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RESEARCH ARTICLE

A Chaotic Circuit With Hidden Attractors and Extreme Event

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ABSTRACT Here, a chaotic quadratic system is presented. The chaotic attractor of the oscillator is studied. It has a stable equilibrium point for most of the studied interval of its parameter. So, its chaotic attractor in that interval is hidden. Bifurcation diagrams of the oscillator are studied by changing two parameters. Bifurcations with two initiation methods are plotted for each parameter, and their results are investigated using their corresponding Lyapunov exponents. Studying the bifurcation diagrams reveals the multistability of the oscillator, which is also discussed using the basin of attractions. The existence of extreme events is examined for the chaotic dynamic. Implementing the circuit of the oscillator shows the feasibility of its chaotic dynamics.

INDEX TERMS Bifurcations, multistability, extreme events, circuit.

I. INTRODUCTION

Chaos is a crucial topic in studying nonlinear dynamics [1], [2]. Chaos in the flows is a mysterious dynamic, and there are many unknown facts about its generation [3], [4]. In the past, there was a hypothesis about the relation of chaotic dynamics and saddle fixed points [5], [6]. From 2011, some works were proposed that were counterexamples for this hypothesis [7], [8]. For example, oscillators with a line of equilibria [9] and without equilibrium [10]. Studying chaotic flows and their dynamics has attracted much attention. Recently the chaotic oscillators have been proposed with different equilibrium points. A chaotic oscillator with various shapes of fixed points has been investigated in [11]. In [12], a physical memristive oscillator containing chaotic dynamics was studied. Chaotic dynamics of extinction in a prey-predator oscillator were discussed in [13]. In [14], the chaotic dynamics of the minimal universal model were investigated. Due to the complexity of chaotic dynamics, their control is critical [15]. Fractional order oscillators have been an interesting challenge [16]. The dynamics of a neuron under fractional-order flux were studied in [17]. Many recently proposed chaotic oscillators in which the basin of attraction of their chaotic dynamics is not related to an equilibrium point are categorized as oscillators with hidden attractors [18]. Hidden attractors and various dynamics of a passive motion model were investigated in [19]. Constructing hidden attractors via memristor Coupling was studied in [20]. Studying the synchronization of chaotic oscillators is very interesting [21]. Chaotic oscillators have an important application in image encryption.

Various tools can be used to study dynamical systems, like bifurcation diagrams, Lyapunov exponents (LEs), and entropies [22], [23], [24]. The basin of attraction is another interesting tool for investigating the effect of initial values

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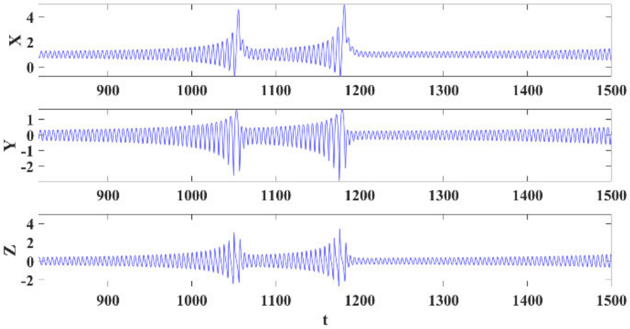

FIGURE 1. Chaotic time series of Oscillator (1) with parameters $p = -0.4$, $l = 0.3$ and $(x_0, y_0, z_0) = (0, 0, 0)$.

[25], [26]. Multistability is a vital feature that can occur in a dynamic system [27], [28]. In a multistable oscillator, the dynamics are varied by changing initial values [29]. Multistability in an improved version of the Chua oscillator has been investigated in [30]. In [31], the asymmetric multistability of a chaotic oscillator was discussed. Extreme events (EEs) are cases that significant amplitude events occur in a signal. There are many EEs in real word dynamics, such as epileptic seizures [32], [33]. Extreme events of coupled maps were investigated in [34]. They have tried to indicate the occurrence of these events. Also, deep learning has been applied to indicate extreme events [35].

Here, a chaotic oscillator is proposed. The chaotic time series and attractors of the oscillator are investigated in Section 2. In addition, the equilibrium point and its stability are analyzed. In Section 3, the behaviors of the oscillator are investigated. Bifurcation diagrams, LEs, and multistability of the system are studied. Its basin of attraction is investigated to show various dynamics by varying initial values. Extreme events are studied in the signal x of the chaotic dynamic. In Section 4, the circuit of the chaotic oscillator is implemented. The paper is concluded in Section 5.

II. THE PRESENTED OSCILLATOR

The oscillator is as follows:

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= z \\ \dot{z} &= -0.3x - 1.5y + 0.1z + 0.9y^2 \\ &\quad -0.8z^2 - 0.3xz + pyz + l \end{aligned} \tag{1}$$

Its chaotic dynamics can be seen in $p = -0.4, l = 0.3$. The parameters of the chaotic dynamics are obtained using a computer search. Figure 1 presents the chaotic time series of the oscillator. The 3-dimensional chaotic dynamic and its 2-dimensional projections are plotted in Fig. 2. In Fig. 2, the 3-dimensional attractor is plotted in green. The 2-dimensional projections of the attractor are presented in blue.

Studying fixed points is one of the basic dynamical analyses of a chaotic oscillator. The fixed points of the system can be obtained by setting zeros the velocities. In $p = -0.4$, the system has a fixed point in $(l/0.3, 0, 0)$. The characteristic equation for the equilibrium is $\lambda^3+(l-0.1)\,\lambda^2+1.5\lambda+0.3 = 0$. The real and imaginary parts of eigenvalues of the fixed points are presented in Fig. 3. In $l > 0.3$, the equilibrium point is stable since the real part of eigenvalues is negative. Also, the equilibrium is a spiral.

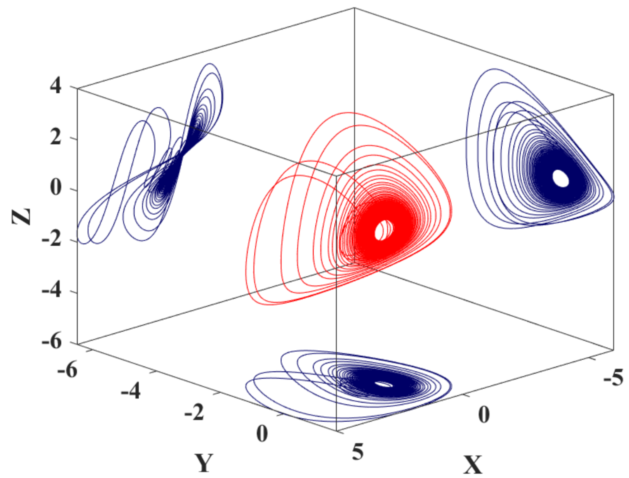

FIGURE 2. Chaotic dynamics of Oscillator (1) with $p = -0.4, l = 0.3$ and $(x_0, y_0, z_0) = (0, 0, 0)$; The 2D projections are shown in dark blue.

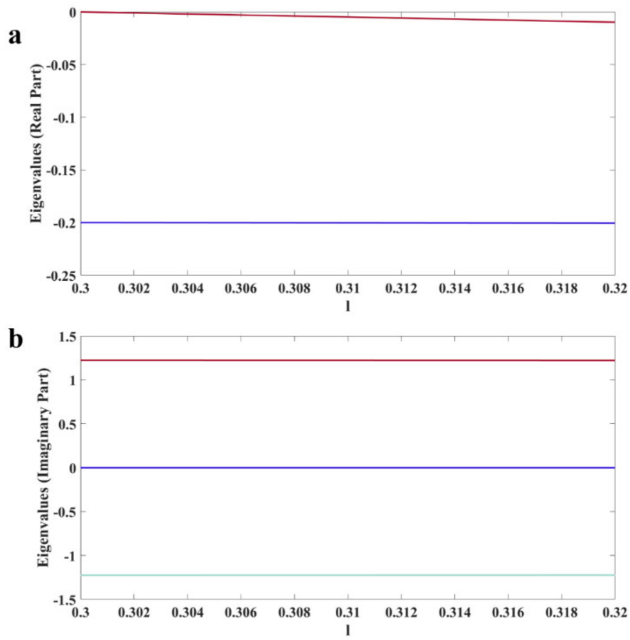

FIGURE 3. Real and imaginary parts of eigenvalues for $(\frac{l}{0.3}, 0, 0)$; In $l > 0.3$, the equilibrium point is stable since the real part of eigenvalues is negative.

The oscillator has only one stable fixed point in $l > 0.3$, so its chaotic dynamics are hidden in that interval.

III. DYNAMICAL PROPERTIES

The chaotic attractor of the proposed system was studied in the previous section. Also, studying the fixed points of the equations revealed that the chaotic dynamics are hidden. Here various dynamical properties of the oscillator are analyzed.

A. BIFURCATION ANALYSIS AND MULTISTABILITY

Various system dynamics by changing parameters can be investigated by plotting bifurcation diagrams. Different methods can be used to compute the bifurcation diagrams from the viewpoint of initial conditions. Different initial conditions can lead to different attractors in a system with multistability. So, by plotting bifurcation diagrams with different initiations, we hope that the multistable dynamics can be revealed. Here, different oscillator dynamics are studied by varying l, and p. Bifurcation of the oscillator by varying l is presented in Fig. 4a. Two bifurcation diagrams are shown in this plot. The green color is the bifurcation by forward initiation method and the first initial values as $(0, 0, 0)$. The brown color is the bifurcation plot by constant initial values as $(0, 0, 0)$. A period-doubling route to chaos is seen in the forward bifurcation diagram. Comparing the forward bifurcation with the brown one presents the multistability of the oscillator. In $l = 0.3058$, the dynamic jumps from chaotic dynamics to the stable equilibrium point $(l/0.3, 0, 0)$ in initial values $(0, 0, 0)$. Lyapunov exponents (LEs) of the oscillator by forwarding continuation method are plotted in Fig. 4b. The diagram presents that the oscillator has chaotic dynamics in $l < 0.31$. The LEs by constant initial values are shown in Fig. 4c. The dynamics jump to the equilibrium point in $l = 0.3058$ with three negative LEs. The LEs are computed using the Wolf algorithm with a run time of 20000.

Another bifurcation is investigated by changing p. The bifurcations with the forward continuation method (green) and constant initial values (brown) are shown in Fig. 5a. The system has chaotic dynamics in $p < -0.08$; then, it jumps to the equilibrium points dynamics. However, the brown diagram shows that the chaotic dynamics coexist with the equilibrium point in $p > -0.08$. Also, the LEs with forwarding continuation method (b) and constant initial values (c) show the difference of dynamics with these two methods.

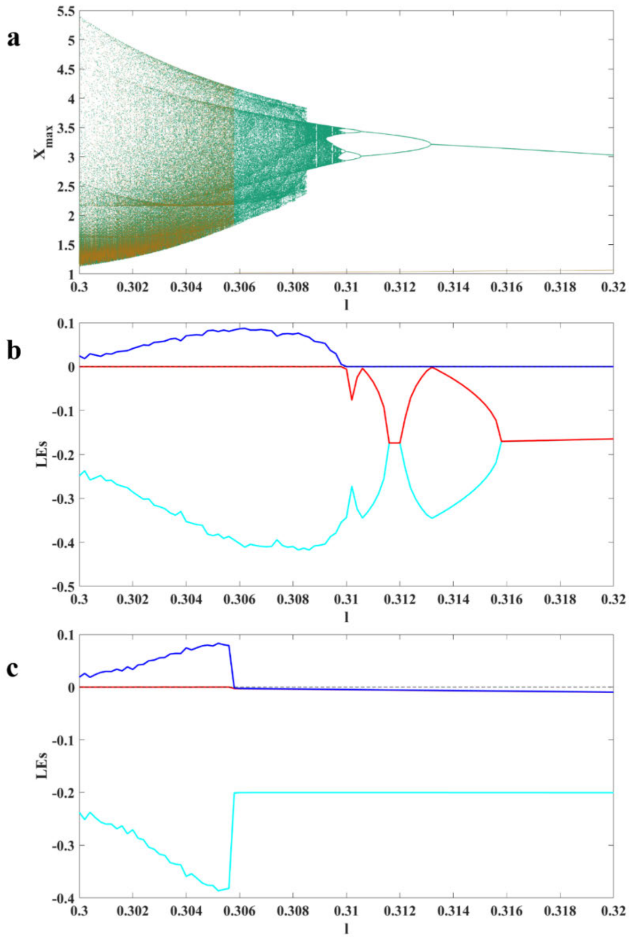

FIGURE 4. Bifurcation plot of Oscillator (1) by varying *l* and its LEs; a) bifurcation diagram with forwarding initiation method in green and with constant initial conditions (0, 0, 0) in brown color; b) LEs corresponding to forward initiation bifurcation diagram; c) LEs corresponding to constant initiation bifurcation diagram; The difference between the two bifurcation plots and LEs reveals the multistability of the system.

B. BASIN OF ATTRACTION

The effect of initial values in the oscillator dynamics can be investigated by computing the basin of attraction plot. The parameters $p = -0.4$ *and* $l = 0.304$ are selected in the region of chaotic dynamics (Fig. 4). Then, two planes are selected to investigate the three-dimensional space of initial values. The first plane is $X_0 - Z_0$ space where $Y_0 = 0$. Figure 6a shows the basin of attraction in this plane. Three colors in this diagram show the three behaviors of the oscillator. The pink regions are the initial values of unstable dynamics. So the pink initial conditions result in unbounded orbits. The green regions result in the stable equilibrium point, and the blue one shows the initial values of chaotic dynamics. The second plane is $X_0 - Y_0$, where $Z_0 = 0$. The same colors are used to show the three different dynamics. The chaotic regions are sprinkled in the equilibrium point region in both planes. To compute the basin, a threshold is defined for the unbounded regions. So the dynamics are marked as unstable if the time series crosses the threshold value. The region of attraction for the stable fixed point is found where the variation of time series becomes smaller than another threshold. Finally, the dynamics that are not periodic and not defined as previous groups are categorized as chaos.

C. EXTREME EVENT

Here, EEs are extracted using a threshold as $Th = mean\,(peaks\,(x)) + 8 \times \sigma_{peaks(x)}$ [36], [37]. $peaks\,(x)$ are the peak values of signal x, and $\sigma_{peaks(x)}$ is their standard deviation. For the x signal of Oscillator (1) in $p = -0.4$, $l = 0.3$, and initial values $(0, 0, 0)$, the threshold is computed as $Th = 5.1681$. The oscillator has only one EE at $t = 182.5$, and also, the signal approaches the threshold at $t = 1160.5$ but cannot cross the threshold.

IV. CIRCUIT IMPLEMENTATION

The circuit of the proposed oscillator is designed to show its feasibility. At first, the oscillator is scaled to have a smaller amplitude, preventing the electronic devices from saturation.

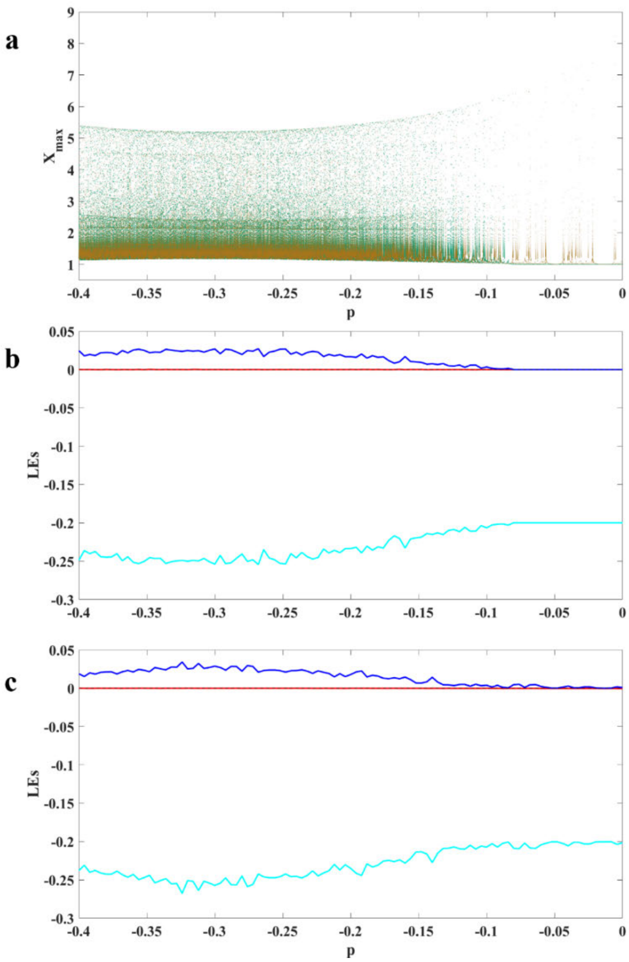

FIGURE 5. Bifurcation plot of Oscillator (1) by varying *p* and its LEs; a) bifurcation diagram with forwarding initiation method in green and with constant initial conditions (0, 0, 0) in brown color; b) LEs corresponding to forward initiation bifurcation diagram; c) LEs corresponding to constant initiation bifurcation diagram; The variation of dynamics from chaos to equilibrium can be seen in this plot.

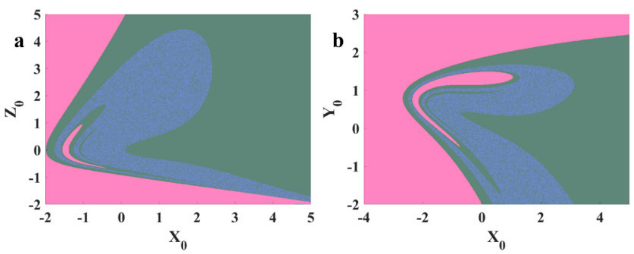

FIGURE 6. Basin of attraction a) in $X_0 - Z_0$ plane with $Y_0 = 0$; b) in $X_0 - Y_0$ plane with $Z_0 = 0$; the pink regions are the initial values of unstable dynamics. The green regions result in the stable equilibrium point, and the blue one shows the initial values of chaotic dynamics. The chaotic regions are sprinkled in the equilibrium point region in both planes.

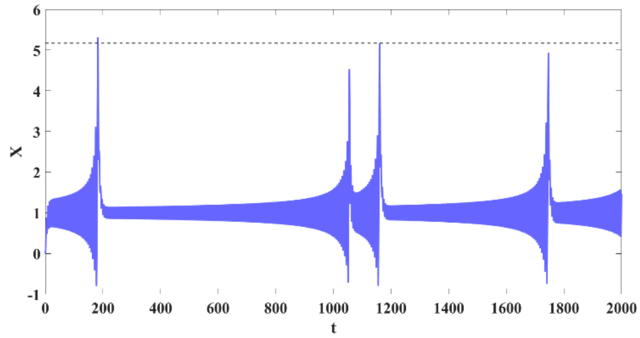

FIGURE 7. The chaotic time series of the oscillator in blue, and the threshold for detecting extreme events in black; The oscillator has only one EE at $t = 182.5$, and also, the signal approaches the threshold at $t = 1160.5$ but cannot cross the threshold.

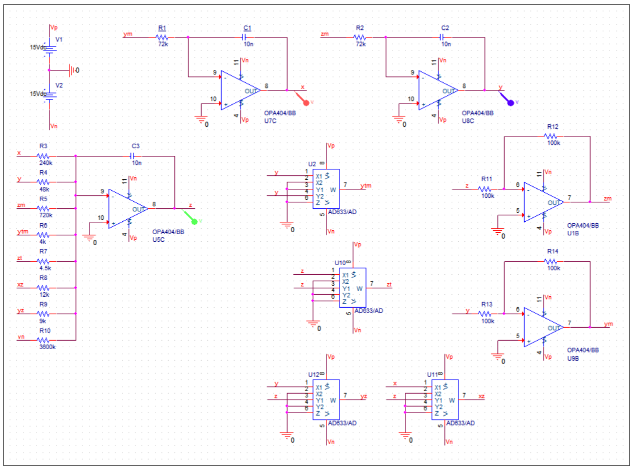

FIGURE 8. The implemented circuit.

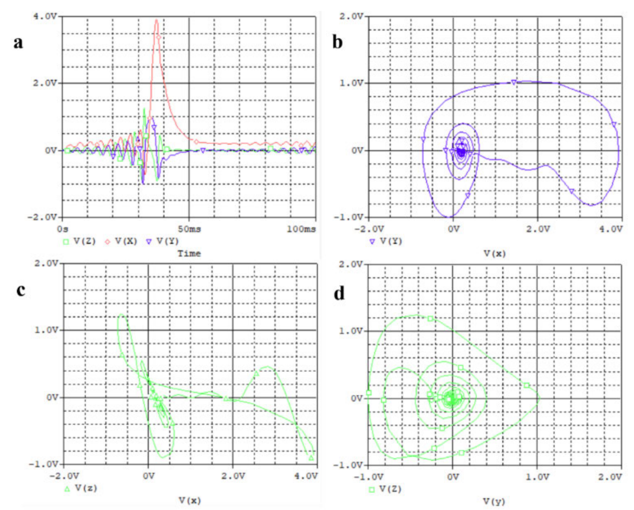

FIGURE 9. The dynamics of the proposed oscillator's circuit; a) time series; projection of attractor in b) $X - Y$; c) $Z - X$; d) $Z - Y$; the attractor is matched with the attractor of Fig. 2.

The changes of variables $X = x/2$, $Y = y/2$, and $Z = z/2$ are used. So Eq. (1) is transformed to:

$$\begin{aligned} \dot{X} &= Y \\ \dot{Y} &= Z \\ \dot{Z} &= -0.3X - 1.5Y + 0.1Z + 0.9 \times 2Y^2 - 0.8 \times Z^2 \\ &\quad -0.3 \times 2XZ - 0.4 \times 2YZ + 0.3 \end{aligned} \tag{2}$$

Then the circuit of the scaled chaotic oscillator is realized by OrCAD-PSpice. The following equations are used to implement the circuit of the oscillator.

$$X(t) = -\frac{1}{R_1 C_1} \int_0^t -Y(t)\, dt$$

$$\begin{aligned} Y(t) &= -\frac{1}{R_2C_2}\int_0^t -Z(t)\,dt \\ Z(t) &= -\frac{1}{R_3C_3}\int_0^t X(t)\,dt - \frac{1}{R_4C_3}\int_0^t Y(t)\,dt \\ &\quad -\frac{1}{R_5C_3}\int_0^t -Z(t)\,dt \\ &\quad -\frac{1}{10R_6C_3}\int_0^t -Y(t)\times Y(t)\,dt \\ &\quad -\frac{1}{10R_7C_3}\int_0^t Z(t)\times Z(t)\,dt \\ &\quad -\frac{1}{10R_8C_3}\int_0^t X(t)\times Z(t)\,dt \\ &\quad -\frac{1}{10R_9C_3}\int_0^t Y(t)\times Z(t)\,dt \\ &\quad +\frac{1}{10R_{10}C_3}\int_0^t v_p(t)\,dt \end{aligned} \quad (3)$$

The initial values are considered as $(\mathbf{0},\mathbf{0},\mathbf{0})$. The resistors and capacitors are considered as $\boldsymbol{R_1 = R_2 = 72k\Omega, R_3 = 240k\Omega, R_4 = 48k\Omega, R_5 = 720k\Omega, R_6 = 4k\Omega, R_7 = 4.5k\Omega, R_8 = 12k\Omega, R_9 = 9k\Omega, R_{10} = 3600k\Omega}$, and $\boldsymbol{C_1 = C_2 = C_3 = 10nF}$. The implemented circuit is shown in Fig. 8. The circuit dynamics are shown in Fig. 9, which are matched with the attractor of Fig. 2.

V. CONCLUSION

A novel chaotic system with a stable fixed point was proposed here. The chaotic attractor was studied. Various dynamics of the oscillator were investigated. Bifurcation diagrams of the oscillator showed its various dynamics by changing two parameters. The bifurcations by different initiation methods showed the existence of multistability. Also, the multistable dynamics were studied with the help of the LE spectrum. The basin of attraction of the dynamics was investigated. The basin of chaotic dynamics was sprinkled in the equilibrium point's basin of attraction. The existence of extreme events was investigated in the chaotic time series of the oscillator. In other words, the oscillator had a chaotic attractor with extreme events in its time series. Also, the system showed multistability in some intervals. The chaotic circuit for the proposed system was implemented to examine the feasibility of the dynamics.

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