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A Memristive Chaotic Oscillator With Increasing Amplitude and Frequency

CHUNBIAO LI[1], WESLEY JOO-CHEN THIO[2], HERBERT HO-CHING IU[3], (Senior Member, IEEE), AND TIANAI LU[1]

[1]Jiangsu Key Laboratory of Meteorological Observation and Information Processing, School of Electronic and Information Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China
[2]Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43210, USA
[3]School of Electrical, Electronic, and Computing Engineering, The University of Western Australia, Perth, WA 6009, Australia

Corresponding author: Chunbiao Li (chunbiaolee@nuist.edu.cn)

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ABSTRACT A chaotic oscillator utilizing a flux-controlled memristor to produce a signal that grows in amplitude and frequency over time is introduced in this paper. It was found that the initial condition can be used to change the starting oscillation as well as the amplitude and frequency. From this, a new regime of homogenous multistability was found, where various attractors with different initial conditions are of the same type but have different amplitudes and frequencies.

INDEX TERMS Homogenous multistability, increasing amplitude and frequency, memristive chaotic oscillator.

I. INTRODUCTION

Chaotic signals have great potential in engineering applications, including secure communication [1]–[3], image encryption [4]–[6], or weak signal detecting [7], [8].Chaotic signals with a controllable amplitude [9]–[11] or frequency [12], [13] especially have promising applications since they do not need an extra peripheral to provide premodulation. Many chaotic circuits use memristors, a two-terminal electronic device, which was postulated in [14] and [15] and has potential applications in the next generation computers and powerful intelligent devices [16], [17]. In this paper we investigate whether a memristor can be utilized to control the amplitude or even the frequency of a chaotic signal. We further investigate the property of multistability in this system, which has attracted great interest in the field of complex problems, such as the phenomenon of conditional symmetric attractors in an asymmetric system [18]–[20] or infinitely many attractors [21], [22] in a periodically offset-boostable system that has not been investigated before. In a pinched hysteresis loop (the finger print of a memristor), it is common to see multistability in memristive chaotic systems, where different attractors [23]–[26] or even extremely multistable attractors are found [27]–[29]. Multistability with the same class of attractors can be called "homogenous multistability" in contrast to "heterogeneous multistability". Memristive dynamical systems have abundant multistable attractors, but the regime of homogenous multistability was rarely reported.

When a chaotic system is equipped with a memristor for amplitude-frequency control, the memristive system will have two unusual properties: a chaotic signal with growing amplitude/frequency and infinitely many homogenous attractors. In Sec. 2, a model of the new memristive chaotic system is proposed. In Sec.3, the properties of the memristive system are demonstrated. In Sec.4, the system was implemented as a chaotic circuit with the experimental results showing agreement with the predicted simulation. The conclusion and discussion is given in the last section.

II. MODEL DESCRIPTION

A new memristive chaotic system is described as,

$$\begin{cases} \dot{x} = W(u)y + yz, \\ \dot{y} = yz - axz, \\ \dot{z} = bz^2 - y^2, \\ \dot{u} = y. \end{cases} \tag{1}$$

where the flux-controlled memductance in the first dimension is $W(u) = k(|u| - c)$ is introduced in the first dimension.

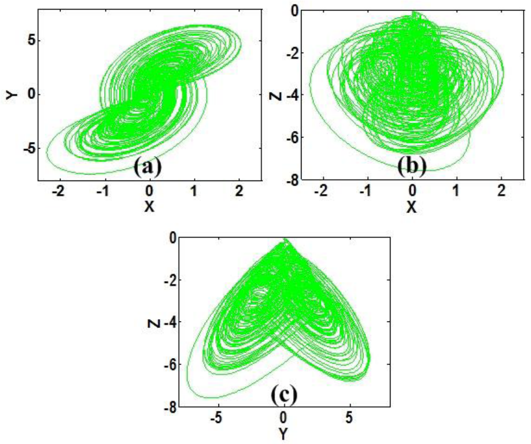

FIGURE 1. **Projections of the chaotic attractor from System (1) with initial condition [1, 0, −1, 1] when $a = 5.5$, $b = 0.55$, $k = 0.05$, $c = 1$ and the time duration is 600.**

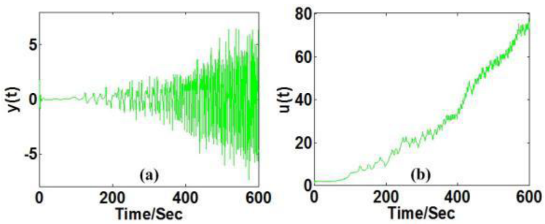

FIGURE 2. **Chaotic oscillation and the internal state from System (1) with initial condition [1, 0, −1, 1] when $a = 5.5$, $b = 0.55$, $k = 0.05$, $c = 1$ and the time duration is 600.**

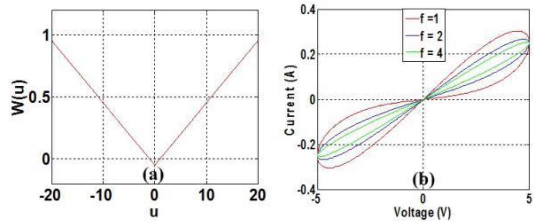

FIGURE 3. **The memductance and pinched hysteresis loop.**

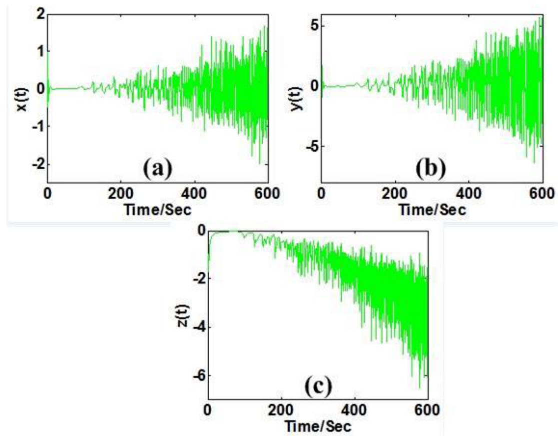

FIGURE 4. **Chaotic signal of System (1) with $k = 0.05$, $c = 1$ and initial conditions [1, 0, −1, 1] over a time duration of 600.**

When $a = 5.5$, $b = 0.55$, $k = 0.05$, $c = 1$, System (1) has a chaotic attractor with Lyapunov exponents (0.1375, 0.0068, −0.0086, −2.2962) with initial conditions (1, 0, −1, 1) and increases in amplitude and frequency over a duration of 600, as shown in Fig.1. The internal state u is determined by the integration of the memristor input variable y. As shown in Fig.2, the increasing value of the control variable u increases the frequency of signals x, y and z. Here the internal state of u is continuously growing which is different from some of other memrister models because the variable y grows with the memductance $W(u)$ and give a positive feedback to the internal state.

System (1) retains the rotational symmetry with a rate of hypervolume contraction given by the Lie derivative, $\nabla V = \frac{\partial \dot{x}}{\partial x} + \frac{\partial \dot{y}}{\partial y} + \frac{\partial \dot{z}}{\partial z} + \frac{\partial \dot{u}}{\partial u} = (2b+1)z$. In contrast to other memristive systems, the above system has an infinite plane of equilibria $(x, 0, 0, u)$ with eigenvalues (0, 0, 0, 0).

Here the flux-controlled memristor is defined as,

$$\begin{cases} i = W(u)y, \\ W(u) = 0.05|u| - 0.05, \\ \dot{u} = y. \end{cases} \tag{2}$$

The flux-controlled memductance is a function of internal state of u, and is associated with the voltage y,

$$\begin{aligned} W\,(u) &= 0.05\,|u| - 0.05 = 0.05\left|\int_{-\infty}^{t} yds\right| - 0.05 \\ &= W_0 + 0.05\left|\int_{0}^{t} yds\right| - 0.05 \end{aligned} \tag{3}$$

where $W_0 = 0.05(\left|\int_{-\infty}^{t} yds\right| - \left|\int_{0}^{t} yds\right|)$. The memductance and the theoretical pinched hysteresis loop are shown in Fig.3.

III. UNIQUE DYNAMICAL BEHAVIOR

A. AMPLITUDE AND FREQUENCY BOOSTING OVER TIME

The original system without a memristor has two coefficients to control the amplitude of the signal [12],

$$\begin{cases} \dot{x} = ny + yz, \\ \dot{y} = yz - axz, \\ \dot{z} = bz^2 - my^2. \end{cases} \tag{4}$$

where parameter n controls the amplitude and frequency of all the signals x, y and z, while m controls the amplitude of x and y. In System (1), the added memristor can control the amplitude and frequency. As the internal state u and consequently the memductance increases over time, so does the amplitude and frequency. As predicted, the chaotic signals in the time domain are modulated by the memristor with increasing amplitude and frequency, as shown in Fig.4. The phase trajectories over time are shown in Fig.5, clearly showing chaotic signals increasing in amplitude and frequency. The frequency spectra of the chaotic signals are shown in Fig. 6. As a comparison, we list the typical information including the average amplitude (AA) and Largest Lyapunov exponent (LLE) (corresponding to a boosted frequency) in Table.1. Here the increasing amplitude is indicated by the growing average value of the absolute values of corresponding chaotic signals

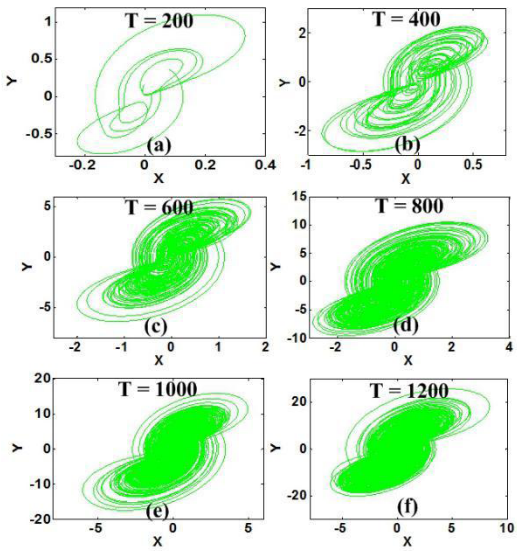

FIGURE 5. Different phase trajectories of System (1) with $k = 0.05$, $c = 1$ and various durations of time under the same initial condition [1, 0, −1, 1].

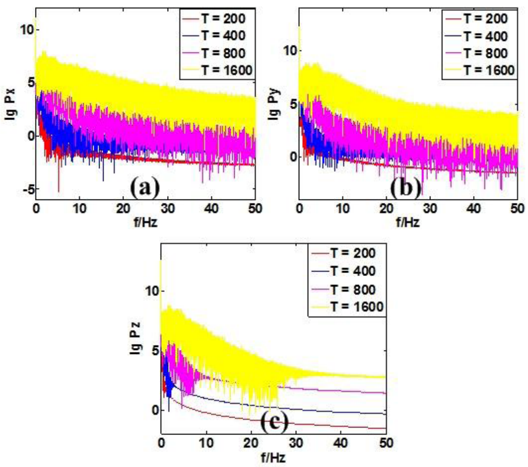

FIGURE 6. Frequency spectra of the chaotic signals from System (1) with $k = 0.05$, $c = 1$ and initial condition [1, 0, −1, 1] when the run time is prolonged.

while the increasing frequency is proven by the increasing largest Lyapunov exponent based on the Wolf algorithm.

B. HOMOGENOUS MULTISTABILITY: INITIAL-CONDITION-TRIGGERED AMPLITUDE AND FREQUENCY BOOSTING

When a dynamical system has coexisting attractors of the same shape but with different positions, amplitude or even frequency, the regime of multistability can be defined as homogenous multistability. Here in System (1), we find a new regime of homogenous multistability, where different initial condition can trigger the same oscillation but with different amplitudes and frequency. In fact, the initial condition determines the start amplitude and frequency of the oscillation process. For example, fix the initial state as $(x_0, y_0, z_0) = (1, 0, -1)$ and the time duration 500, revise the initial value of the internal state u_0, chaotic signals stand different stages of amplitude and frequency. As shown in Fig. 7, when the initial state u_0 is 0.5, the amplitude and frequency are both in small scale. The same trend can be seen in the average value and the largest Lyapunov exponent, as shown in Table.2. As shown in Fig.8, when the initial condition u_0 varies in [0, 8], the average of the state variable u revise positively and dramatically, while the average of the variable x, y, and z will increase accordingly. The increasing frequency can be identified by the slowly climbing slope of the largest

TABLE 1. Average amplitude (AA) of chaotic signal of System (1) with $k = 0.05$, $c = 1$ and the initial condition [1, 0, −1, 1] and largest Lyapunov exponent (LEE).

Cases	T	AA: (mean($\|x\|$, $\|y\|$, $\|z\|$, $\|u\|$))	LLE
A1	200	(0.0449, 0.1443, 0.2208, 5.8607)	0.0398
B1	400	(0.1212, 0.4327, 0.6578, 14.8009)	0.0701
C1	600	(0.2465, 0.8837, 1.3491, 29.2505)	0.1526
D1	800	(0.3837, 1.3842, 2.1138, 44.8955)	0.2348
E1	1000	(0.5265, 1.8868, 2.8919, 61.1531)	0.3418
F1	1200	(0.6748, 2.4159, 3.7028, 77.7349)	0.4492

TABLE 2. Average amplitude of chaotic signal of System (1) with $k = 0.05$, $c = 1$ and the initial condition [1, 0, −1, u_0] and largest Lyapunov exponent when T = 1000.

Cases	u_0	AA: (mean($\|x\|$, $\|y\|$, $\|z\|$, $\|u\|$))	LLE
A2	0.5	(0.3212, 1.1674, 1.7779, 37.7247)	0.2063
B2	1	(0.5265, 1.8868, 2.8919, 61.1531)	0.3202
C2	2	(0.6698, 2.4210, 3.6921, 76.8133)	0.5137
D2	4	(0.8422, 3.0538, 4.6563, 96.4674)	0.5862
E2	8	(0.7143, 2.5771, 3.9379, 82.1217)	0.6646
F2	16	(1.1997, 4.3158, 6.5991, 136.4677)	0.7262

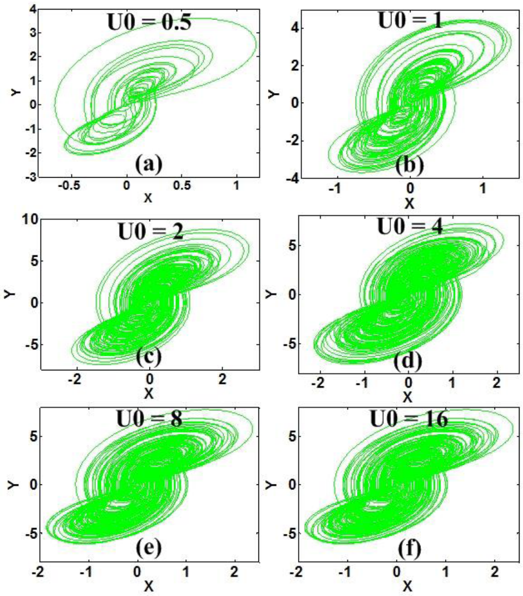

FIGURE 7. Phase trajectories of System (1) with $k = 0.05$, $c = 1$ and initial conditions $(1, 0, -1, u_0)$ under the same time (T = 500).

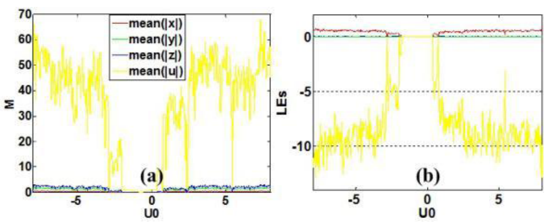

FIGURE 8. The average value of the chaotic signals and the corresponding Lyapunov exponents of System (1) with $k = 0.05$, $c = 1$ and the initial conditions $(1, 0, -1, u_0)$, u_0 varies in [−8, 8]. Here the run time of T is 1000.

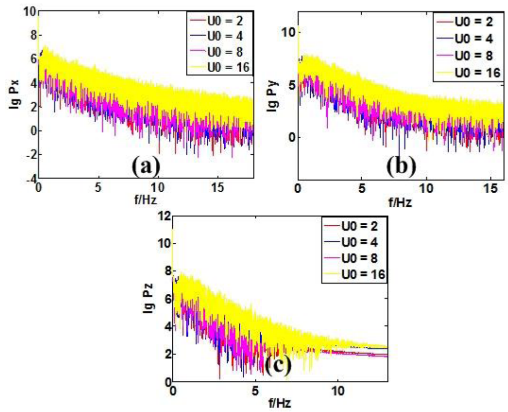

FIGURE 9. Frequency spectra of the chaotic signals of System (1) with $k = 0.05$, $c = 1$ and initial conditions $(1, 0, -1, u_0)$. Here the run time of T is 1000.

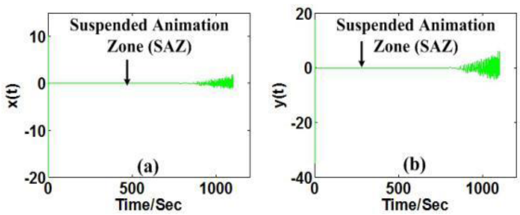

FIGURE 10. Suspended animation in System (1) with $k = 0.05$, $c = 1$ and initial conditions [−20, 0, −1, 0.5] under the time duration 1100.

Lyapunov exponent. In the other direction when the internal state u_0 varies in $[-8, 0]$, the amplitude and frequency evolution shows the same regularity as in the positive direction since flux-controlled memductance is an absolute function of the internal state. Frequency spectra in Fig. 9 show the same characteristic in oscillation. Typical information including the average amplitude and the Largest Lyapunov exponent (corresponds to a boosted frequency) is listed in Table.2.

Moreover, a crisis in amplitude control still exists [12]. The boosting of the amplitude and frequency may encounter a risk since some initial conditions can lead to a direct death of oscillation. For example, when $(x_0, y_0, z_0, u_0) = (-1, 0, -1, 0.5)$, $(1, 5, -1, 0.5)$, $(1, 0, 5, 0.5)$, $(1, 0, -1, -0.5)$, the oscillation is stopped by the initial condition and System (1) converges to a fixed point. Note that some initial conditions will result in a state of suspended animation, such as in $(-20, 0, -1, 0.5)$, System (1) comes back to the oscillation until the time is about over 850, as shown in Fig.10. The initial condition in the x dimension can also adjust the amplitude and frequency in a way which is not a positive correlation and different from the u dimension, as shown in Fig. 11. All the coexisting attractors as shown in Fig.7 and Fig.11 indicate the special regime of homogenous multistability.

IV. CIRCUIT IMPLEMENTATION

From Eq. (1), we design the analog circuit shown in Fig. 12 where the circuit equations in terms of the circuit parameters are

$$\begin{cases} \dot{x} = \dfrac{1}{C_1}W(u)y + \dfrac{1}{R_1C_1}yz, \\ \dot{y} = \dfrac{1}{R_2C_2}yz - \dfrac{1}{R_3C_2}xz, \\ \dot{z} = \dfrac{1}{R_4C_3}z^2 - \dfrac{1}{R_5C_3}y^2. \end{cases} \tag{5}$$

where memristor $W(u)$ in Fig. 13 and its state is defined as,

$$\begin{cases} i = W(u)y, \\ W(u) = \dfrac{R_f}{R_d}|u| - \dfrac{R_f}{R_e}V_{dd}, \\ \dot{u} = \dfrac{1}{R_aC_a}y. \end{cases} \tag{6}$$

The system was rescaled by $u \to 10u$ to delay the saturation time of the circuit. The circuit consists of four channels to realize the integration, addition, and subtraction of state variables x, y, z and u. The operational amplifier TL084 performs the addition, inversion, and integration, and the analog multiplier AD633/AD performs the nonlinear product operation. The circuit is powered by ±15V. The state variables x, y, and z in Eq. (1) correspond to the state voltages of the three channels, while u corresponds to the internal state of the memristor. For the system parameters $a = 5.5$, $b = 0.55$, $k = 0.05$, $c = 1$, the circuit element values are $C_1 = C_2 = C_3 = 1\text{uF}$, $R_1 = R_2 = R_5 = R_6 = R_7 = R_8 = R_9 = 1\text{k}\Omega$,

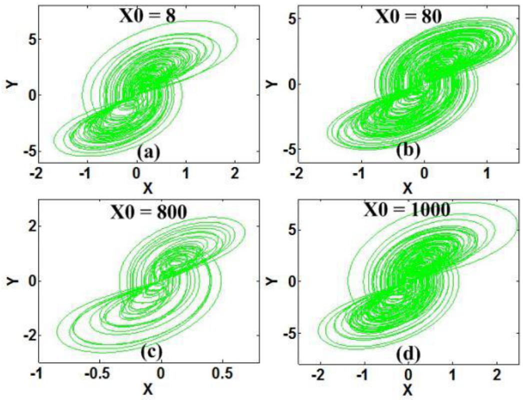

FIGURE 11. Phase trajectories of System (1) with $k = 0.05$, $c = 1$ and initial conditions $[x_0, 0, -1, 0.5]$ under the same time (T = 500).

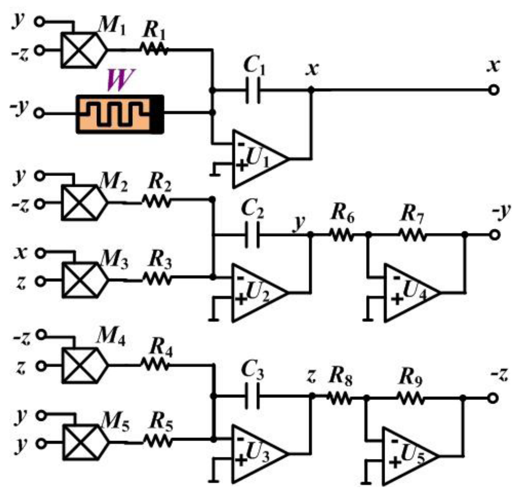

FIGURE 12. Circuit schematic of the memristive system.

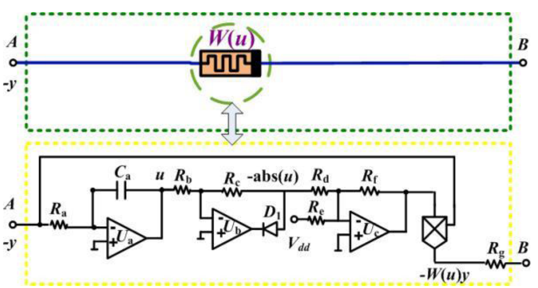

FIGURE 13. Equivalent circuit of the flux-controlled memristor.

$R_3 = 180\text{k}\Omega$ and $R_4 = 1.8\text{k}\Omega$. The memristor circuit is shown in Fig. 13 and has the following parameter values, $C_4 = 1\text{uF}$, $R_a = 100\text{k}\Omega$, $R_b = 470\Omega$, $R_c = 470\Omega$, $R_d = 2\text{k}\Omega$, $R_e = 300\text{k}\Omega$, $R_f = 1\text{k}\Omega$ and $R_g = 1\text{k}\Omega$. The time scale is set at 1000 to observe the increase in frequency and amplitude before saturation. Figure 14 shows a plot of the experimental memductance and pinched hysteresis loop, while Figure 15 shows the time evolvement of the chaotic signal with increasing amplitude and frequency. Figure 16 shows the phase portraits observed in the oscilloscope.

FIGURE 14. Plot of experimental memductance and pinched hysteresis loop (CH1: u, CH2: $W(u)$ for the left and CH1: input voltage, CH2: the current for the right).

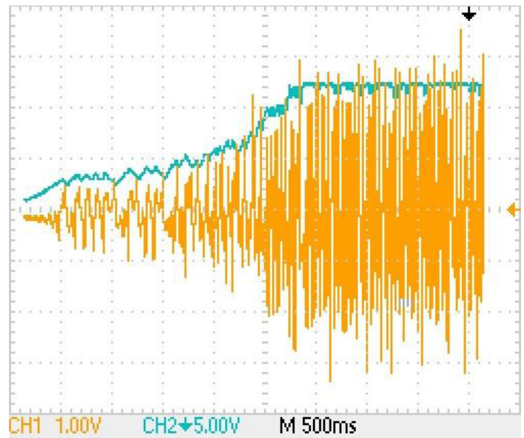

FIGURE 15. Time evolvement of the chaotic signal with increasing amplitude and frequency (CH1: x, CH2: u).

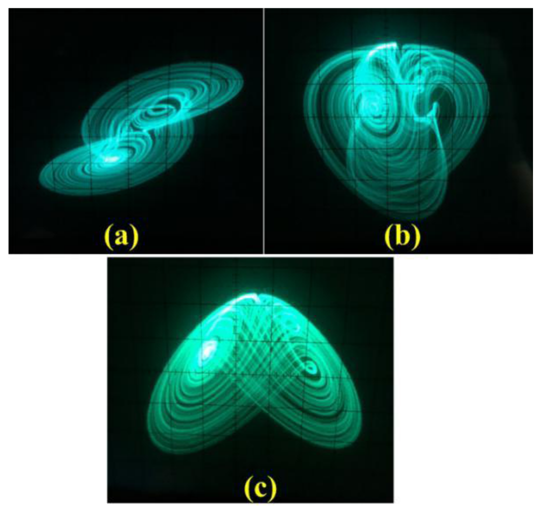

FIGURE 16. Phase trajectory of System (6) from oscilloscope (a) *x-y* (b) *x-z* (c) *y-z*.

V. CONCLUSIONS AND DISCUSSION

When a memristor was introduced into a chaotic system for amplitude-frequency control, a new chaotic oscillator was generated where the output chaotic signals increase in amplitude and frequency over time. The initial conditions can be used to extract chaotic signals with different amplitudes and frequencies, corresponding to a new regime of homogenous multistability which was found and demonstrated. Chaotic signals with increasing amplitude and frequency meet the broad requirement in application engineering. Regarding the physical implementation, the memristor is utilized as a power element to control the amplitude and frequency, whereas the amplitude is typically controlled by resistor and the frequency is controlled by capacitor.

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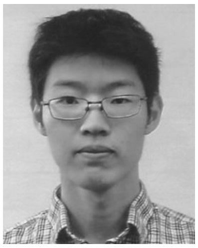
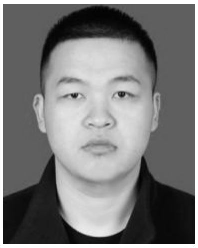
CHUNBIAO LI received the master's and Ph.D. degree in succession from the Nanjing University of Science and Technology in 2004 and 2009. From 2010 to 2014, he was a Post-Doctoral Fellow with the School of Information Science and Engineering, Southeast University. He was a Visiting Scholar with the Department of Physics, University of Wisconsin-Madison, from 2012 to 2013.

He is currently an Associate Professor with the School of Electronic and Information Engineering, Nanjing University of Information Science and Technology. His research interests include the areas of nonlinear dynamics and chaos, including nonlinear circuits, systems, and corresponding applications. He has received several awards for his teaching and research in Jiangsu Province.



WESLEY JOO-CHEN THIO is currently pursuing the B.S. degree in electrical and computer engineering with The Ohio State University in 2018. His current research interests include nonlinear and chaotic circuits. He has several publications in this field.

HERBERT HO-CHING IU received the B.Eng. degree (Hons.) in electrical and electronic engineering from The University of Hong Kong, Hong Kong, in 1997, and the Ph.D. degree from The Hong Kong Polytechnic University, Hong Kong, in 2000. In 2002, he joined the School of Electrical, Electronic and Computer Engineering, The University of Western Australia, as a Lecturer, where he is currently a Professor. His research interests include power electronics, renewable energy, nonlinear dynamics, current sensing techniques, and memristive systems. He has authored over 100 papers in these areas. He has received two IET Premium Awards in 2012 and 2014. He also received the Vice-Chancellor's Mid-Career Research Award in 2014 and the IEEE PES Chapter Outstanding Engineer in 2015. He currently serves as an Associate Editor for the IEEE Transactions on Circuits and Systems II, the IEEE Transactions on Power Electronics, the IEEE Access, the *IEEE Circuits and Systems Magazine*, the *IET Power Electronics*, and the *International Journal of Bifurcation and Chaos*, an Editorial Board Member of the IEEE *Journal of Emerging and Selected Topics in Circuits and Systems* and the *International Journal of Circuit Theory and Applications*. He is a Co-Editor of the *Control of Chaos in Nonlinear Circuits and Systems* (Singapore: World Scientific, 2009) and a Co-Author of the *Development of Memristor Based Circuits* (World Scientific, 2013).



TIANAI LU is currently pursuing the master's degree in information and communication engineering from the Nanjing University of Information Science and Technology, China. His current research interests include nonlinear and chaotic circuits.