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Current Feedback Operational Amplifier Based Oscillators

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Abstract. This paper demonstrates the practicality of the current feedback operational amplifier (CFOA) in realizing grounded capacitor (or grounded resistor) oscillator circuits. The paper begins with a description of the minimum passive component oscillators, using one or two CFOAs. Next, two new single CFOA oscillators with independent control on the condition of oscillation are generated from the single CFOA minimum component oscillator. Three new oscillator circuits using two CFOAs are introduced. Grounded capacitor and grounded resistor oscillators using three CFOAs with independent control on the condition of oscillation and on the frequency of oscillation are also included. The proposed grounded component oscillators are suitable for VLSI implementation. PSpice simulations and experimental results demonstrating the performance of some of the proposed oscillators are given.

Key Words: Oscillators, current feedback, op amps

1. Introduction

Many oscillators are available in the literature using the conventional op amp [1], whose finite gain bandwidth product affects both the condition of oscillation and the frequency of oscillation [2]. The current feedback operational amplifier (CFOA) has proved to be a very versatile building block in analog signal processing [3]. Recently there has been a great interest in realizing sinusoidal oscillators using the CFOA [4–8]. The oscillators reported in [4] employ a single CFOA, among which there is only one grounded C oscillator, it employs however three capacitors. A systematic generation of canonic single resistance controlled oscillators using a single CFOA has been presented in [5]. Each of the five oscillators given in [5] however employs one floating capacitor. The Wien bridge oscillator given in [6] is based on a direct replacement of the voltage op amp by a CFOA and it has also one floating capacitor. The oscillators given in [7,8] employ two CFOA and they have the advantage of using grounded capacitors, which is highly desirable in integrated circuits [9]. The oscillator reported in [7] employs however three floating resistors, and the one given in [8] has two floating resistors.

This paper concentrates on the application of the CFOA in realizing grounded C oscillators. Two minimum passive component oscillators are first considered. New grounded C single CFOA oscillators with independent control on the condition of oscillation are generated from the minimum component single CFOA oscillator. Four new grounded C oscillators using two CFOAs are given. Two novel grounded C, grounded R oscillators using three CFOAs with independent control on the condition of oscillation and on the frequency of oscillation are also given.

2. The Minimum R, C Oscillators

In this section two grounded C, minimal passive component oscillators are considered. The first circuit employs a single CFOA and the second circuit uses two CFOAs.

Fig. 1 represents the 2R, 2C single CFOA oscillator which is based on the current conveyor version of the Wien bridge oscillator [10]. The state equation in matrix form is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{1}$$

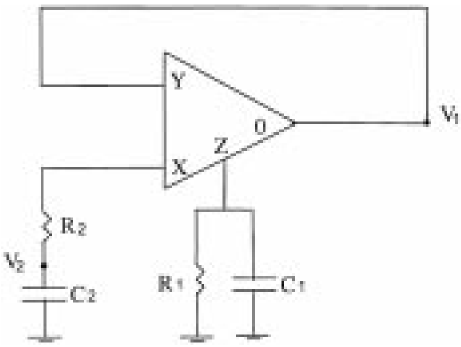


Fig. 1. The minimum passive component grounded C (or grounded R) oscillator using a single CFOA.

where

$$a_{11} = \frac{1}{C_1 R_2}\left(1 - \frac{R_2}{R_1}\right), a_{12} = -\frac{1}{C_1 R_2}, a_{21} = \frac{1}{C_2 R_2}, a_{22} = -\frac{1}{C_2 R_2}$$

The condition of oscillation and the radian frequency of oscillation are given by:

$$\frac{C_1}{C_2} + \frac{R_2}{R_1} = 1 \tag{2}$$

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_1 R_2}} \tag{3}$$

It is seen that the condition of oscillation and the frequency of oscillation are dependent on the four passive elements, which limits the practicality of this minimum component oscillator.

PSpice simulations have been carried out using the AD844 biased with ± 9 V and taking $R_1 = 1\,\text{k}\Omega$, $C_1 = 1\,\text{nF}, C_2 = 2\,\text{nF}$ and R_2 was decreased from the theoretical value of $0.5\,\text{k}\Omega$ to $0.46\,\text{k}\Omega$ in order to start oscillations. The simulated f_0 was obtained as 160.9 kHz which is slightly higher than its theoretical value of 159.15 kHz.

The second $2R$, $2C$ oscillator circuit is shown in Fig. 2, which is based on a loop of two opposite polarity voltage integrators [3]. The state equation in matrix form is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_1 R_1} \\ -\frac{1}{C_2 R_2} & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{4}$$

Since $a_{11} = a_{22} = 0$, there is no control on the condition of oscillation and the radian frequency of oscillation is given by equation (3).

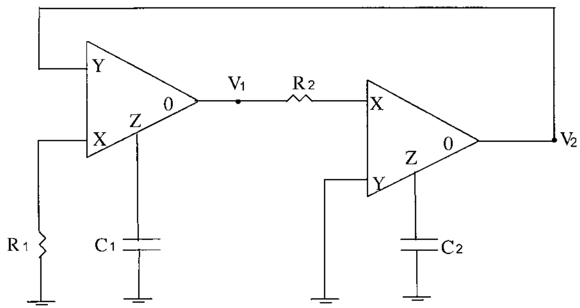


Fig. 2. The minimum passive component grounded C oscillator using two CFOAs.

PSpice simulations have been performed for this oscillator using the AD844 and taking $R_1 = R_2 = 1\,\text{k}\Omega$ and $C_1 = C_2 = 1\,\text{nF}$. The simulated f_0 was obtained as 153.43 kHz, that is the percentage error in f_0 equal to -3.6%.

The main disadvantage of this simple oscillator is that there is no control on the condition of oscillation. It is worth noting that this oscillator may be obtained as a special case from four alternative bandpass-lowpass filters given in [3], by grounding the input port and setting the resistor R_1 which controls Q as open circuit.

3. Single CFOA Grounded *C* Oscillators

In this section, two oscillators having the advantage that the condition of oscillation can be controlled without affecting the frequency of oscillation are given.

Fig. 3(a) represents the first grounded C, single CFOA oscillator which is a modified version of the oscillator of Fig. 1 by adding the resistors R_3 and R_4 in order to provide independent control on the condition of oscillation. The state equation in matrix form is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1 R_2}\left[\frac{R_3}{(R_3+R_4)} - \frac{R_2}{R_1}\right] & -\frac{1}{C_1 R_2} \\ \frac{1}{C_2 R_2}\left(\frac{R_3}{R_3+R_4}\right) & -\frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{5}$$

Therefore, the condition of oscillation is given by:

$$\frac{C_1}{C_2} + \frac{R_2}{R_1} = \frac{R_3}{R_3 + R_4} \tag{6}$$

which can be controlled by varying R_3 or R_4 without affecting ω_0 which is still given by equation (3).

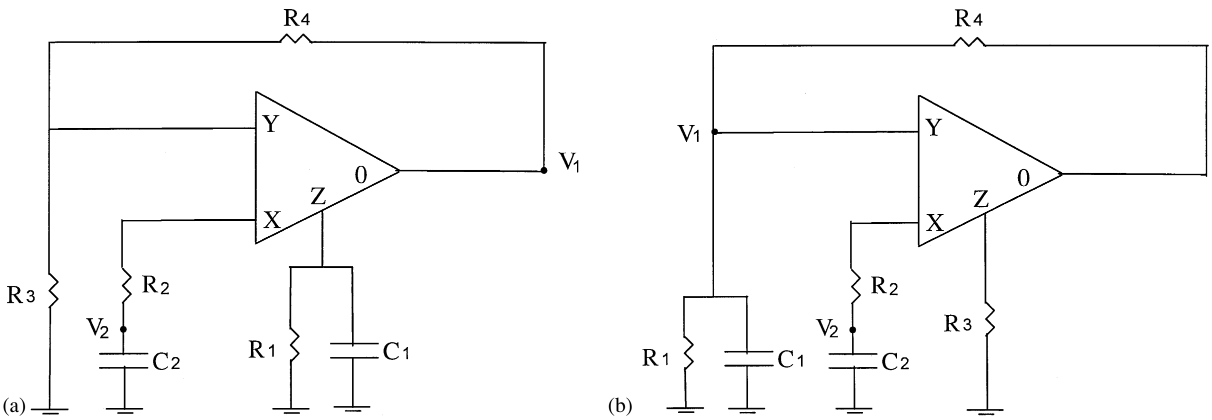


Fig. 3. Two modified grounded *C* oscillators using a single CFOA.

PSpice simulations have been performed for the oscillator of Fig. 3(a) with $R_1 = 2\,\text{k}\Omega, R_2 = 0.5\,\text{k}\Omega, C_1 = 0.5\,\text{nF}, C_2 = 2\,\text{nF}$ and $R_3 = 1\,\text{k}\Omega$. To start oscillations R_4 was decreased from its theoretical value of $1\,\text{k}\Omega$ to $0.75\,\text{k}\Omega$ and the simulated f_0 was obtained as 162.28 kHz, thus the percentage error in f_0 equal to 1.96%.

The second proposed single CFOA, grounded *C* oscillator circuit is shown in Fig. 3(b). The state equation in matrix form is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1R_2}\left[\frac{R_3-R_2}{R_4} - \frac{R_2}{R_1}\right] & -\frac{1}{C_1R_2}\frac{R_3}{R_4} \\ \frac{1}{C_2R_2} & -\frac{1}{C_2R_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{7}$$

Thus the condition of oscillation and the radian frequency of oscillation are given by:

$$\frac{C_1}{C_2} + \frac{R_2}{R_1} + \frac{R_2}{R_4} = \frac{R_3}{R_4} \tag{8}$$

$$\omega_0 = \sqrt{\frac{1 + \frac{R_1}{R_4}}{C_1C_2R_1R_2}} \tag{9}$$

It is seen that the grounded resistor R_3 controls the condition of oscillation without affecting the frequency of oscillation.

PSpice simulations have been carried using the AD844 and taking $C_1 = C_2 = 1\,\text{nF}$, $R_1 = R_2 = R_4 = 1\,\text{k}\Omega$. To start oscillations R_3 was increased from its theoretical value of $3\,\text{k}\Omega$ to $3.13\,\text{k}\Omega$. Fig. 4(a) represents the voltage waveform obtained at the output of the CFOA. Fig. 4(b) represents the frequency spectrum, from which f_0 is obtained as 213.02 kHz, thus the percentage error in f_0 equal to −5.35%.

4. Two CFOA Grounded *C* Oscillators

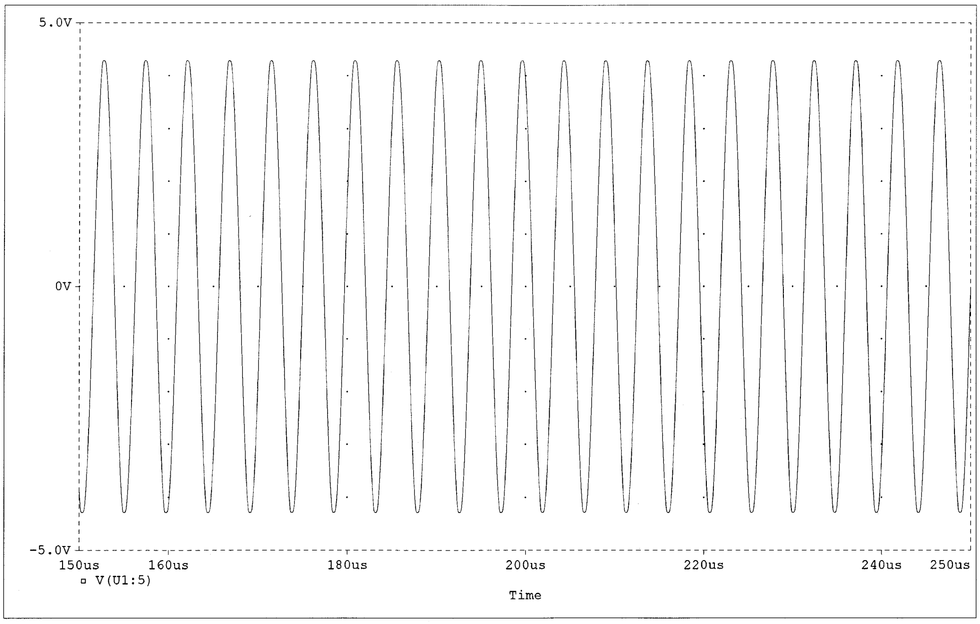
In this section three new grounded *C* oscillators using two CFOAs are given. Each of the first two circuits employs four resistors, one of them is floating, and has the advantage that a single grounded resistor controls the condition of oscillation without affecting the frequency of oscillation. The third circuit uses three resistors only, one of them is floating, and has the additional advantage that the condition of oscillation is controlled by a grounded resistor and the frequency of oscillation is adjusted by the other grounded resistor without affecting each other.

The oscillator of Fig. 5(a) is generated from the circuit of Fig. 1 by adding a noninverting voltage controlled voltage source (VCVS) [3], whose output is fedback to the noninverting input of the first CFOA, in order to control the condition of oscillation.

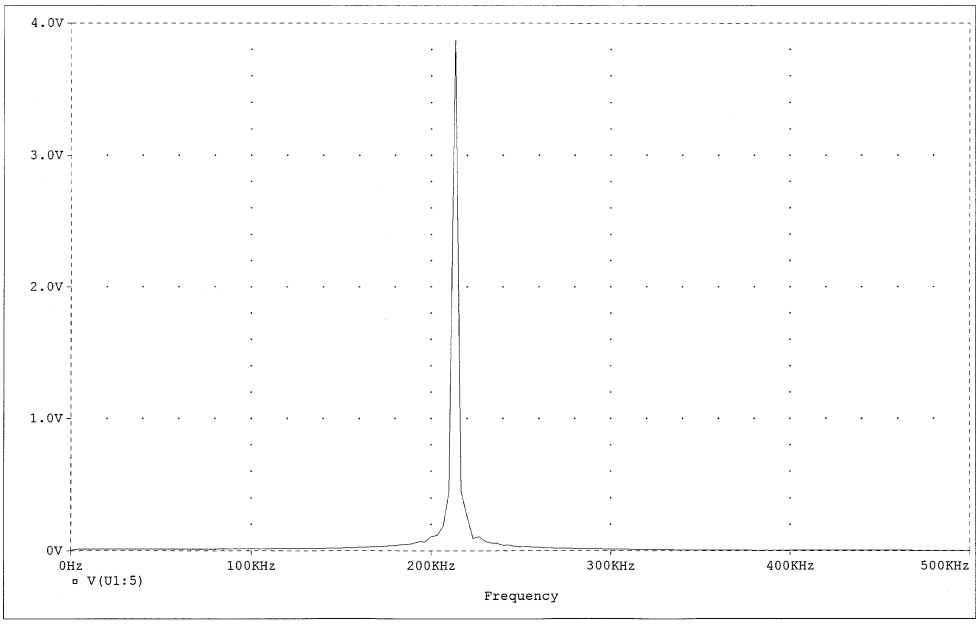
The state matrix equation is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1R_2}\left[\frac{R_3}{R_4} - \frac{R_2}{R_1}\right] & -\frac{1}{C_1R_2} \\ \frac{1}{C_2R_2}\frac{R_3}{R_4} & -\frac{1}{C_2R_2} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{10}$$

It is seen that the coefficients a_{12} and a_{22} are the same as those of the oscillator of Fig. 1, on the other hand



(a)



(b)

Fig. 4. (a) The output voltage waveform of the oscillator of Fig. 3(b). (b) The frequency spectrum of the oscillator of Fig. 3(b).

a_{11} and a_{21} differs from those of the circuit of Fig. 1. The condition of oscillation is given by:

$$\frac{C_1}{C_2}+\frac{R_2}{R_1}=\frac{R_3}{R_4} \tag{11}$$

which can be controlled by varying R_3 or R_4 without affecting the frequency, which is still given by equation (3).

Interchanging the R_2C_2 and the R_4 branches, an alternative circuit is obtained which is shown in Fig.

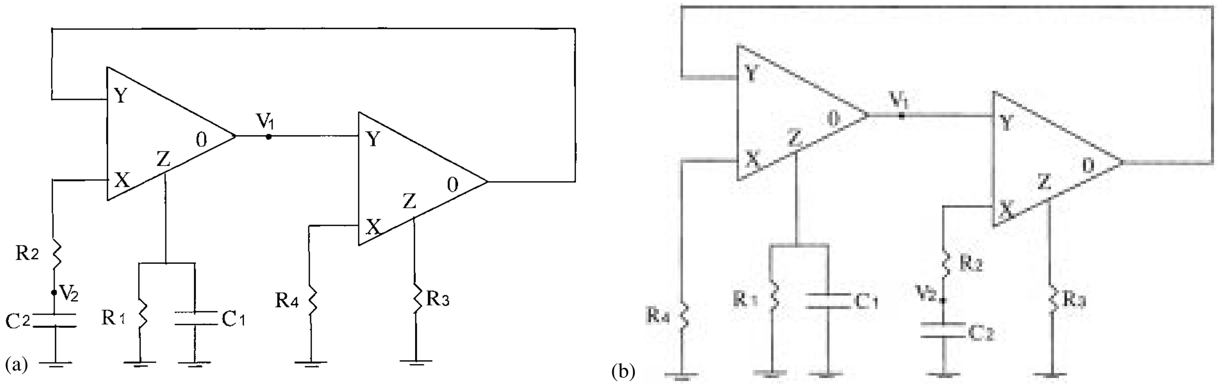


Fig. 5 Two new grounded *C* (or grounded *R*) oscillators using two CFOAs.

5(b), and has the same equations for the frequency of oscillation and the condition of oscillation as given by equations (3) and (11) respectively.

PSpice simulations for this oscillator have been carried out using the AD844, and taking $R_1 = R_2 = R_3 = 1\,\mathrm{k\Omega}, C_1 = C_2 = 1\,\mathrm{nF}$. To start oscillations R_4 was decreased from its nominal value of $500\,\Omega$ to $450\,\Omega$. The simulated f_0 was found to be 153.43 kHz which corresponds to an error of -3.6% from its theoretical value.

The most attractive oscillator circuit using two CFOAs is shown in Fig. 6(a). This circuit employs one resistor less than the oscillators of Fig. 5(a) and 5(b). The state matrix equation is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1}\left[\frac{1}{R_3} - \frac{1}{R_1}\right] & -\frac{1}{C_1 R_3} \\ \frac{1}{C_2 R_2} & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{12}$$

The condition of oscillation and the radian frequency of oscillation are given by:

$$R_1 = R_3 \tag{13}$$

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_2 R_3}} \tag{14}$$

The resistor R_1 controls the condition of oscillation without affecting ω_0, which is controlled by R_2 without affecting the condition of oscillation. The voltage V_1 waveform is shown in Fig. 6(b) which is obtained with $R_2 = R_3 = 1\,\mathrm{k\Omega}, C_1 = C_2 = 1\,\mathrm{n}F$. To start oscillations R_1 was increased from its theoretical value of $1\,\mathrm{k\Omega}$ to $1.1\,\mathrm{k\Omega}$. The frequency obtained is 149 kHz, which is slightly lower than the ideal theoretical value. This error is mainly due to *Rx* and *Cz* of the CFOA, which can be minimized by subtracting the value of *Rx* from the design values of R_2, R_3 and subtracting the value of *Cz* from the design values of C_1 and C_2. For the AD844, $Rx = 65\,\Omega$ and $Cz = 5.5\,\mathrm{PF}$.

Comparing this oscillator with that given in [8], it is seen that although both oscillators employ the same number of circuit components, the oscillator given in [8] has one grounded resistor only and two floating resistors. That is the frequency of oscillation in [8] is controlled independently by a floating resistor, rather than by a grounded resistor as in the proposed oscillator.

4.1. *Two CFOA Grounded C, Grounded R Oscillator*

It has been demonstrated that the oscillator circuit of Fig. 6(a) has several advantages, that are desirable from any oscillator, it has however one floating resistor. In this section the realization of a grounded *C*, grounded *R* oscillator using two CFOA is considered. It is shown that a third capacitor must be used in order to achieve this objective.

Fig. 7 represents the proposed oscillator circuit, whose state matrix equation is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_1 R_4}\left[\frac{C_2}{C_3} - \frac{R_4}{R_1}\right] & -\frac{1}{C_1 R_3}\left[\frac{C_2}{C_3} - \frac{R_3}{R_2}\right] \\ \frac{1}{C_3 R_4} & -\frac{1}{C_3 R_3} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{15}$$

The condition of oscillation is given by:

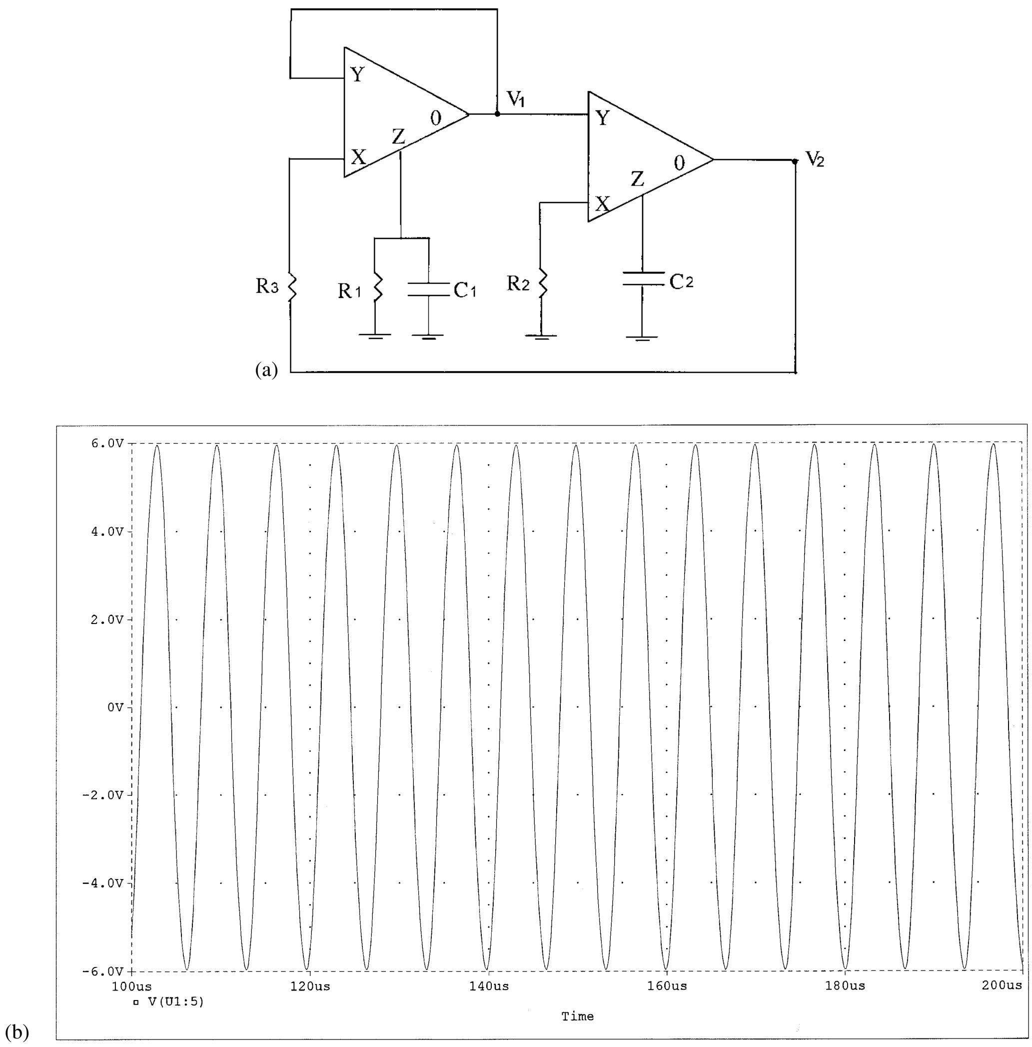


Fig. 6. (a) A new grounded *C* oscillator using two CFOAs. (b) The voltage V_1 waveform of the oscillator of Fig. 6(a).

$$\frac{C_1}{R_3}+\frac{C_3}{R_1}=\frac{C_2}{R_4} \tag{16}$$

The radian frequency of oscillation is given by:

$$\omega_0=\sqrt{\frac{1}{C_1C_3}\left[\frac{1}{R_1R_3}-\frac{1}{R_2R_4}\right]} \tag{17}$$

It is seen that the grounded capacitor C_2 controls the condition of oscillation without affecting ω_0, which is adjusted by the grounded resistor R_2 without disturbing the condition of oscillation. From equations (16) and (17) it is seen that none of the three capacitors can be removed if the circuit is to oscillate. It can be concluded that, it is not possible to realize a minimum-capacitor two-CFOA oscillator with grounded *C* and grounded *R*. It is worth noting that, the voltage V_1 waveform observed at the output of the first CFOA was slightly distorted, thus this circuit is only suitable for use as a single output oscillator.

5. Three CFOA Grounded *C*, Grounded *R* Oscillators

In this section, grounded *C*, grounded *R* oscillator circuits using three CFOAs are introduced. Fig. 8(a)

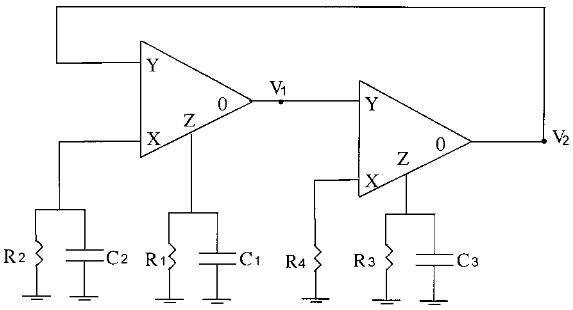


Fig. 7. A new grounded C, grounded R oscillator using two CFOA.

represents the first proposed oscillator circuit, whose state matrix equation is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_1R_1} \\ -\frac{1}{C_2R_2} & \frac{1}{C_2}\left[\frac{1}{R_3} - \frac{1}{R_4}\right] \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \quad (18)$$

Thus the condition of oscillation and the radian frequency of oscillation are given by:

$$R_3 = R_4 \quad (19)$$

$$\omega_0 = \frac{1}{\sqrt{C_1C_2R_1R_2}} \quad (20)$$

It is seen that the condition of oscillation can be controlled either by R_3 or R_4 without affecting ω_0, which can be independently controlled either by R_1 or R_2. PSpice simulations have been carried out using

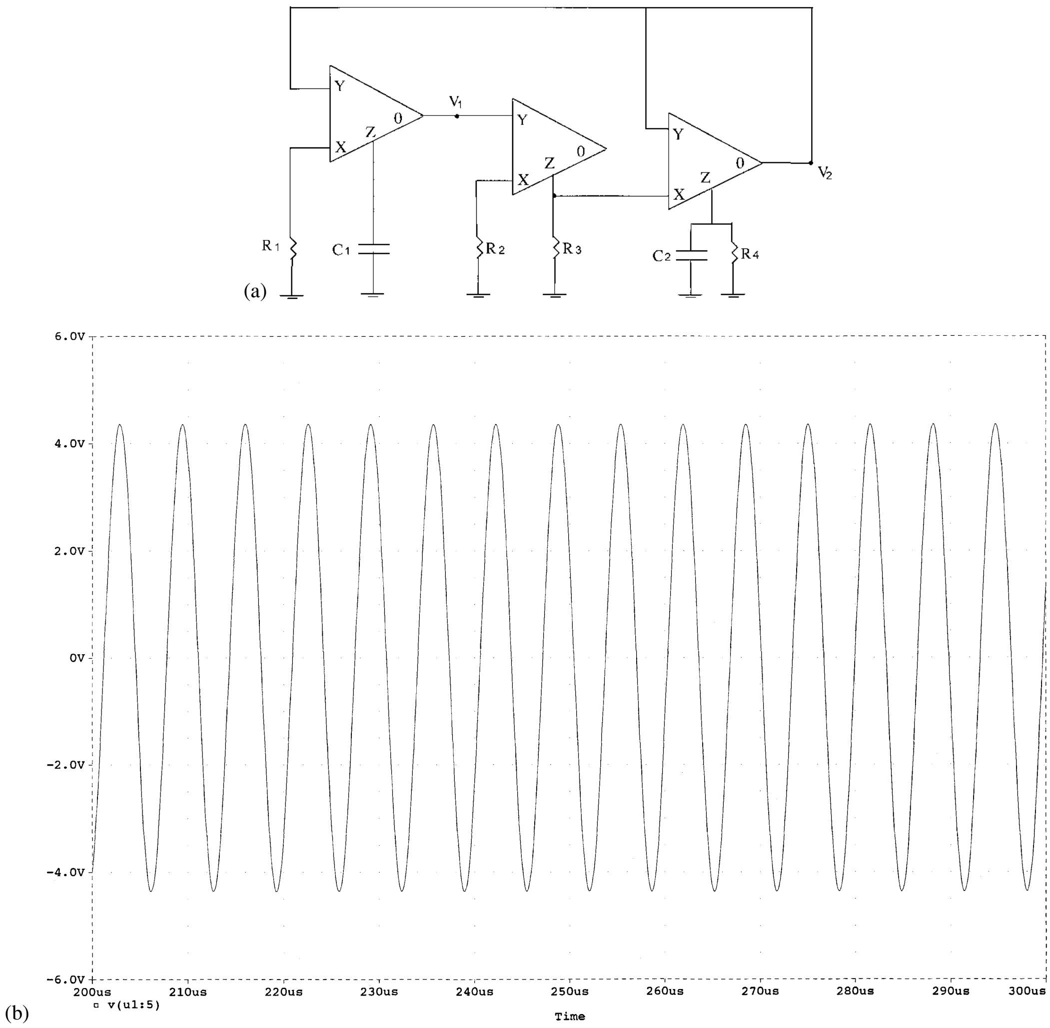


Fig. 8. (a) A new grounded C, grounded R oscillator using three CFOAs. (b) The voltage V_1 waveform of the oscillator of Fig. 8(a).

three AD844 CFOAs, and taking $C_1 = C_2 = 1\,\text{nF}$, $R_1 = R_2 = R_4 = 1\,\text{k}\Omega$. To start oscillations R_3 was decreased from its nominal value of $1\,\text{k}\Omega$ to $0.95\,\text{k}\Omega$. Fig. 8(b) represents the voltage V_1 waveform. From the simulations f_0 was obtained as 152 kHz, thus the percentage error in f_0 equal to -4.5%.

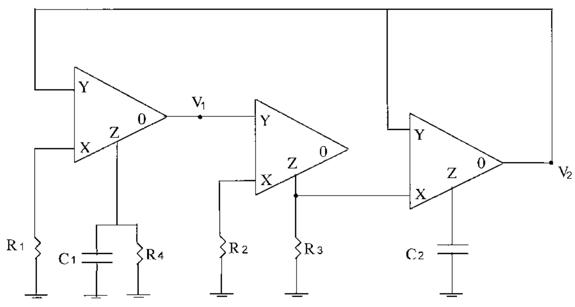
The second proposed circuit is shown in Fig. 9(a) which differs from that of Fig. 8(a) in the position of the resistor R_4. The state matrix equation in this case is given by:

$$\begin{bmatrix} \frac{dv_1}{dt} \\ \frac{dv_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_1R_4} & \frac{1}{C_1R_1} \\ -\frac{1}{C_2R_2} & \frac{1}{C_2R_3} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{21}$$

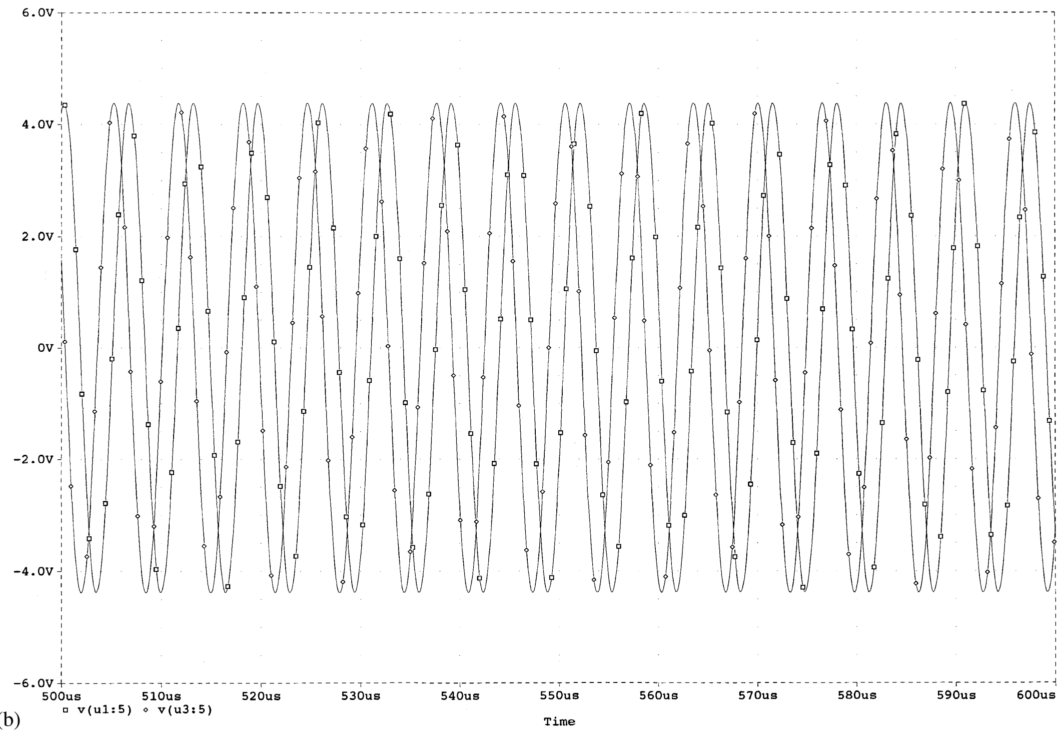
Thus the condition of oscillation and the radian frequency of oscillation are given by:

$$C_1R_4 = C_2R_3 \tag{22}$$

$$\omega_0 = \sqrt{\frac{1}{C_1C_2}\left[\frac{1}{R_1R_2} - \frac{1}{R_3R_4}\right]} \tag{23}$$



(a)



(b)

Fig. 9. (a) An alternative grounded C, grounded R oscillator using three CFOAs. (b) The V_1 and V_2 waveforms of the oscillator of Fig. 9(a).

The frequency of oscillation can be controlled by R_1 or R_2 without affecting the condition of oscillation. A practical design is to take $C_1 = C_2, R_3 = R_4$ and with magnitudes much larger than R_1 and R_2. In this case R_3 or R_4 controls the condition of oscillation without affecting ω_0, whose expression will be given approximately by that of equation (20). This oscillator may serve as a two phase oscillator.

Fig. 9(b) represents the V_1 and V_2 waveforms obtained using three AD844 CFOAs and with $C_1 = C_2 = 1\,\text{nF}$, $R_1 = R_2 = 1\,\text{k}\Omega$ and $R_3 = R_4 = 10\,\text{k}\Omega$. The simulated $f_0 = 153.6\,\text{kHz}$, again the small error in f_0 can be compensated by subtracting the value of R_x from both R_1, R_2 and the value of C_z from both C_1 and C_2.

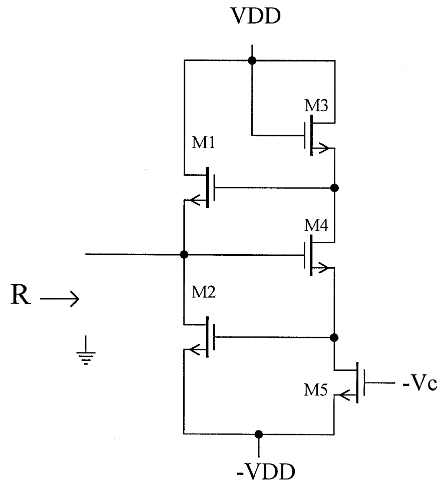


Fig. 10. The MOS grounded resistor [12].

6. The CFOA—MOS-C Oscillators

The oscillators reported in the previous section are well suited for VLSI implementation. It is well known that grounded resistors can be realized in VLSI, using the differential difference amplifier (DDA) [11] or the transconductance amplifier (TA). In this section, the MOS grounded resistor shown in Fig. 10 [12] is used to implement the resistors in the oscillator circuit of Fig. 8(a), thus a CFOA-MOS-C oscillator is obtained. The magnitude of the MOS resistor is given by [12]:

$$R = \frac{1}{2K(2V_C - V_{DD})} \tag{24}$$

where $K = \mu_n$ Cox (W/L), μ_n is the electron mobility, Cox is the gate oxide capacitance per unit area, W/L is the transistor aspect ratio.

PSpice simulations have been performed for the oscillator of Fig. 8(a) using four MOS grounded resistors with the transistors aspect ratios as given in Table 1. The voltage $V_{DD} = 5\,\text{V}$, and the voltage V_C was taken equal to 3.9 V for the MOS resistors R_1, R_2 and R_4. On the other hand, to start oscillations the control voltage V_C of the resistor R_3 was adjusted to 4.05 V. Fig. 11 represents the output voltage waveform obtained from the simulations. The simulations were based on using the $2\,\mu$m SCNA SPICE parameters (obtained through MOSIS). From the simulations, f_0 was obtained as 158.9 kHz which is very close to its theoretical value of 159.15 kHz.

Table 1. The transistor aspect ratio.

Transistor	Aspect Ratio W μm/L μm
M1, M2	26/6
M3, M4	4/4
M5	16/4

Table 2. The experimental results of the oscillator of Fig. 6(a).

Oscillator Circuit Parameters			Oscillation Frequency	
$C_1 = C_2$ nF	$R_2 = R_3$ kΩ	R_1 (to start) kΩ	Measured	Theoretical
100	13	13.5	113 Hz	122.4 Hz
10	13	13.45	1.26 kHz	1.224 kHz
100	1	1.181	1.43 kHz	1.59 kHz
1	13	13.75	13.6 kHz	12.24 kHz
10	1	1.206	16 kHz	15.9 kHz
0.12	13	13.1	90 kHz	102 kHz
1	1	1.206	173.5 kHz	159 kHz

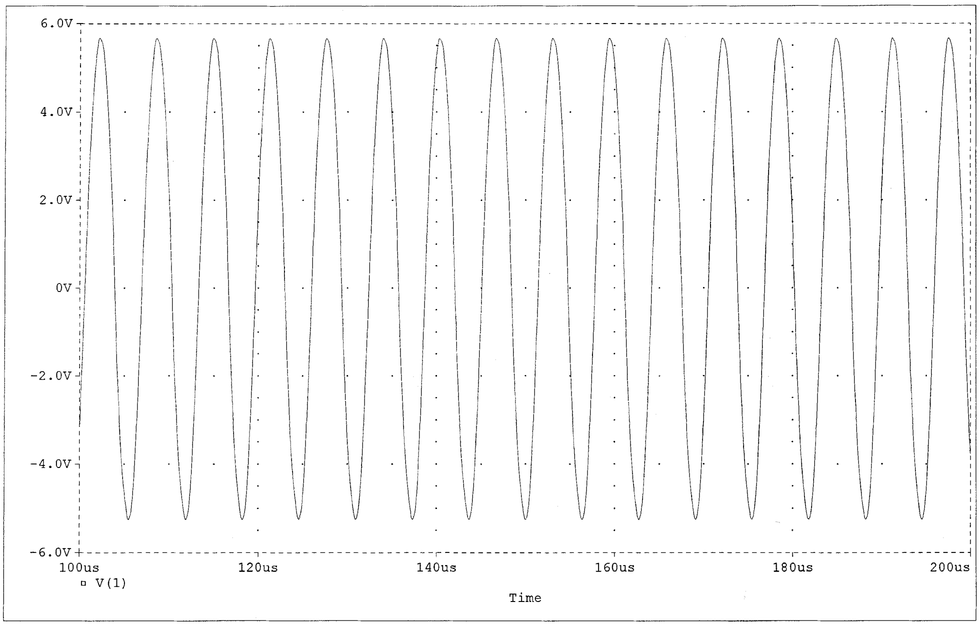


Fig. 11. The voltage waveform of the oscillator of Fig. 8(a) using MOS grounded resistors.

7. Experimental Results

To verify the theoretical analysis, the oscillator circuit of Fig. 6(a) was realized using the analog device AD844 biased with $\pm 9\,\mathrm{V}$. Table 2, includes the experimental results obtained.

Fig. 12 represents the oscilloscope output waveforms V_1 and V_2 of the oscillator of Fig. 6(a) with, $C_1 = C_2 = 1\,\mathrm{nF}$, $R_2 = R_3 = 13\,\mathrm{k\Omega}$, and R_1 was adjusted to $13.75\,\mathrm{k\Omega}$ to start oscillations.

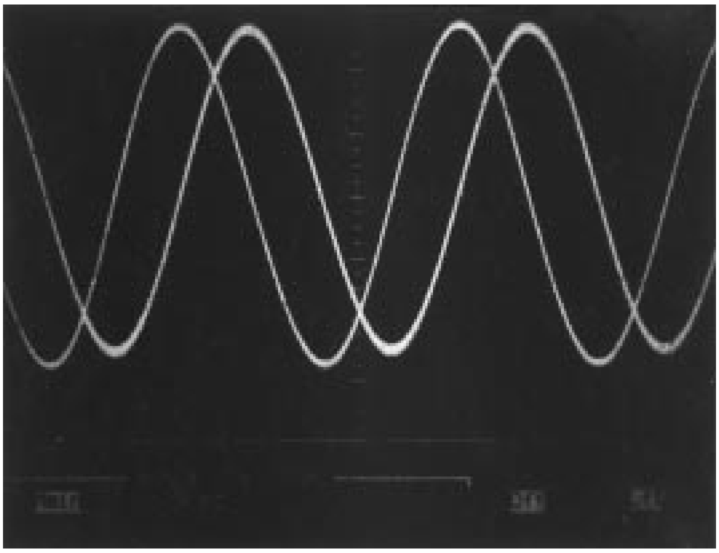


Fig. 12. Oscilloscope photograph of the V_1 and V_2 of the oscillator of Fig. 6(a). Vertical 1 V/div; horizontal 20 μs/div.

8. Conclusions

The practicality of the CFOA in realizing grounded *C* (or grounded *R*) oscillators has been demonstrated by several new circuits. The oscillators of Figs 1, 5(a) and 5(b) can be classified either as grounded *C* or grounded *R* oscillators. An attractive oscillator circuit which employs two CFOAs, two grounded capacitors and three resistors, with independent control on the condition of oscillation and on the frequency of oscillation has been given in Fig. 6(a). Experimental results of this oscillator have been included. It was found that it is not possible to realize a grounded *C*, grounded *R* oscillator using two CFOAs with the minimum number of capacitors namely two. Two new grounded *C*, grounded *R* oscillators using three CFOAs and are suitable for VLSI implementation, have been described. PSpice simulations have been included.

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