Optik 126 (2015) 765–768

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Dynamics analysis and circuit implementation of a new three-dimensional chaotic system

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ARTICLE INFO

Article history:
Received 28 January 2014
Accepted 9 February 2015

Keywords:
A novel three-dimensional chaotic system
Lyapunov exponent (LE)
Bifurcation diagram
Circuit implementation

ABSTRACT

In this paper, a novel three-dimensional quadratic autonomous double-wing chaotic system is introduced and analyzed theoretically. The chaotic system is constructed with three control parameters and two different nonlinear items, in which one of the nonlinear term constituted by the sign function and the other nonlinear constituted by the square function. Some of its detailed basic dynamical properties, such as theoretical analysis, numerical simulation, the equilibrium point, Lyapunov exponent (LE) spectrum and bifurcation diagram are investigated either analytically or numerically. Moreover, an analog circuit diagram is designed to realize the new chaotic system. Circuit experiment result of the chaotic attractor is identical to computer simulation, and the chaotic characteristic is verified.

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1. Introduction

There have attracted increasing interest in exploiting nonlinear dynamics in many engineering areas, such as telecommunications, electrical engineering, chemical reaction analysis and design, material engineering, information processing, biological systems, etc. This is due to the prominent characteristics (sensitive to initial value, pseudo random sequence, unstable, bounded, etc) of chaos in some technological and engineering applications, where chaos can provide certain features for special purposes [1–4]. Much attention has been paid to feasibly and effectively generating chaos via some hardware devices such as analog circuit, field programmable gata array (FPGA) and digital signal processor (DSP) implementation [5–7].

The Lorenz system that can produce an eminent two-scroll butterfly shaped chaotic attractor [8], has served as a paradigm model for intensively studying chaotic dynamic behaviour in the last three decades. Recently, there has been increasing interest in generating chaos since Chen and Ueta [9] found a new Lorenz-like chaotic system particularly, called the Chen chaotic system, from a linear feedback control approach, which is not topologically similar to the Lorenz system. In 2002, Lü and Chen [10] discovered the critical chaotic system, called the Lü chaotic system hereafter, which represents the transition between the Lorenz and the Chen systems. Thereafter a very rich family of the so-called Lorenz system family or unified system was introduced as a relation of the Lorenz, Chen and Lü systems [11,12]. Over the last few years, there have been carried out some studies of these typical chaotic systems [13–17].

Chaotic circuit is an important expression of chaos and is also an attractive research fields. In 1984, Chua proposed the first chaotic circuit, which builds a bridge between the chaos theory and the chaotic circuit. Lately, the pursue of designing hardware circuits to generate chaotic attractors has become an important means to electronic engineers, not only because of their theoretical interest, but also due to their potential engineering applications [18] in information systems and various chaos-based technologies [19–25].

In this paper, we propose a new chaotic system and analyze it by using frequency spectral analyses, Lyapunov exponent (LE) spectrum, bifurcation diagram, and circuit implementation. The system has three chaotic parameters and two non-linear terms, in which one of nonlinear terms is the product term $z \cdot \mathrm{sgn}(x)$, the other nonlinear terms is the squared term x^2. The analysis of frequency spectra indicates that the system has a quite broad frequency bandwidth, which is very suitable for practical applications such as secure communications. Moreover, the spectrum of LE shows that the system has a very large positive LE among a certain range of parameters. System orbits extensively extend in one orientation, but rapidly shrink in another orientation, which raise the system's orbital randomness and disorder. Furthermore, detailed

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http://dx.doi.org/10.1016/j.ijleo.2015.02.029
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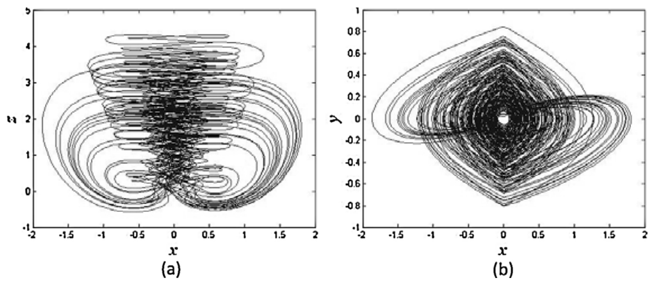

Fig. 1. The chaotic attractors of the proposed chaotic system; (a) x–y phase plane strange attractor; (b) x–z phase plane strange attractor.

bifurcation diagram analysis demonstrates the evolutionary processes of the system, among sinks, periodic orbits, and chaos, showing two coexisting sinks and two coexisting periodic orbits, as well as their combination. Finally, the built circuit verifies the simulated chaos.

This paper is organized as follows. In Section 2, a new chaotic system is proposed. The basic dynamical properties of the new chaotic system are analysed in Section 3. In Section 4, a module-based electronic circuit realization of the new chaotic system is presented. Section 5 summarizes this work.

2. The new chaotic system

A new chaotic system is presented in this paper, the autonomous nonlinear of differential equations that describe the system are

$$\begin{cases} \dot{x} = ay \\ \dot{y} = -z\text{sgn}\quad(x) - cy \\ \dot{z} = bx^2 - 1 \end{cases} \tag{1}$$

where x, y and z are the states and the constant a, b, c are positive parameters of the system. The new system (1) has totally five terms on the right-hand side with two different nonlinear items, namely, $z \cdot \text{sgn}(x)$ and x^2. Typical values of the parameters are $a = 14$, $b = 3$, $c = 0.5 \sim 4.5$, the positive real constant parameters. When $c = 1$, system (1) displays a two-wing chaotic attractor, the computer simulation results of system (1) is shown in Fig. 1, an x–z phase plane and a x–y phase plane, respectively.

3. Dynamical analysis of the new chaotic system

3.1. Equilibra

To analyze dynamic properties of the new system, the initial stage is to find its equilibria, and then to analyse the local dynamical properties of the system orbits near these fixed points based on the relevant linear systems.

The equilibria of the new system (1) can be founded by solving the following algebraic equations:

$$\begin{cases} ay = 0 \\ -z \cdot \text{sgn}\quad(x) - cy = 0 \\ bx^2 - 1 = 0 \end{cases} \tag{2}$$

where $a = 14$, $b = 3$, $c = 1$. Obviously, the dynamical system (1) has two nontrivial equilibrium points, i.e. $(P_1(\sqrt{3}/3, 0, 0)$ and $P_2(-\sqrt{3}/3, 0, 0)$.

3.2. Jacobians matrices

The Jacobian matrix of system (1) at the first equilibrium point p_1 is defined as

$$J(P_1) = \begin{bmatrix} 0 & a & 0 \\ -z & -c & -\text{sgn}\quad(x) \\ 2bx & 0 & 0 \end{bmatrix} \tag{3}$$

To obtain its eigenvalues, we let the characteristic equation $\det[\lambda I - J(P)] = 0$. Three eigenvalues that correspond to equilibrium p_1 are respectively gained as follows: $\lambda_1 = -4.0124$, $\lambda_2 = 1.5062 + j3.1334$, and $\lambda_3 = 1.5062 - j3.334$. Here, λ_1 is a negative real number, λ_2 and λ_3 are a pair of complex conjugate eigenvalues with positive real parts.

The equilibrium $P_1(\sqrt{3}/3, 0, 0)$ is a saddle-focus point; this equilibrium point p_1 is unstable.

For the second equilibrium point $P_2(-\sqrt{3}/3, 0, 0)$, it has a Jacobin matrix equal to

$$J(P_2) = \begin{bmatrix} 0 & a & 0 \\ -z & -c & -\text{sgn}(x) \\ 2bx & 0 & 0 \end{bmatrix} \tag{4}$$

We let the characteristic equation $\det[\lambda I - J(P)] = 0$,which has the eigenvalues $\lambda_1 = 3.3420$, $\lambda_2 = -2.1710 + j3.1302$ and $\lambda_2 = -2.1710 - j3.1302$. The result shows that λ_1 is positive real number, λ_2 and λ_3 form a complex conjugate pair and their real parts negative. Equilibrium $P_2(-\sqrt{3}/3, 0, 0)$ is a saddle-focus point, therefore, this equilibrium point p_2 is also unstable.

According to the Routh–Hurwitz criterion [26], the above brief analyses show that the two equilibrium points (p_1 and p_2) of the proposed nonlinear systems are all saddle focus-nodes.

3.3. A dissipative system and existence of the attractor

The divergence of the dynamic system (1) is

$$\nabla V = \frac{\partial \dot{x}}{\partial x} + \frac{\partial \dot{y}}{\partial y} + \frac{\partial \dot{z}}{\partial z} = -c \tag{5}$$

with $c = 1$, here ∇V is a negative constant, the system (1) is a dissipative system, which converges exponentially

$$\text{d}V/\text{d}t = e^{-ct} \tag{6}$$

In other words, an initial volume element V_0 is apparently contracted by the flow into a volume element $V_0\exp(-t)$ as time goes. It means that each volume containing the dynamical system trajectory shrinks to zero volume at an exponential rate $-c$ as $t \to \infty$. Therefore, system orbits are ultimately confined into a specific limit set of zero-volume. Consequently, the dynamical system ultimately goes toward an attractor.

3.4. Spectrum, bifurcations and Lyapunov exponent

In the logarithm frequency spectrum, an apparently continuous broadband power spectrum $\log|x|$ of the system (1) as shown in Fig. 2.

Apparently, the evolution process of the chaos trajectory is very sensitive to initial states. If the given initial values are changed, the chaotic dynamical properties fade away soon, we call it sensitive dependence on initial states.

When c varies from 4.5 to 0.5, the corresponding bifurcation diagram of x is shown in Fig. 3 and the LE spectrum is depicted in Fig. 4.

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