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## OpAmp-, CFOA- and OTA-Based Configurations to Design Multi-Scroll Chaotic Oscillators

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### ABSTRACT

Continuous time chaotic oscillators have been implemented by using several commercially available electronic devices. In this study, the generic circuit topologies based on Operational Amplifier (OpAmp), Current-Feedback Operational Amplifier (CFOA) and Operational Transconductance Amplifier (OTA), are summarized. These topologies allows an electronic designer to realize chaotic oscillators modeled with piecewise-linear functions, as it is shown herein by designing saturated function series.

**Key words:** Multi-scroll, chaotic oscillator, circuit synthesis, operational amplifier, current-feedback operational amplifier, operational transconductance amplifier

### INTRODUCTION

Nowadays, a wide number of publications dealing with chaotic oscillators and their electronic realizations have been introduced by Carbajal-Gomez *et al.* (2011) Elabbasy and El-Dessoky (2008), Fatehi Marj *et al.* (2009), Gonzales *et al.* (2000), Munoz-Pacheco and Cuautle (2009, 2010), Sanchez-Lopez *et al.* (2008, 2010, 2011), Tlelo-Cuautle (2011a, b) and Trejo-Guerra *et al.* (2009, 2010a-c, 2011). Among the active devices used in their implementation one can found operational amplifiers (OpAmps) (Munoz-Pacheco and Tlelo-Cuautle, 2009, 2010), unity-gain cells (Duarte-Villasenor *et al.*, 2011; Sanchez-Lopez *et al.*, 2008), current conveyors (Sanchez-Lopez *et al.*, 2010; Ahmed and Soliman, 2011; Tlelo-Cuautle *et al.*, 2010b; Trejo-Guerra *et al.*, 2009), Current-Feedback Operational Amplifiers (CFOAs) (Carbajal-Gomez *et al.*, 2011; Trejo-Guerra *et al.*, 2010c) and Operational Transconductance Amplifiers (OTAs) (Garcia-Ortega *et al.*, 2007; Gonzales *et al.*, 2000). All these active devices can enhance the performances of the chaotic oscillators, when they are designed at the transistor level of abstraction, e.g., using metal-oxide-semiconductor field-effect-transistors (MOSFETs) (Duarte-Villasenor *et al.*, 2011; Ibrahim *et al.*, 2011; Rashtian *et al.*, 2008; Riyadi *et al.*, 2010; Tlelo-Cuautle *et al.*, 2010a; Trejo-Guerra *et al.*, 2011, 2010a). Unfortunately, very few information on the generic topologies being used in the realization of chaotic oscillators can be found in the literature. That way, this article summarizes the OpAmp-, CFOA- and OTA-based generic topologies used in the implementation of chaotic oscillators modeled by Piecewise-linear (PWL) functions. Some related works based on saturated function series can be found by Carbajal-Gomez *et al.* (2011), Munoz-Pacheco and Tlelo-Cuautle (2009, 2010); Sanchez-Lopez *et al.* (2010, 2011), Tlelo-Cuautle (2011a, b) and Trejo-Guerra *et al.* (2010b, c).

**OPAMP-, CFOA- AND OTA-BASED GENERIC TOPOLOGIES**

The OpAmp is a two-port device whose ideal behavior is described by:

$$v_{out} = A_v(v_{in+} - v_{in-}) \tag{1}$$

where,  $A_v$  is the voltage-gain and  $v_{in+}$  and  $v_{in-}$  are the noninverting and inverting inputs. The CFOA has four terminals X, Y, Z and W (Duarte-Villasenor *et al.*, 2011; Tlelo-Cuautle *et al.*, 2010b). Y is an input port driving voltage, X is a bidirectional port sensing voltage from Y to X ( $v_x = v_y$ ) and injecting current from X to Z ( $i_z = i_x$ ). Z is a bidirectional port as X but sensing current from X to Z and injecting voltage from Z to W ( $v_w = v_z$ ). W is an output port measuring voltage from Z. The OTA processes voltage to current. The transfer characteristic is denoted by the transconductance  $g_m$  (Garcia-Ortega *et al.*, 2007).

In Table 1-4, we summarize the generic topologies for realizing linear operations.

The saturated function series can be modeled by PWL functions (Munoz-Pacheco and Tlelo-Cuautle, 2009, 2010). For instance, Eq. 1 is a PWL approximation of a saturated function serie, as already shown by Carbajal-Gomez *et al.* (2011), Munoz-Pacheco and Tlelo-Cuautle (2009, 2010) and Trejo-Guerra *et al.* (2010b, c):

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

Using the finite gain model of the OpAmp, as shown in Fig. 1 (Munoz-Pacheco and Tlelo-Cuautle, 2010), Eq. 2 can be implemented using electronic devices. The description of Fig. 1 is given by Eq. 3. Equation 4 describes a negative shift operation, required to generate the saturated functions. Some circuit realizations of PWL functions are already given by

Table 1: OPAMP-, CFOA- and OTA-based inverter

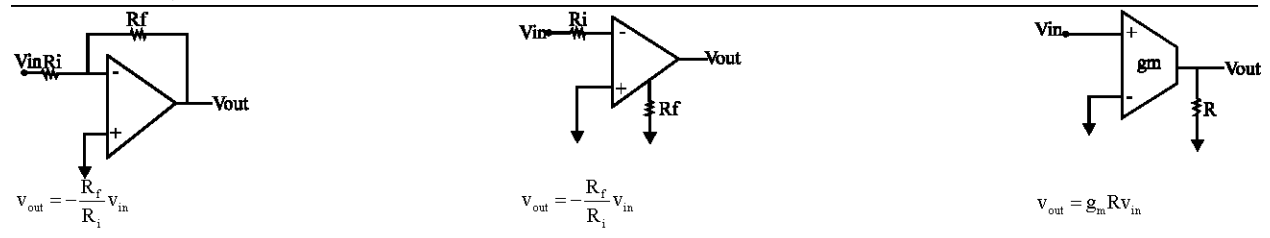


Table 2: OPAMP-, CFOA- and OTA-based integrator

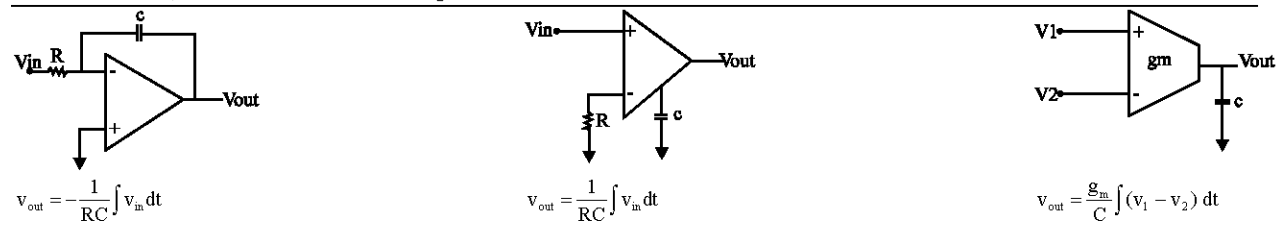


Table 3: OPAMP-, CFOA- and OTA-based adder

$V_{out} = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$	$V_{out} = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right)$	$V_{out} = \frac{1}{g_4} (g_1 V_1 + g_2 V_2 + g_3 V_3)$

Table 4: OPAMP-, CFOA- and OTA-based subtractor

<p>If <math>R_A = R_B = R_C = R_D</math>, then</p> $V_{out} = V_2 - V_1$	<p>If <math>R_A = R_B = R_C = R_D</math> then</p> $V_{out} = V_2 - V_1$	$V_{out} = \frac{g_{m1}}{g_{m2}} (V_1 - V_2)$

Basic topologies to implement saturated function series

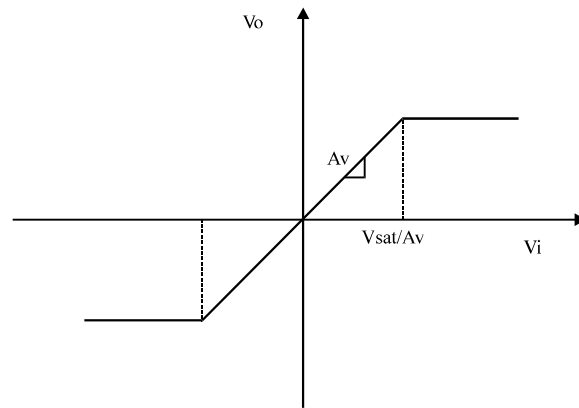


Fig. 1: Finite gain behavior of the OpAmp

Carbajal-Gomez *et al.* (2011), Munoz-Pacheco and Tlelo-Cuautle (2010), Sanchez-Lopez *et al.* (2010), Tlelo-Cuautle (2011a, b) and Trejo-Guerra *et al.* (2010c):

$$v_0 = \frac{Av}{2} \left( \left| v_i + \frac{V_{sat}}{Av} \right| - \left| v_i - \frac{V_{sat}}{Av} \right| \right) \quad (3)$$

$$V_o = \frac{Av}{2} \left( \left| V_i + \frac{V_{sat}}{Av} + E \right| - \left| V_i - \frac{V_{sat}}{Av} + E \right| \right) \quad (4)$$

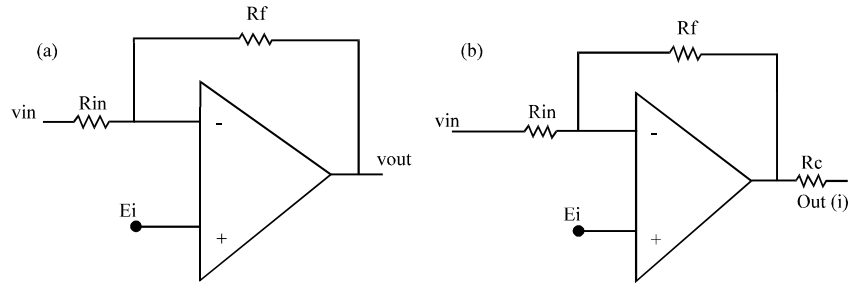


Fig. 2(a-b): (a) OpAmp basic cell and (b) Transforming voltage to current through  $R_c$ .

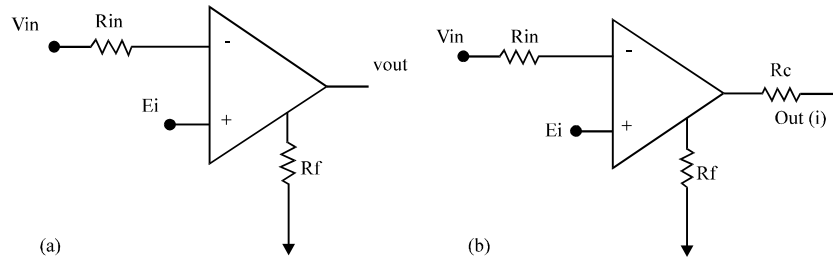


Fig. 3(a-b): (a) CFOA basic cell and (b) Transforming voltage to current through  $R_c$ .

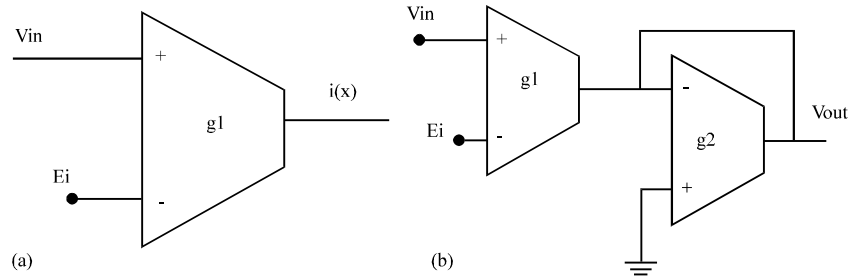


Fig. 4(a-b): (a) OTA basic cell and (b) Transforming voltage to voltage through  $g_2$ .

The basic cell to implement the saturated function series using OpAmps is shown in Fig. 2, where,  $E_i$  indicates positive or negative shift described by  $E$  in Eq. 3 (Munoz-Pacheco and Tlelo-Cuautle, 2010). The basic cell to implement the saturated function series using CFOA and OTA are shown in Fig. 3 and 4, respectively. For the last case, the basic cell in Fig. 4(a),  $i(x)$  denotes the output current  $I_o$  which is described by:

$$I_o = \frac{g_m}{2} \left( \left| V_i + \frac{I_{sat}}{g_m} + E \right| - \left| V_i - \frac{I_{sat}}{g_m} + E \right| \right) \quad (5)$$

### SCROLLS CHAOTIC OSCILLATOR

Here, we just review the realization of multi-scroll chaotic oscillators from (Tlelo-Cuautle, 2011a, b). Lets us consider the dynamical system described by the state equations (Chattopadhyay *et al.*, 2011; Munoz-Pacheco and Tlelo-Cuautle, 2009, 2010), given by Eq. 5, where,  $f(x; k, h, p, q)$  is defined by Eq. 1 and  $x, y$  and  $z$  are the state variables, with  $a = b = c = d =$  real positive constants.

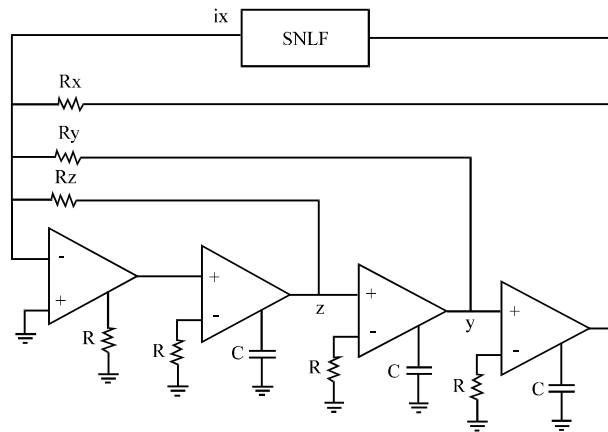


Fig. 5: Multi-scroll chaotic oscillator implemented with CFOAs

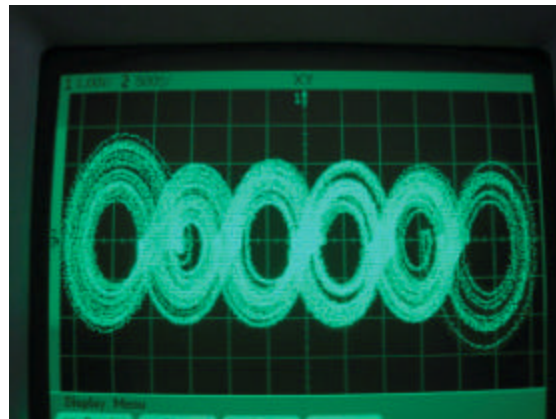


Fig. 6: 6-scrolls attractor from Fig. 5

$$\begin{aligned}
 \dot{x} &= y \\
 \dot{y} &= z \\
 \dot{z} &= -ax - by - cz + df(x; k, h, p, q)
 \end{aligned}
 \tag{6}$$

The CFOA-based realization is shown in Fig. 5, where the PWL function named SNLF is implemented using the basic cell shown in Fig. 3. The experimental result is shown in Fig. 6. This chaotic oscillator can be used to implement secure communication systems as the ones designed and shown by Carbajal-Gomez *et al.* (2011), Gonzales *et al.* (2000), Munoz-Pacheco and Tlelo-Cuautle (2010), Tlelo-Cuautle (2011a, b) and Trejo-Guerra *et al.* (2009).

## CONCLUSION

This study was devoted to show the generic circuit topologies based on OpAmps, CFOAs and OTAs and used in the design of multi-scroll chaos generators. The realization of saturated functions series was also described by using the three active devices, from a PWL function approach. As a result, an electronic designer has at his disposal three kinds of circuit topology realizations of multi-scroll chaotic oscillators.

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