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Design and Implementation of a 1-D Multi-Scroll Chaotic Circuit Based on CFOAs

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Abstract: In this study, a method is proposed to design a one-dimensional (1-D) multi-scroll chaotic circuit by using Current Feedback Operational Amplifiers (CFOAs). A chaotic circuit is designed which consists of three integrators and one nonlinear circuit. The circuit can generate 1-D multi-scroll chaotic attractors. The central frequency of the circuit is higher with fewer active devices and simpler circuit construction. Numeral simulation, circuit simulation experiments are performed and results show that the method is feasible and circuit design is correct.

Key words: Multi-scroll chaotic attractors, current feedback operational amplifier, circuit implementation

INTRODUCTION

Chaotic system has become a popular area since the first system was proposed (Lorenz, 1963) and many achievements have been reported (Trejo-Guerra *et al*., 2009; Chua *et al*., 1986). At the same time, chaotic systems are widely used in the secure communication systems and information encryption (Trejo-Guerra *et al*., 2009). The 1-D multi-scroll chaotic systems were proposed (Suykens and Vandewalle, 1993) and based on it much more complex multi-scroll chaotic systems are achieved by using different nonlinear function such as piecewise-linear function, Saturated nonlinear function series (SNFs) and sine function, etc. (Ma *et al*., 2014; Yalcin, 2007; Munoz-Pacheco and Tlelo-Cuautle, 2008). The chaotic circuits are designed with Opamps. However, compared with the conventional Opamp, the Current Feedback Operational Amplifier (CFOA) has better frequency characteristics, which can improve the central frequency of the circuit and it has better port characteristic, which can simplify the circuit construction and the circuit design become more flexible. A lot of chaotic systems are implemented with CFOA, so studying this area becomes a hot topic. One scroll chaotic attractor was realized with one CFOA and one nonlinear element (Elwakil and Kennedy, 1998). Two scroll chaotic attractors are implemented with CFOAs (Elwakil and Kennedy, 2000). The 1-D multi-scroll chaotic attractors are implemented with CFOAs and Opamps (Yalcin *et al*., 2001), but the central frequency of circuit is hard to improve any more for the Opamps. The A 1-D multi-scroll chaotic circuit also can be implemented only use the CFOAs, but the circuit construction is complex and many active devices are used (Trejo-Guerra *et al*., 2010, 2013; Ortega-Torres *et al*., 2014; Munoz-Pacheco *et al*., 2012). E.g. the nonlinear circuit used many active devices (Trejo-Guerra *et al*., 2010, 2013; Ortega-Torres *et al*., 2014) and the nonlinear circuit was realized with an active device (Munoz-Pacheco *et al*., 2012). A 1-D multi-scroll chaotic circuit can be implemented just by the current conveyors and nonlinear circuit only use an active device, but there are many the active devices in the chaotic circuit (Sanchez-Lopez *et al*., 2010). The central frequency of these circuits is lower.

The present study aims to propose a method to realize a1-D multi-scroll chaotic system only by using CFOAs.

MATERIALS AND METHODS

In this study, a method is proposed to realize a 1-D multi-scroll chaotic system only by CFOAs and a chaotic circuit is designed which consists of three integrators and one nonlinear circuit. The circuit can generate 1-D multi-scroll chaotic attractors. Its central frequency is higher with fewer active elements and simpler circuit construction. A real chaotic circuit is produced. Numeral simulation, circuit simulation and experiment are performed.

RESULTS

A non-linear function can be approximated by a saturated function series, Eq. 1 is an expression of PWL and the saturated function series is expressed as:

$$f(x;k,h,p,q)=\sum_{i=-p}^{q} f_i(x;k,h) \quad (1)$$

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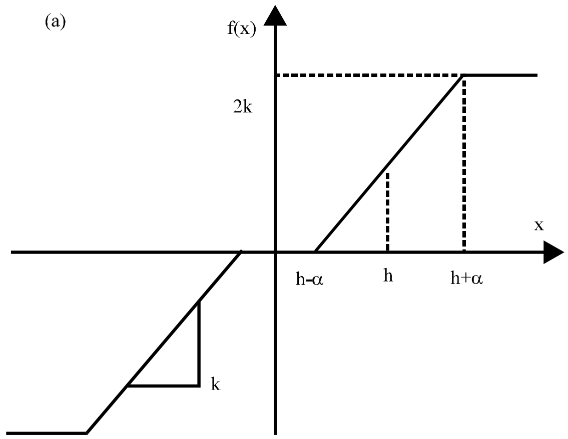

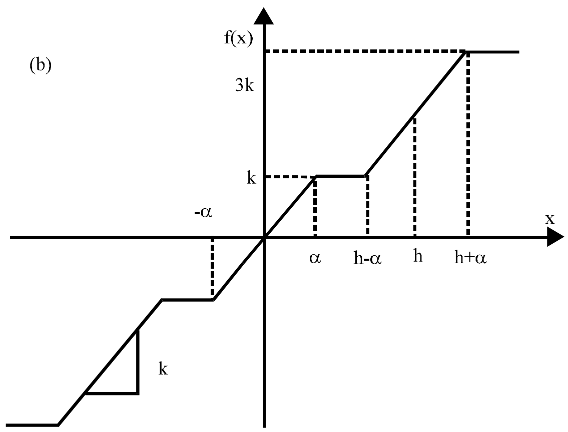

Fig. 1(a-b): PWL description of a SNLF: (a) 5 and (b) 7 segments

where, k>0 is the slope of the saturated function, h>2 is the delay of the center of the slope, p and q are positive integers and Eq. 1 can be expressed as:

$$f(x,k,h,p,q)=\begin{cases}(2q+1)k, & \text{if } x>qh+1\\ (x-ih)k+2ik, & \text{if } |x-ih|\le 1,\ -p\le i\le q\\ (2i+1)k, & \text{if } ih+1<x<(i+1)h-1,\ -p\le i\le q-1\\ -(2q+1)k, & \text{if } x<-qh-1\end{cases}\tag{2}$$

Equation 2 is described by Fig. 1 and it is a saturated function with 5 and 7 segments.

Ma *et al*. (2014), Yalcin (2007), Munoz-Pacheco and Tlelo-Cuautle (2008), Munoz-Pacheco *et al*. (2012) and Sanchez-Lopez *et al*. (2010), expressed a general 1-D multi scroll chaotic system as:

$$\begin{cases}\dot{x}=y\\ \dot{y}=z\\ \dot{z}=a(-x-y-z+f(x;k,h,p,q))\end{cases}\tag{3}$$

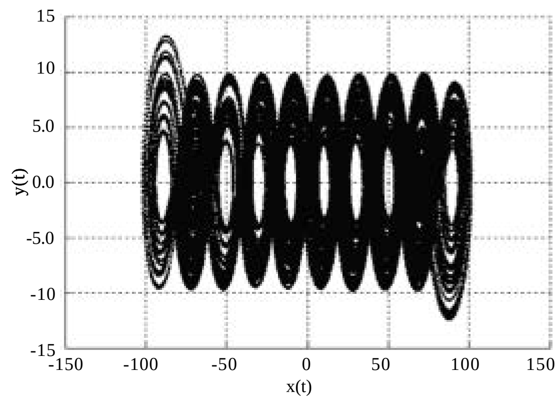

Fig. 2: 10-scroll projection on x-y plane without DR scaling

When k = 10, h = 20, p = q = 4, system (3) can generate 10 scroll chaotic attractors shown in Fig. 2.

It can be seen in Fig. 2 that the range of attractors is x∈ (-150, 150), y∈ (-15, 15). The above range of the attractors is out of the effective range of the active devices. To solve this problem Eq. 2 is transferred as:

$$f(x,k,h,p,q)=\begin{cases}(2q+1)k, & \text{if } x>qh+\alpha\\ (k/\alpha)(x-ih)+2ik, & \text{if } |x-ih|\le \alpha,\ -p\le i\le q\\ (2i+1)k, & \text{if } ih+\alpha<x<(i+1)h-\alpha,\ -p\le i\le q-1\\ -(2q+1)k, & \text{if } x<-qh-\alpha\end{cases}\tag{4}$$

where, k and α<1, s = k/α is the slope. When k = 0.5, α = 0.0064, s = 78.125, h = 1, p = q = 4, system (3) can generate 10 scroll chaotic attractors shown in Fig. 3.

It can be seen in Fig. 3 that the range of attractors is x∈ (-6, 6), y∈ (-0.6, 0.8). It is to say that the effective range of the active devices can meet the range of the attractors and then a chaotic circuit can be designed.

It is known that the saturated circuit is one of the PWL circuit. In this study, the PWL model of the CFOA is characteristics by saturated circuit. The finite gain model of the CFOA is shown in Fig. 4. Equation 4 can be realized by the CFOA.

From Fig. 4, the PWL approximation of the CFOA is accurate and its equation is expressed as:

$$\begin{cases}v_o=\dfrac{A_v}{2}\left(\left|v_i+\dfrac{E_{sat}}{A_v}\right|-\left|v_i-\dfrac{E_{sat}}{A_v}\right|\right)\\ i_-=i_+=0\end{cases}\tag{5}$$

where, E_{sat} is positive saturated value, $-E_{sat}$ is negative saturated value, A_v is voltage gain, v_o∈ [$-E_{sat}$, E_{sat}] is linear.

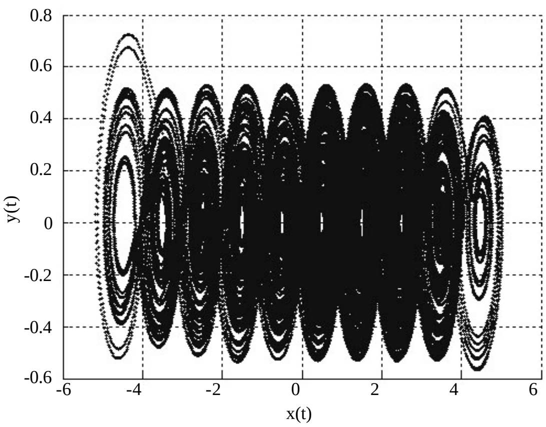

Fig. 3: 10-scroll projection on x-y plane with DR scaling

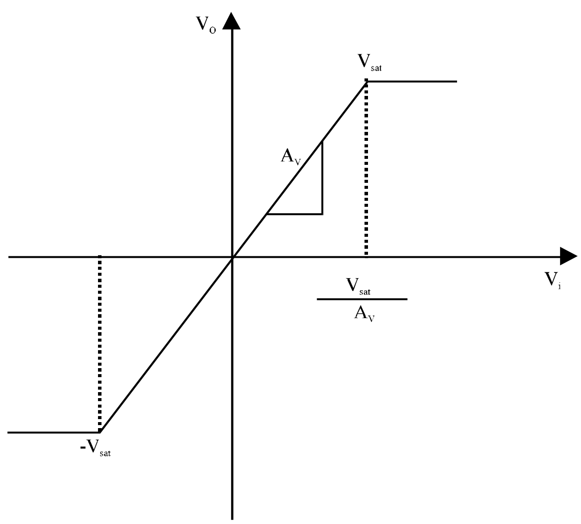

Fig. 4: CFOA finite-gain model

The saturated nonlinear function designed with CFOA can be seen in Fig. 5a. Figure 5a is the basic cell of the saturated nonlinear function. By connecting several basic cells in parallel, as shown in Fig. 5b and multi-scroll saturated function can be realized.

As shown in Fig. 5 that $s = V_{sat}/\alpha$ is the slope, $\alpha = V_{sat}/A_v$ is the break point, $k = V_{sat}$ is the saturated value, $i_o = V_o/R_c$ is the output current. The expressions of k, α s, h are given by the following equations according to Munoz-Pachecoand Tlelo-Cuautle (2008) and Munoz-Pacheco *et al.* (2012):

$$k = R_{ix} I_{sat}, I_{sat} = \frac{V_{sat}}{R_c}, \alpha = \frac{R_a |V_{sat}|}{R_b}, s = \frac{h}{\alpha}, h = \frac{E_i}{(1+R_a/R_b)} \quad (6)$$

Equation 3 can be implemented, as shown in Fig. 6.

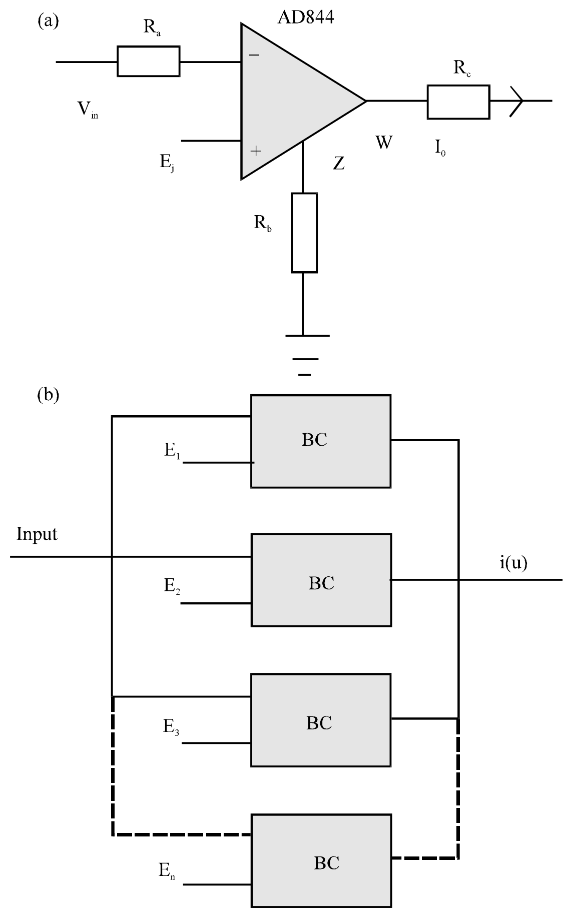

Fig. 5(a-b): Saturated function: (a) Basic cell and (b) Multi-scroll saturated function circuit

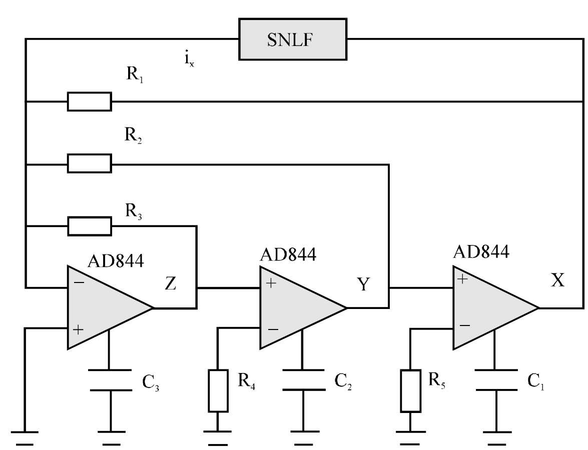

Fig. 6: Multi-scroll chaotic circuit of system (3) with CFOAs

To reduce the impact of the parasitic elements parameters, the value of R_a, R_b, R_1, R_2, R_3, R_4 and R_5 should

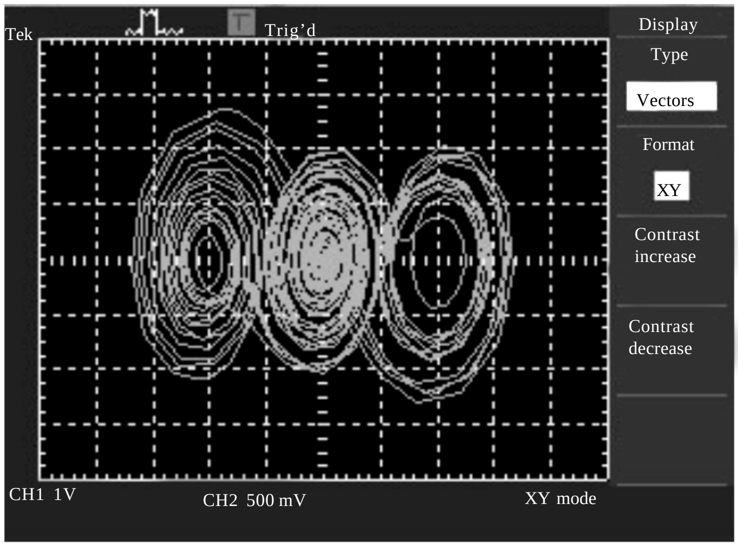

Fig. 7: 3-scroll projection on x-y plane; horizontal-axes: 1V/div and vertical-axes: 0.5V/div

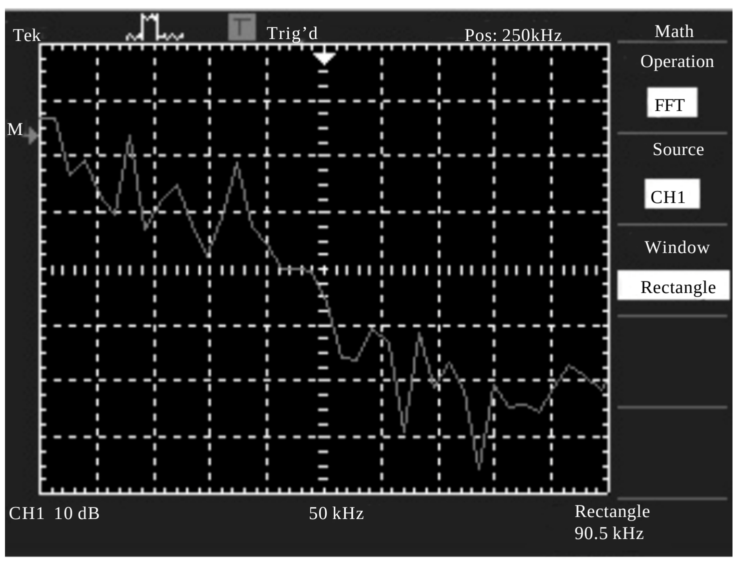

Fig. 8: Frequency spectrum of 3-scroll chaotic attractors

be as high as possible. So, R_a=1 kΩ and R_b=1 MΩ are determined and then from Fig. 6 the following expression can be obtained:

$$\begin{cases} \dot{x} = \dfrac{1}{R_5C_1}y \\ \dot{y} = \dfrac{1}{R_4C_2}x \\ \dot{z} = \dfrac{1}{R_1C_3}x - \dfrac{1}{R_2C_3}y - \dfrac{1}{R_3C_3}z + \dfrac{1}{C_3}i(x) \end{cases} \quad (7)$$

In order to verify circuit design, when VDD = 10 V, VEE = -10 V, E_1 = ±1 V, h_1 = 1 system (3) can generate 3-scroll chaotic attractors. When a = 0.7, k = 1, α = 0.0064, s = 156.25, circuit parameters can be obtained:

$$R_1 = R_2 = R_3 = 10\ \text{k}\Omega,\ R_4 = R_5 = 7\ \text{k}\Omega,\ R_c = 64\ \text{k}\Omega,$$
$$C_1 = C_2 = C_3 = 2.2\ \text{nF}$$

The multisim simulation results of 3-scroll can be seen in virtual oscilloscope shown in Fig. 7.

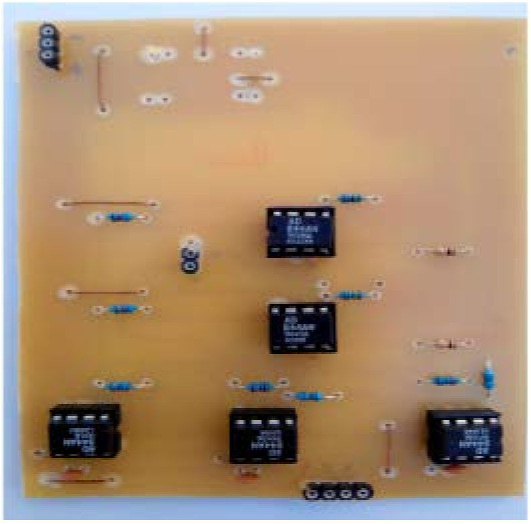

Fig. 9: Real chaotic circuit on a PCB

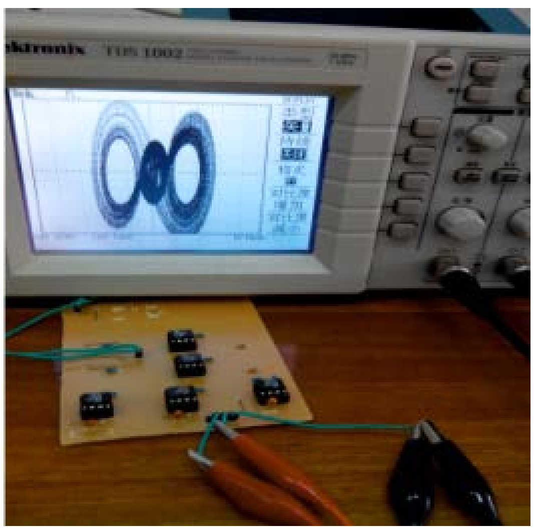

Fig. 10: Real chaotic circuit in operation

To improve the central frequency of the circuit, the value of capacitor is reduced. When $C_1 = C_2 = 100$ pF, $C_3 = 143$ pF, the frequency spectrum for the 3-scroll attractors is shown in Fig. 8.

In order to verify simulation result, a real chaotic circuit is produced, as shown in Fig. 9 and experiment is performed, as shown in Fig. 10.

From Fig. 9 and 10, the designed circuit can generate 3-scroll attractors.

DISCUSSION

In the literature (Trejo-Guerra *et al.*, 2010; Munoz-Pacheco *et al.*, 2012), a 1-D multi-scroll chaotic circuit wasdesigned only using the CFOAs, respectively and in the literature (Sanchez-Lopez *et al.*, 2010), a 1-D multi-scroll chaotic circuit was designed only using the CCII+s. But there are many active devices in these circuits. In this study, a 1-D multi-scroll chaotic circuit also is designed only using CFOAs. In order to know about the number of active devices for these circuits and a table is made. So the results are shown in Table 1.

Table 1: Number of active devices in the literature

Literature	Integrators	Basic cell
Trejo-Guerra *et al.* (2010)	8	2
Munoz-Pacheco *et al.* (2012)	4	1
Sanchez-Lopez *et al.* (2010)	4	1
The present study	3	1

From Table 1, it can be concluded that the designed chaotic circuit used fewer the active devices for good port characteristic of the CFOA.

From Fig. 8, the central frequency of the 3-scroll chaotic is 250 kHz. It can be concluded that the central frequency of the designed chaotic circuit is higher for good frequency characteristic of the CFOA.

CONCLUSION

In this study a method is proposed to realize a one-dimensional (1-D) multi-scroll chaotic system only with CFOAs and its circuit is designed which consists of three integrators and one nonlinear circuit. Compared with to Trejo-Guerra *et al.* (2010), Munoz-Pacheco *et al.* (2012) and Sanchez-Lopez *et al.* (2010), the advantages of the chaotic circuit are: (1) The central frequency of the circuit is improved for the good frequency characteristics of the CFOA; (2) CFOA has good portcharacteristics, which results in the circuit construction become simpler and active components become fewer.

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