstepping control method [80-86], sliding mode control method [87-98], etc.

Recently, chaos theory is found to have important applications in several areas such as chemistry [99-107], biology [108-125], memristors [126-128], electrical circuits [129], etc.

This paper discusses the Rucklidge chaotic system ([130], 1992) for nonlinear double convection. This paper starts with a detailed description of the Rucklidge's nonlinear double convection system and the parameter values for which the Rucklidge system exhibits chaotic behaviour. Next, a sliding mode control law is devised for the global chaos synchronization of the identical Rucklidge chaotic systems. The main results for the chaos synchronization of the Rucklidge chaotic systems are established using Lyapunov stability theory. Next, the sliding mode control results are illustrated with numerical simulations using MATLAB.

2. Nonlinear Double Convection Rucklidge Chaotic System

In fluid mechanics modelling, cases of two-dimensional convection in a horizontal layer of Boussinesq fluid with lateral constraints were considered by Rucklidge [130]. When the convection takes place in a fluid layer rotating uniformly about a vertical axis and in the limit of tall thin rolls, convection in an imposed vertical magnetic field and convection in a rotating fluid layer are both modelled by a new third-order set of ordinary differential equations, which produces chaotic solutions like the Lorenz model [1].

The double convection Rucklidge chaotic system is described by the 3-D model

$$\begin{cases} \dot{x} = -ax + by - yz \\ \dot{y} = x \\ \dot{z} = -z + y^2 \end{cases} \tag{1}$$

The system (1) is chaotic when the system parameters are chosen as

$$a = 2, \quad b = 6.7 \tag{2}$$

For numerical simulations, we take the initial conditions $x(0) = 1.2, y(0) = 0.8$ and $z(0) = 1.4.$

The 3-D phase portrait of the double convection Rucklidge chaotic system is depicted in Figure 1.

The 2-D projections of the double convection Rucklidge chaotic system on the $(x, y),\ (y, z),\ (x, z)$ coordinate planes are shown in Figures 2-4.

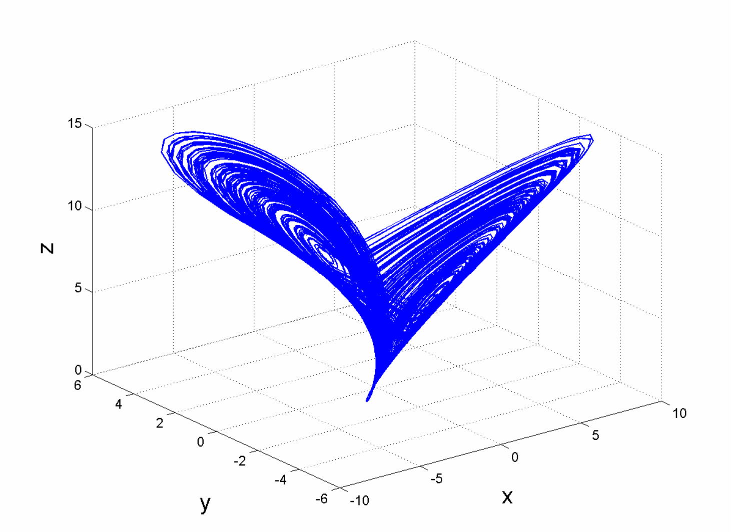

Figure 1. The 3-D phase portrait of the double convection Rucklidge chaotic system

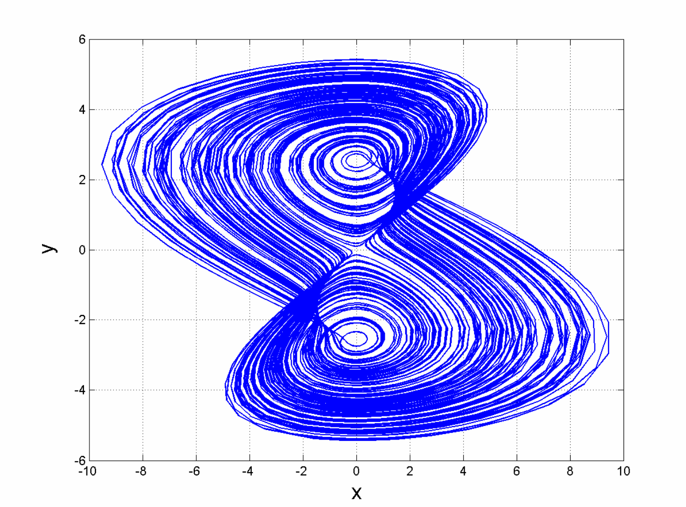

Figure 2. The 2-D projection of the Rucklidge chaotic system on the (x, y) plane

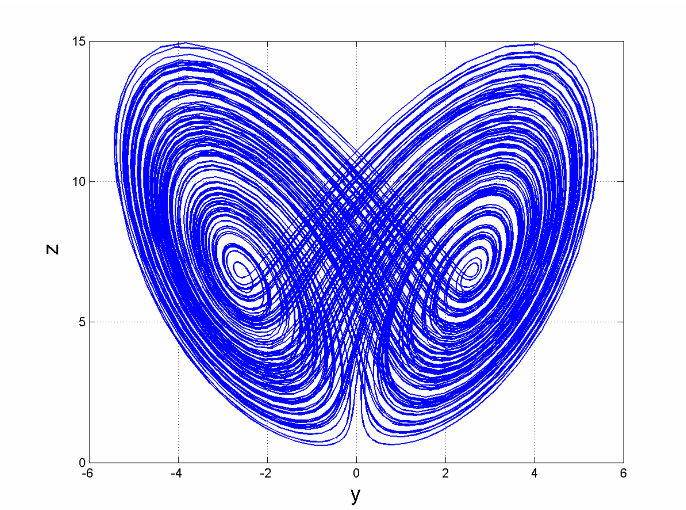

Figure 3. The 2-D projection of the Rucklidge chaotic system on the (y, z) plane

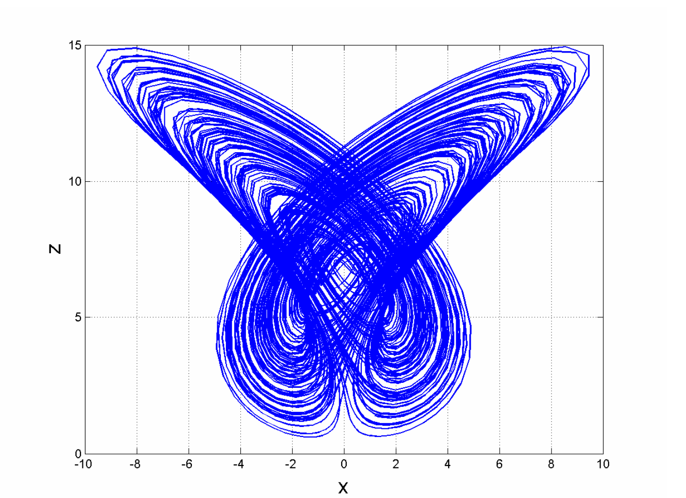

Figure 4. The 2-D projection of the Rucklidge chaotic system on the (x, z) plane

3. Computational Analysis of the Double Convection Rucklidge Chaotic System

The Lyapunov exponents of the double convection Rucklidge system (1) have been obtained in MATLAB as

$$L_1 = 0.1877,\ L_2 = 0,\ L_3 = -3.1893 \tag{3}$$

Thus, the Lyapunov dimension of the chemical chaotic attractor (1) is deduced as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} = 2.0589 \tag{4}$$

The double convection Rucklidge chaotic system (1) has an unstable equilibrium at $(x, y, z) = (0, 0, 0)$.
The eigenvalues of the linearized system matrix of the attractor (3) at the origin are:

$$\lambda_1 = 1.7749,\ \lambda_2 = -1,\ \lambda_3 = -3.7749. \tag{5}$$

Since there is a positive eigenvalue in the set (5), the origin is a saddle-point and hence an unstable equilibrium of the double convection Rucklidge chaotic system (1).

4. Global Chaos Synchronization of Nonlinear Double Convection Rucklidge Chaotic Systems

In this section, we use sliding mode control method to design a discontinuous feedback control law for globally synchronizing the identical nonlinear double convection Rucklidge chaotic systems.

As the master system, we consider the controlled double convection Rucklidge chaotic system given by

$$\begin{cases} \dot{x}_1 = -ax_1 + by_1 - y_1 z_1 \\ \dot{y}_1 = x_1 \\ \dot{z}_1 = -z_1 + y_1^2 \end{cases} \tag{6}$$

In (6), x_1, y_1, z_1 are the states, and a, b are the system parameters.
We take the parameter values as in the chaotic case (2), i.e. $a = 2$ and $b = 6.7$.
As the slave system, we consider the controlled double convection Rucklidge chaotic system given by

$$\begin{cases} \dot{x}_2 = -ax_2 + by_2 - y_2 z_2 + u_x \\ \dot{y}_2 = x_2 + u_y \\ \dot{z}_1 = -z_2 + y_2^2 + u_z \end{cases} \tag{7}$$

In (7), x_2, y_2, z_2 are the states, and u_x, u_y, u_z are the sliding mode controls to be determined.
The synchronization error between the Rucklidge chaotic systems (6) and (7) is defined by

$$\begin{cases} e_x = x_2 - x_1 \\ e_y = y_2 - y_1 \\ e_z = z_2 - z_1 \end{cases} \tag{8}$$

Then the error dynamics is obtained as

$$\begin{cases} \dot{e}_x = -ae_x + be_y - y_2 z_2 + y_1 z_1 + u_x \\ \dot{e}_y = e_x + u_y \\ \dot{e}_z = -e_z + y_2^2 - y_1^2 + u_z \end{cases} \tag{9}$$

In this paper, we use Vaidyanathan's theorem [97] to devise a novel sliding mode controller to stabilize the errors $e_x(t), e_y(t), e_z(t)$ as $t \to \infty$.
First, we write the system (9) in matrix form as

$$\dot{e} = Ae + \psi(X_1, X_2) + u \tag{10}$$

where

$$e = \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix}, \quad A = \begin{bmatrix} -a & b & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \quad \psi(X_1, X_2) = \begin{bmatrix} -y_2 z_2 + y_1 z_1 \\ 0 \\ y_2^2 - y_1^2 \end{bmatrix}, \quad u = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \tag{11}$$

We find $B \in R^3$ such that (A, B) is completely controllable.
A simple choice for B is given by

$$B = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}. \tag{12}$$

Thus, we set the nonlinear feedback control u as

$$u = -\psi(X_1, X_2) + Bv, \tag{13}$$

where v is the sliding mode control which is determined as follows.
We select the sliding variable as

$$s = Ce = \begin{bmatrix} 2.1 & 0 & -2 \end{bmatrix} e = 2.1 e_x - 2e_z \tag{14}$$

With the choice of $C = \begin{bmatrix} 2.1 & 0 & -2 \end{bmatrix}$, the eigenvalues of the matrix $E = \left[I - B(CB)^{-1} C \right] A$ are given by

$$\text{eig}(E) = \{-2.3007, -119.3993, 0\}. \tag{15}$$

This shows that the dynamics along the sliding manifold is globally asymptotically stable.
Next, we take the sliding constants as $k = 6$ and $q = 0.2$.
Then the sliding mode control v is obtained by the Vaidyanathan's theorem [97] as

$$v(t) = -(CB)^{-1} \left[C(kI + A)e + qs^2 \, \text{sgn}(s) \right] \tag{16}$$

A simple calculation gives

$$v(t) = -84e_x - 140.7e_y + 100e_z - 2s^2 \, \text{sgn}(s) \tag{17}$$

As an application of Vaidyanathan's theorem [97], we obtain the following result.

Theorem 1. The nonlinear double convection Rucklidge chaotic attractors (6) and (7) are globally and asymptotically synchronized for all initial conditions by the sliding mode control u given by (13), where $\psi(X_1, X_2)$ is defined by (11), B is defined by (12) and v is defined by (17). ■

5. Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the Rucklidge chaotic systems (6) and (7), when the sliding mode control law (13) is applied.

We take the sliding mode constants as $k = 6$ and $q = 0.2$.

We take the initial conditions of the master Rucklidge system (6) as

$$x_1(0) = 5.9, \; y_1(0) = 14.1, \; z_1(0) = 7.4.$$

We take the initial conditions of the slave Rucklidge system (7) as

$$x_2(0) = 11.5, \; y_2(0) = 8.3, \; z_2(0) = 2.9.$$

The parameter values are taken as in (2) for the chaotic case, viz. $a = 2$ and $b = 6.7$.

Figures 5-7 show the synchronization of the Rucklidge chaotic systems (6) and (7).

Figure 8 shows the time-history of the synchronization errors e_x, e_y, e_z.

From Figures 5-8, it is clear that the Rucklidge chaotic systems (6) and (7) are completely synchronized in approximately four seconds.

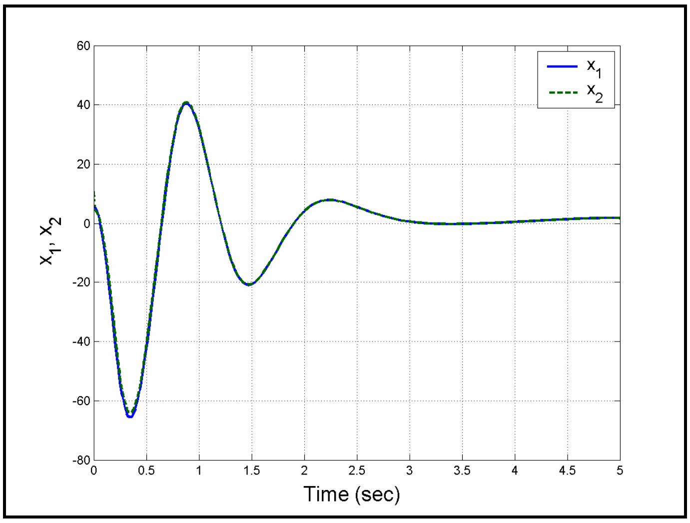

Figure 5. Synchronization of the states x_1 and x_2

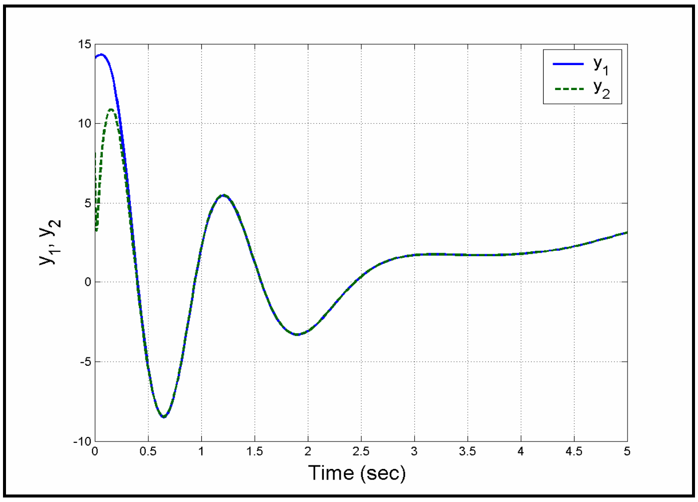

Figure 6. Synchronization of the states y_1 and y_2

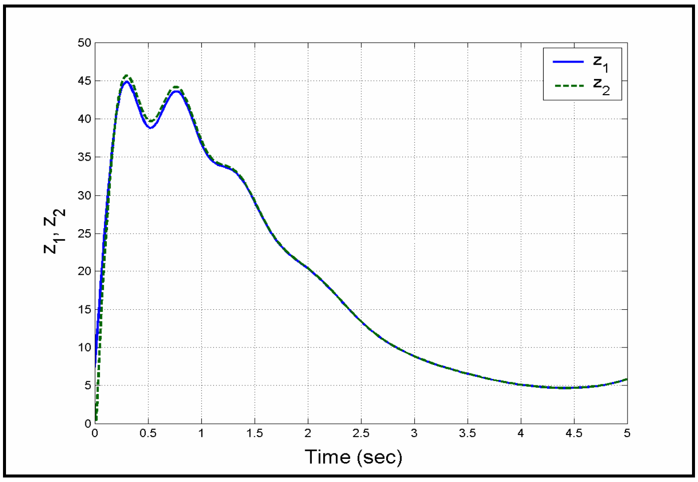

Figure 7. Synchronization of the states z_1 and z_2

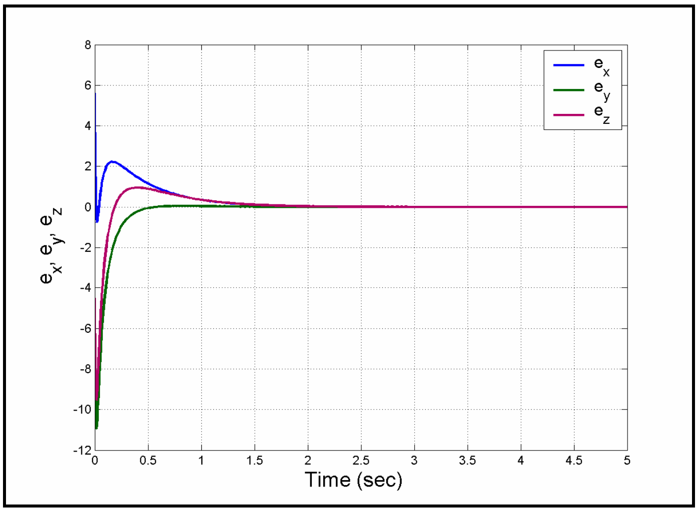

Figure 8. Time-history of the synchronization errors e_x, e_y, e_z

6. Conclusions

In this paper, new results have been derived for the analysis and global chaos synchronization of nonlinear double-convection Rucklidge chaotic systems (1992). After analyzing the dynamic and qualitative properties of the double-convection Rucklidge chaotic system, we have designed a sliding mode controller for the global chaos synchronization of the states of the Rucklidge chaotic system. The main results have been proved using Lyapunov stability theory and numerical simulations have been illustrated using MATLAB.

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