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A novel 3-D chaotic system with line equilibrium: dynamical analysis, coexisting attractors, offset boosting control and circuit design

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Abstract. A 3-D new chaotic system with five nonlinearities is proposed in this paper. A novel feature of our chaotic system is that there is no linear term in it. We also show that the chaotic system consists of equilibrium points on the z-axis (line equilibrium) as well as two equilibrium points on the (x, y)-plane. The dynamical properties of the new chaotic system are described in terms of phase portraits, bifurcation diagram, Lyapunov exponents, coexisting attractors, coexisting bifurcation and offset boosting control. Finally, an electronic circuit realization of the new chaotic system is presented in detail to confirm the feasibility of the theoretical chaotic model.

1. Introduction

Chaotic systems are characterized by their high sensitivity to small changes in initial conditions [1-2] and they have many applications in science and engineering such as weather systems [3-4], ecology [5], neurons [6-7], biology [8-10], cellular neural networks [11-12], chemical reactors [13-14], oscillators [15-20], robotics [21-24], encryption [25-30], finance systems [31-32], circuits [33-45], etc.

In the chaos literature, there is good interest in finding chaotic systems with infinite number of equilibrium points such as line equilibrium [46-50], square equilibrium [51], ellipse equilibrium [52], conch equilibrium [53], circle equilibrium [54], heart-shaped equilibrium [55], etc.

In this research paper, we report the finding of a new chaotic system with equilibrium points on the $z-$axis (line equilibrium) as well as two equilibrium points on the $(x, y)-$plane. We describe the phase plots of the chaotic system and do a rigorous dynamic analysis by finding bifurcation diagrams, Lyapunov exponents, equilibrium points, etc. Bifurcation analysis gives valuable information about the chaotic systems [56-61].

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Section 2 describes the new chaotic system, its phase plots and equilibrium points. Section 3 describes the dynamic analysis of the new chaotic system. Section 4 depicts an electronic circuit realization of the new chaotic system. Section 5 draws the main conclusions.

Methodology of this work can be detailed as follows. Section 2 describes a dynamical analysis of the properties of the new 3-D chaotic system reported in this work. We calculate the equilibrium of the system and show that the system has line equilibrium. We display the phase portraits of the system. Section 3 describes a detailed bifurcation analysis of the new 3-D chaotic system including multi-stability and coexisting attractors. Section 4 gives a circuit simulation for the new 3-D chaotic system.

2. A new chaotic system with line equilibrium

In this work, we report a new 3-D system given by the dynamics

$$\begin{cases} \dot{x} = z \ \mathrm{sign}(y) \\ \dot{y} = x|x| - y|y| \\ \dot{z} = a|x| - bxy \end{cases} \tag{1}$$

Where x, y, z are state variables and a, b are positive constants.

In this paper, we show that the dynamical system (1) is *chaotic* for the parameter values

$$a = 0.6, \ b = 1.6 \tag{2}$$

For numerical simulations, we take the initial values of the system (4) as $X(0) = (0.2, 0.2, 0.2)$.

Figure 1 shows the phase portrait of the new system (4) for $(a,b) = (0.6, 1.6)$ and initial conditions $X(0) = (0.2, 0.2, 0.2)$. Figures 1 (a)-(c) show the 2-D phase plots of the new chaotic system (1) in (x, y), (y, z), (x, z) coordinate planes, while Figure 1 (d) shows the 3-D phase plot of the new chaotic system (1).

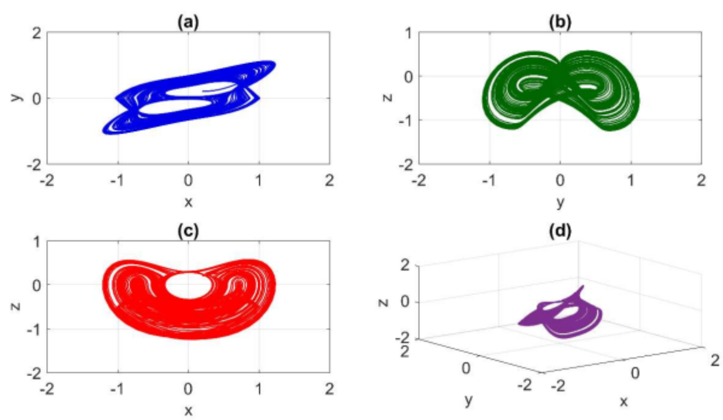

Figure 1. Plots of the new chaotic system (1) for $(a,b) = (0.6, 1.6)$ and $X(0) = (0.2, 0.2, 0.2)$

We take the parameters a and b as in the chaotic case (2), *i.e.* $(a,b) = (0.6, 1.6)$.

The equilibrium points of the new chaotic system (1) are obtained by solving the system:

$$z \ \mathrm{sign}(y) = 0 \tag{3a}$$

$$x|x| - y|y| = 0 \tag{3b}$$

$$a|x| - bxy = 0 \tag{3c}$$

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Solving the equations (3), we obtain the set of equilibrium points

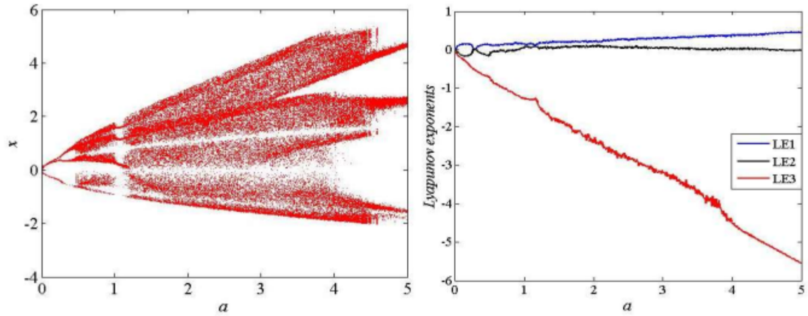
$$S=\{(x,y,z)\in R^3 : x=0,\ y=0\}\cup\{(0.3750,0.3750,0),(-0.3750,-0.3750,0)\}.$$

Thus, the new chaotic system (1) has the whole of z-axis as its equilibrium points as well as the two points (0.3750, 0.3750, 0) and (-0.3750,-0.3750, 0) on the (x, y) – plane.

3. Numerical Study

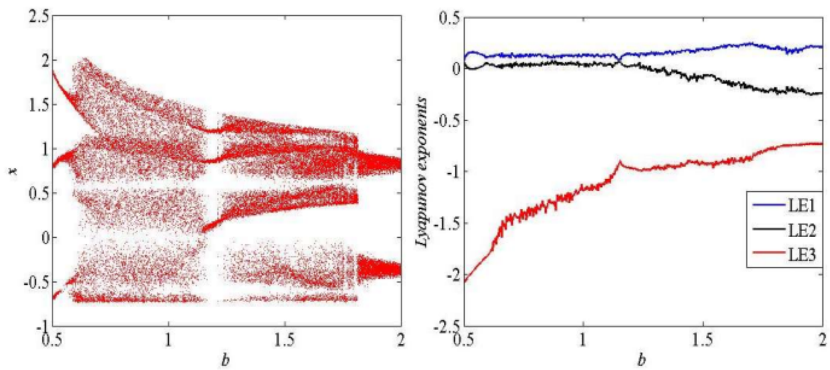
3.1 Bifurcation and Chaos

We fix b = 0.6 and vary a in the range of [0, 5]. The bifurcation diagram for varying a and the related graphs of Lyapunov exponents are provided in Figure 2 (a), (b). Obviously, from the bifurcation diagram, one can get that the system is in periodic state in the beginning, then goes into chaos. In addition, there is a big periodic window. Similarly, from Figure 3 (a), one can see that the system changes from period to chaos in the whole region except for a large period-3 window in the region of [1.1, 1.3]. Note that the bifurcation diagram and the Lyapunov exponents match well with each other.



(a) (b)

Figure 2 (a) Bifurcation diagram of system (1) versus the parameter a for b = 0.6 and initial conditions (x(0), y(0), z(0)) = (0.2, 0.2, 0.2); **(b)** Lyapunov spectrum of system (1) when varying the parameter a for b = 0.6, and initial conditions (x(0), y(0), z(0)) = (0.2, 0.2, 0.2).



(a) (b)

Figure 3 (a) Bifurcation diagram of the system (1) versus the parameter b for a = 1.6 and initial conditions (x(0), y(0), z(0)) = (0.2, 0.2, 0.2); **(b)** Lyapunov spectrum of the system (1) when varying the parameter b for b = 1.6, and initial conditions (x(0), y(0), z(0)) = (0.2, 0.2, 0.2).

3.2 Coexisting attractor

In this work, the bifurcation diagrams of the system (1) versus a [0, 5] are shown in Figure 4, where the blue color starts from the initial conditions (0.2 0.2 0.2) and the red color starts from the initial conditions (-0.2 -0.2 0.2), respectively. As can be seen from the bifurcation diagram, there exists coexisting attractors in the very narrow regions of [0.25, 0.5] and [4.5, 5]. The coexisting chaotic attractors can be seen in Fig. 5a, when $a = 4.5$ and the coexisting periodic attractors can be seen in Fig. 5b, when $a = 0.25$.

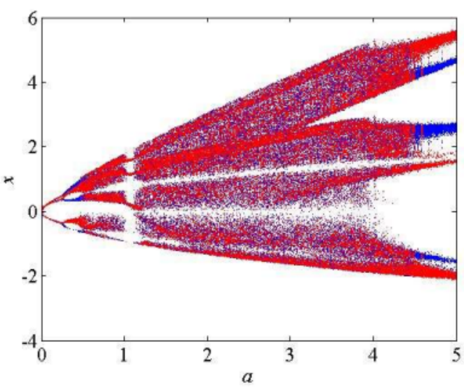


Figure 4 The bifurcation diagrams of the system (1) with a from 0 to 5 for b = 1.6. condition: (x (0) , y (0) , z (0)) = (0.2 0.2 0.2) (*blue*), (x (0) , y (0) , z (0)) = (-0.2 -0.2 0.2), (*red*)

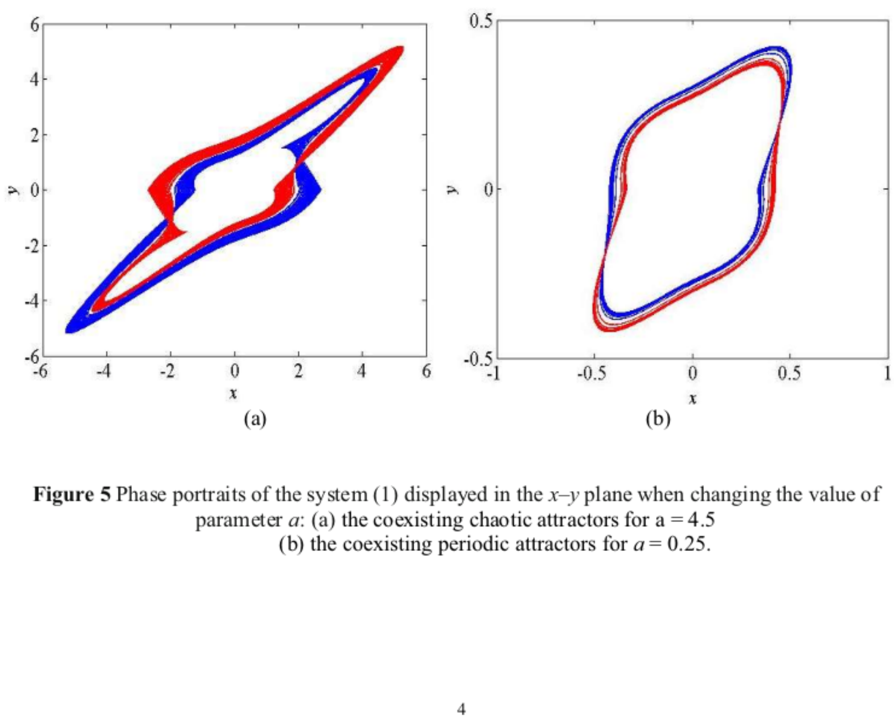


Figure 5 Phase portraits of the system (1) displayed in the x–y plane when changing the value of parameter a: (a) the coexisting chaotic attractors for a = 4.5 (b) the coexisting periodic attractors for a = 0.25.

3.3 Offset boosting control

Clearly, the state variable z appears only once in the first equation of the system. Therefore, we can control the state variable z conveniently. The state variable z is offset-boosted by replacing z with $z + k$, in which k is a constant. The system can be rewritten as

$$\begin{cases} \dot{x} = sign(y)(z+k) \\ \dot{y} = x|x| - y|y| \\ \dot{z} = a|x| - bxy \end{cases} \tag{4}$$

Consequently, the chaotic signal z can be transformed from a bipolar signal to a unipolar signal when varying the control parameter k. When increasing the boosting controller k, the chaotic signal z is boosted from a bipolar signal to a unipolar one as illustrated in Figure 6. Phase portraits of system (1) are adjusted according to the boosting controller as illustrated in Figure 7.

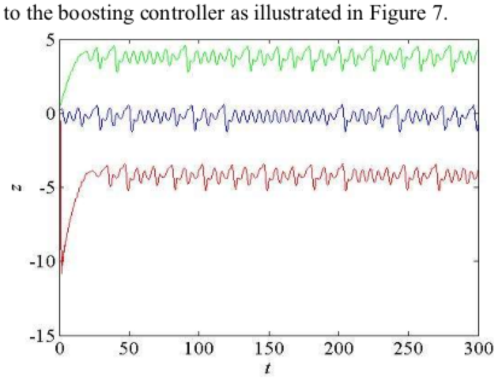


Figure 6 The signal z with different values of the offset boosting controller k: k = 0 (blue colour); k = 4 (red colour); n = -4 (green colour).

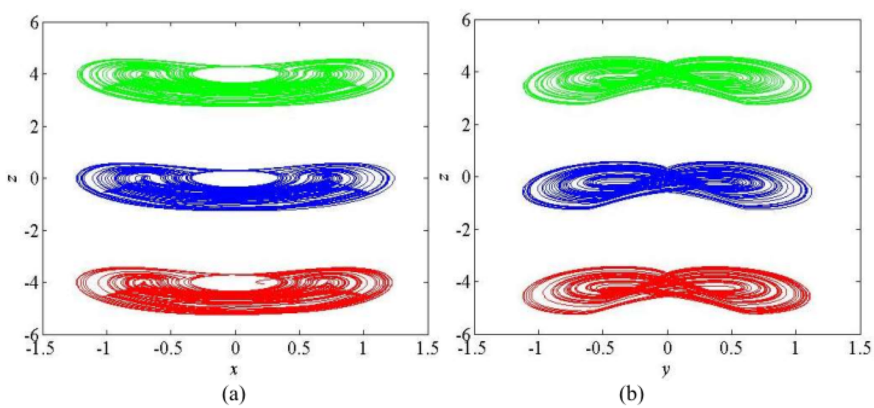


Figure 7 Phase portraits in different planes and different values of the offset boosting controller k: (a) x - z plane, (b) y - z plane for k = 0 (blue colour), k = 4 (red colour), k = -4 (green colour).

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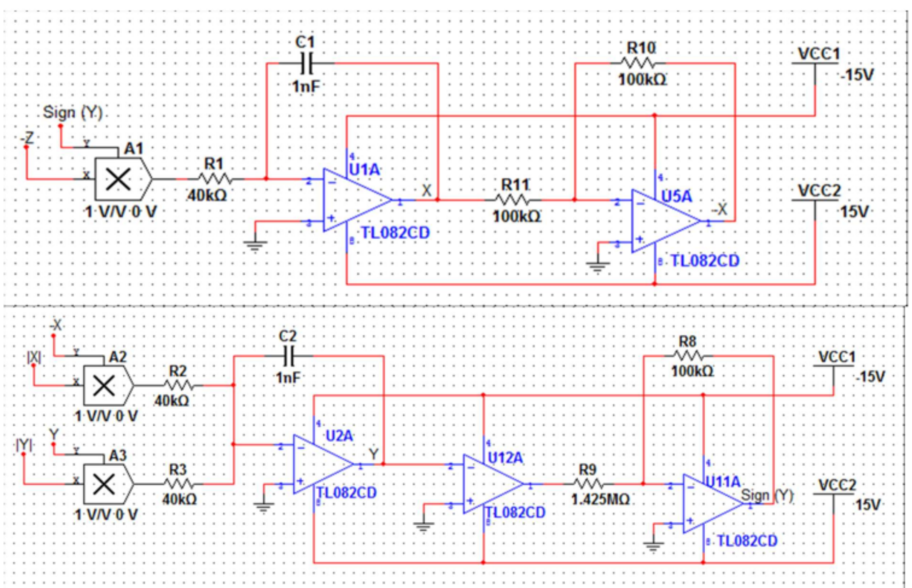
4. Circuit implementation of the new chaotic system

In this work, the electronic circuit design of signum nonlinearity (1) is presented. The electronic circuit is designed in MultiSIM platform. The signum nonlinearity which detailed electronic circuit is depicted in Figure 8 consists of two resistors and two operational amplifiers. A detailed analysis of the signum circuit can be found in [62].

The circuital equations of the designed new chaotic system are given by

$$\begin{cases} \dot{x} = \dfrac{1}{10C_1R_1} z\,sign(y) \\ \dot{y} = \dfrac{1}{10C_2R_2} x\,|x| - \dfrac{1}{10C_2R_3} y\,|y| \\ \dot{z} = -\dfrac{1}{C_3R_4} |x| - \dfrac{1}{10C_3R_5} xy \end{cases} \tag{5}$$

Where x, y, and z are the voltages across the capacitors C_1, C_2 and C_3, respectively. The circuit has been implemented by using MultiSIM $R_1 = R_2 = R_3 = 40$ kΩ, $R_4 = 66.67$ kΩ, $R_9 = 1.425$ MΩ, $R_5 = 25$ kΩ, $R_6 = R_7 = R_8 = R_{10} = R_{11} = R_{12} = R_{13} = R_{14} = R_5 = R_{16} = R_{17} = R_{18} = R_{19} = R_{20} = R_{21} = 100$ kΩ, $C_1 = C_2 = C_3 = 1$ nF. Obtained MultiSIM results in Figure 9 indicate that the circuit exhibits chaotic attractors. The MultiSIM results (see Figure 9) based simulations are carried out to confirm the results of theoretical analysis (see. Figure 1).



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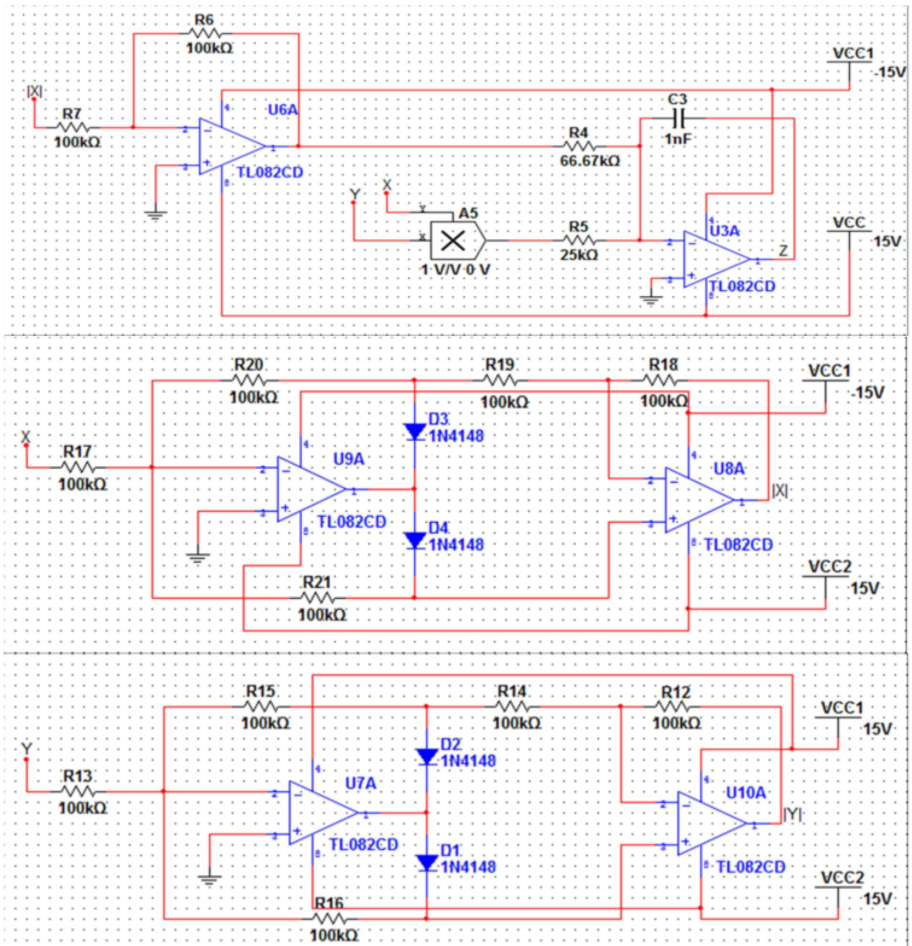
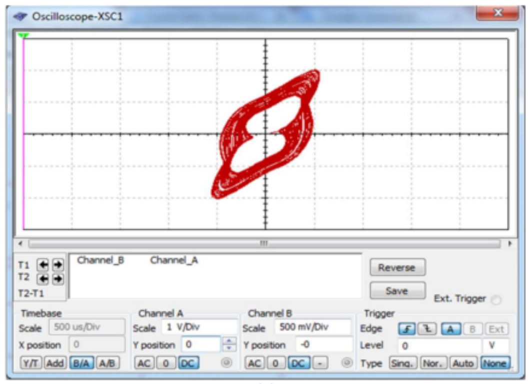
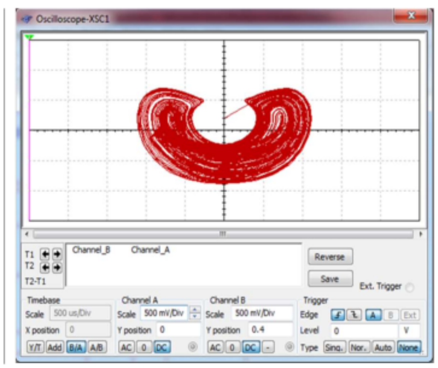
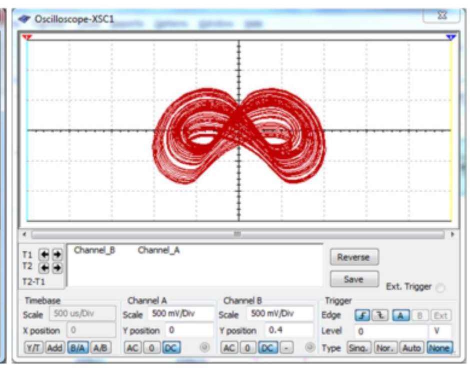


Figure 8 The electronic circuit schematic of new chaotic system (1)



(a)





(b) (c)

Figure 9 MultiSIM chaotic attractors of the new chaotic system (1)
(a) x_1- x_2 plane (b) x_2- x_3 plane and (c) x_1-x_3 plane.

5. Conclusions

A new chaotic system with five nonlinearities was announced in this paper. Our proposed chaotic system has a novel feature that there is no linear term in it. We also showed that the chaotic system has equilibrium points on the z-axis (line equilibrium) as well as two equilibrium points on the (x, y)-plane. The dynamical properties of the new chaotic system were analyzed in terms of phase portraits, bifurcation diagram, etc. Finally, an electronic circuit realization of the new chaotic system was displayed in detail to confirm the feasibility of the theoretical chaotic model.

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