Current-Mode Analog Circuit Design

Current-Mode Oscillators
Realization of DO-OTA-C oscillators
Realization of FTFN-Based Current-Mode Oscillators

Hakan Kuntman, 2009

Realization of DO-OTA-C oscillators

- Sinusoidal oscillators play an important role in instrumentation, communication and signal processing applications.
- Sinusoidal oscillators based on OTA-C structures have attracted considerable attention in recent years because they offer several advantages over conventional op-amp based oscillators as well as providing the evaluation of fully integrated oscillators in VLSI design with CMOS technology.
- OTAs :
- provide highly linear electronic tunability of their transconductance *(gm)*
- require just a few or even no resistors for their internal circuitry
- have more reliable high frequency performance
- OTAs are increasingly replacing operational amplifiers

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Realization of DO-OTA-C oscillators

- A general sinusoidal oscillator circuit can be described by a second order characteristic equation as follows:

$$(s^2 + bs + \Omega_o^2)I_{out} = 0$$

- b = 0 is oscillation condition and Ω_o is oscillation frequency.

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- The general biquadratic transfer function is

$$H(s) = \frac{I_o(s)}{I_i(s)} = \frac{a_2 s^2 + a_1 s + a_0}{s_2 + b_1 s + b_0}$$

- There are two possible methods of obtaining sinusoidal oscillator from this transfer function.
- In the first method the characteristic equation of the oscillator is obtained by

$$(s_2 + bs + \Omega_o^2) I_{out} = 0$$

- Equating input current of filter, in(s) to zero.
- In this case the following oscillator characteristic equation is obtained:

Realization of DO-OTA-C oscillators

- The second way is connecting the output terminal of filter to the input terminal.
- The resulting oscillator characteristic equation is expressed as:

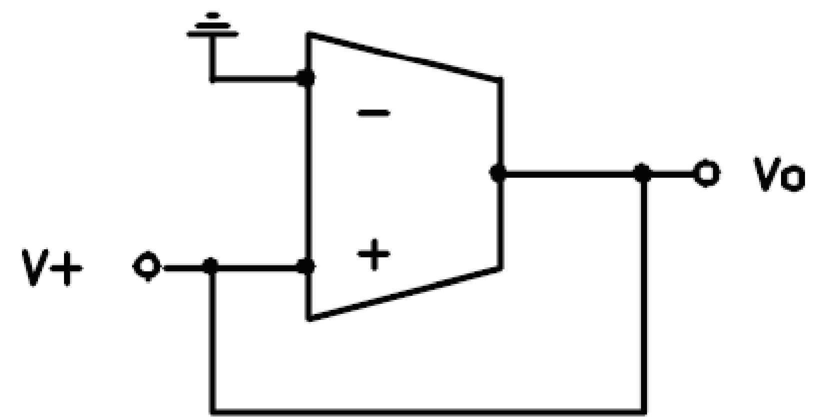
$$\left[s_2 + \left(\frac{b_1 - a_1}{1 - a_2}\right)s + \left(\frac{b_0 - a_0}{1 - a_2}\right)\right] \cdot I_o(s) = 0$$

- If the oscillation condition is satisfied by equating the coefficient of s to zero, this two equation yields undamped oscillators.

Realization of DO-OTA-C oscillators

- In this study nine DO-OTA-C sinusoidal oscillator structures
- are obtained by converting filters [10-13] into oscillators.
- The equation giving the oscillation condition of an oscillator must include both positive and negative terms to obtain stable oscillation which can be achieved by equating the oscillation condition term to zero.
- Negative and positive resistors implemented with CMOS DO-OTAs are added to oscillator networks.
- These configurations have oscillation frequencies controlled by transconductance gain without affecting oscillation condition and capability of operation at high frequencies.
- All of the proposed topologies are very atractive in both monolotic integrated technology

Realization of DO-OTA-C oscillators



Negative resistor implemented with OTA

$$R_n = -\frac{1}{g_m}$$

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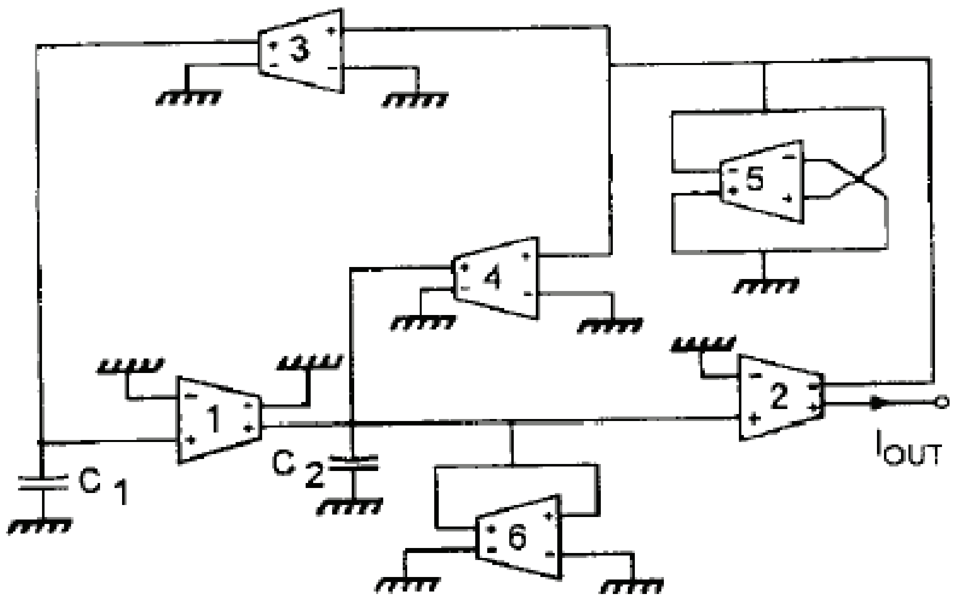
Realization of DO-OTA-C oscillators



(a)

b	Ω_o^2
$\dfrac{\dfrac{g_{m2} \cdot g_{m4}}{g_{m5}} - g_{m6}}{C_2}$	$\dfrac{g_{m1} \cdot g_{m2} \cdot g_{m3}}{C_1 C_2 g_{m5}}$

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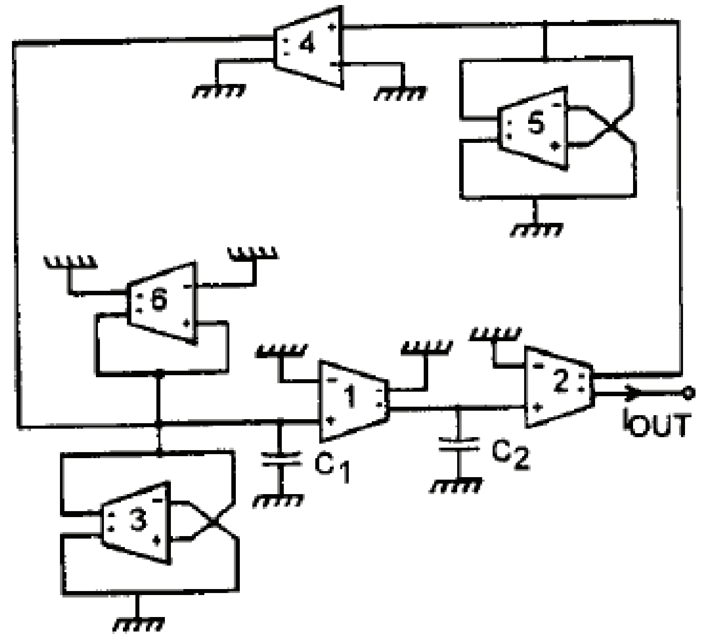
Realization of DO-OTA-C oscillators



(b)

b	Ω_o^2
$\dfrac{g_{m3} - g_{m6}}{C_1}$	$\dfrac{g_{m1} \cdot g_{m2} \cdot g_{m4}}{C_1 C_2 g_{m5}}$

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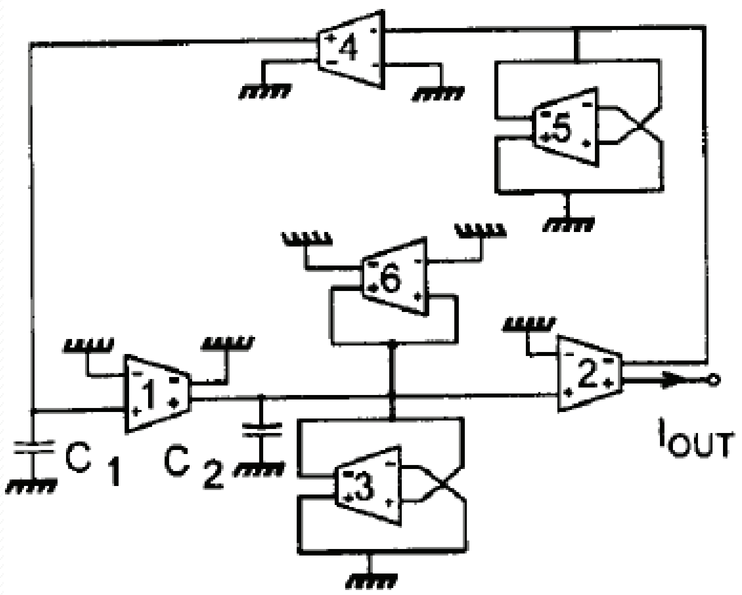
Realization of DO-OTA-C oscillators



(c)

b	Ω_o^2
$\dfrac{g_{m3} - g_{m6}}{C_2}$	$\dfrac{g_{m1} \cdot g_{m2} \cdot g_{m4}}{C_1 C_2 g_{m5}}$

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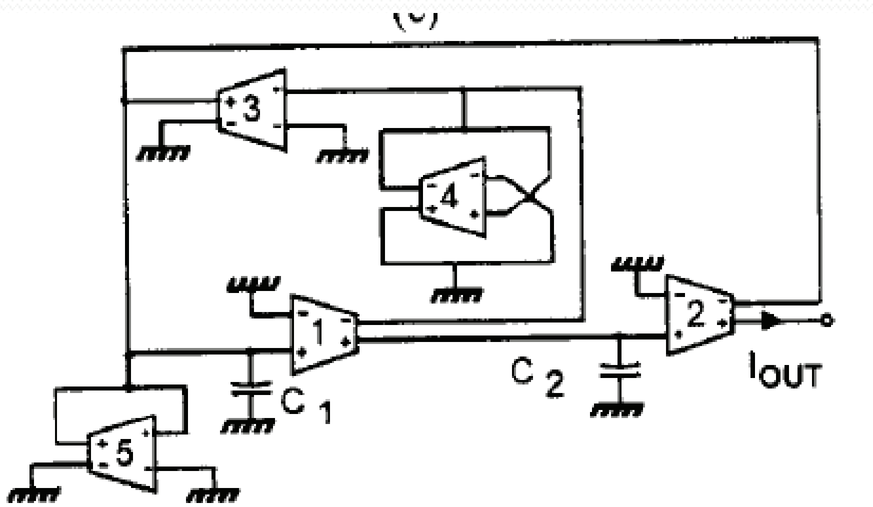
Realization of DO-OTA-C oscillators



(d)

b	Ω_o^2
$\dfrac{\dfrac{g_{m1}g_{m3}}{g_{m4}} - g_{m5}}{C_1}$	$\dfrac{g_{m1} \cdot g_{m2}}{C_1 C_2}$

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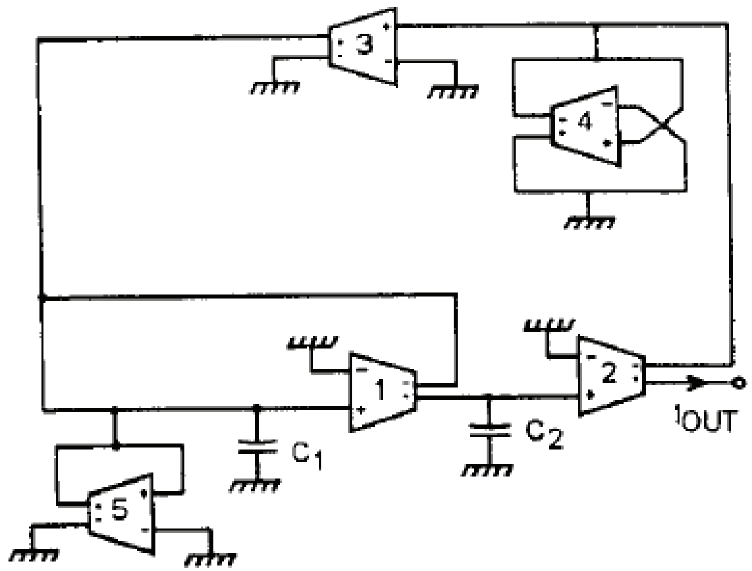
Realization of DO-OTA-C oscillators



(e)

b	Ω_o^2
$\frac{g_{m1} - g_{m5}}{C_1}$	$\frac{g_{m1} \cdot g_{m2} \cdot g_{m3}}{C_1 C_2 g_{m4}}$

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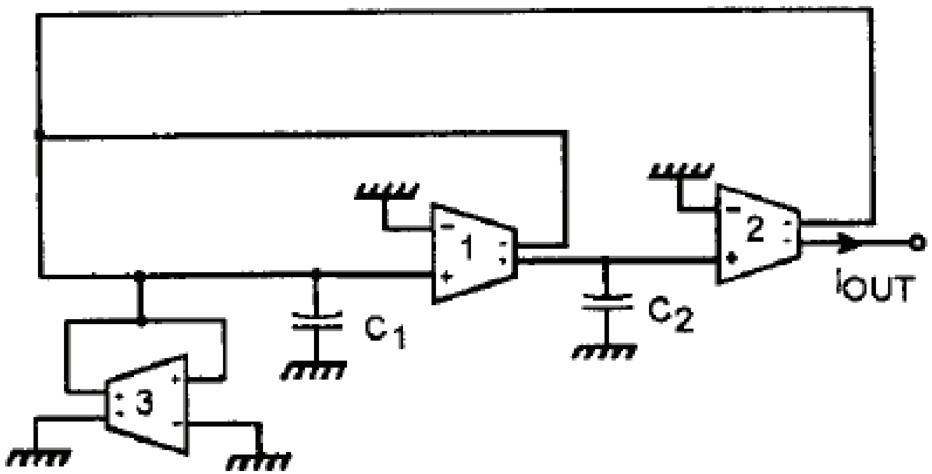
Realization of DO-OTA-C oscillators



(f)

b	Ω_o^2
$\frac{g_{m1} - g_{m3}}{C_1}$	$\frac{g_{m1} \cdot g_{m2}}{C_1 C_2}$

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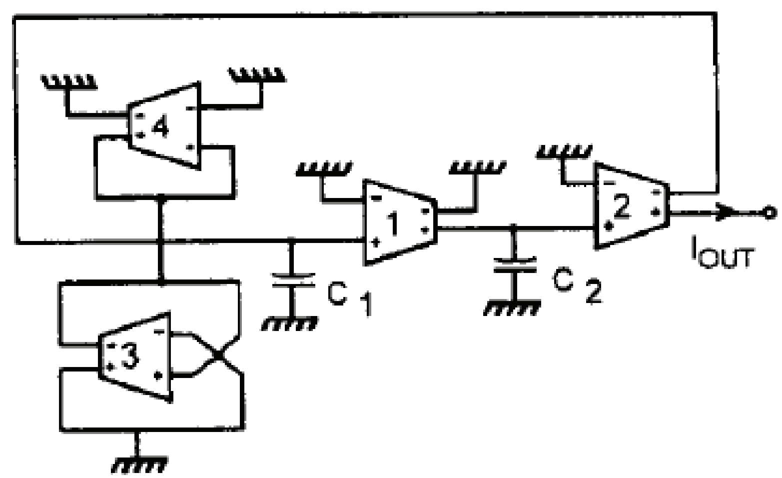
Realization of DO-OTA-C oscillators



(g)

b	Ω_o^2
$\frac{g_{m3} - g_{m4}}{C_1}$	$\frac{g_{m1} \cdot g_{m2}}{C_1 C_2}$

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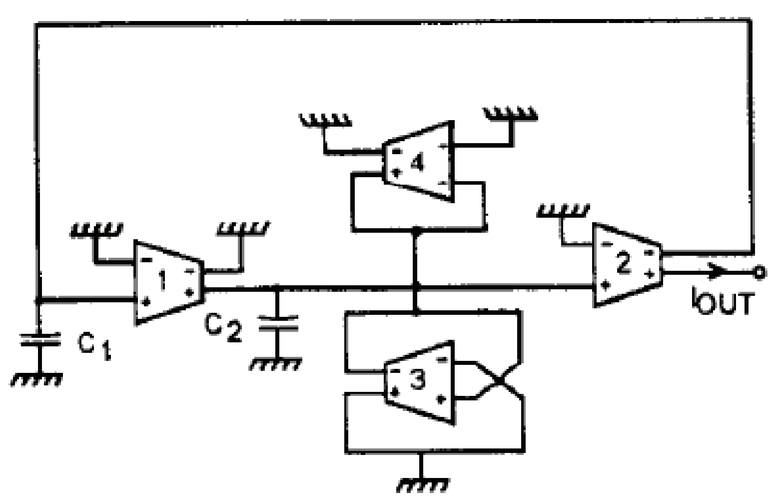
Realization of DO-OTA-C oscillators



(h)

b	Ω_o^2
$\frac{g_{m3} - g_{m4}}{C_2}$	$\frac{g_{m1} \cdot g_{m2}}{C_1 C_2}$

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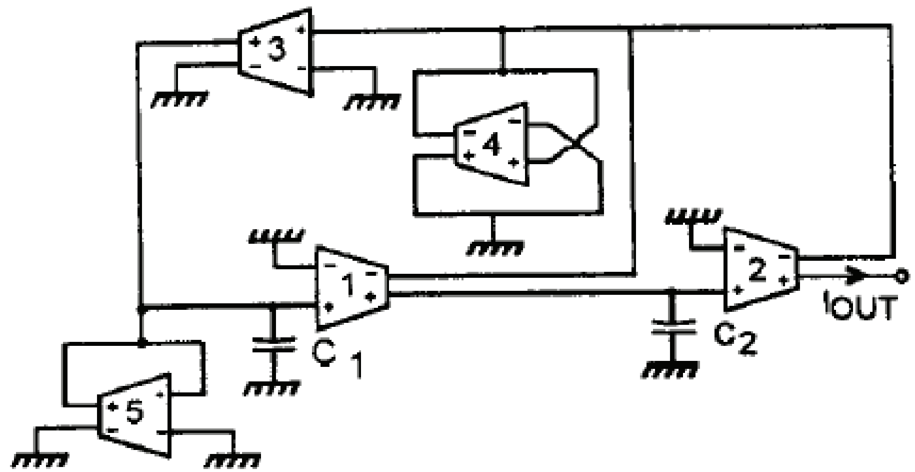
Realization of DO-OTA-C oscillators



(i)

b	Ω_o^2
$\dfrac{\dfrac{g_{m1}g_{m3}}{g_{m4}} - g_{m5}}{C_1}$	$\dfrac{g_{m1} \cdot g_{m2} \cdot g_{m3}}{C_1 C_2 g_{m4}}$

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Realization of DO-OTA-C oscillators

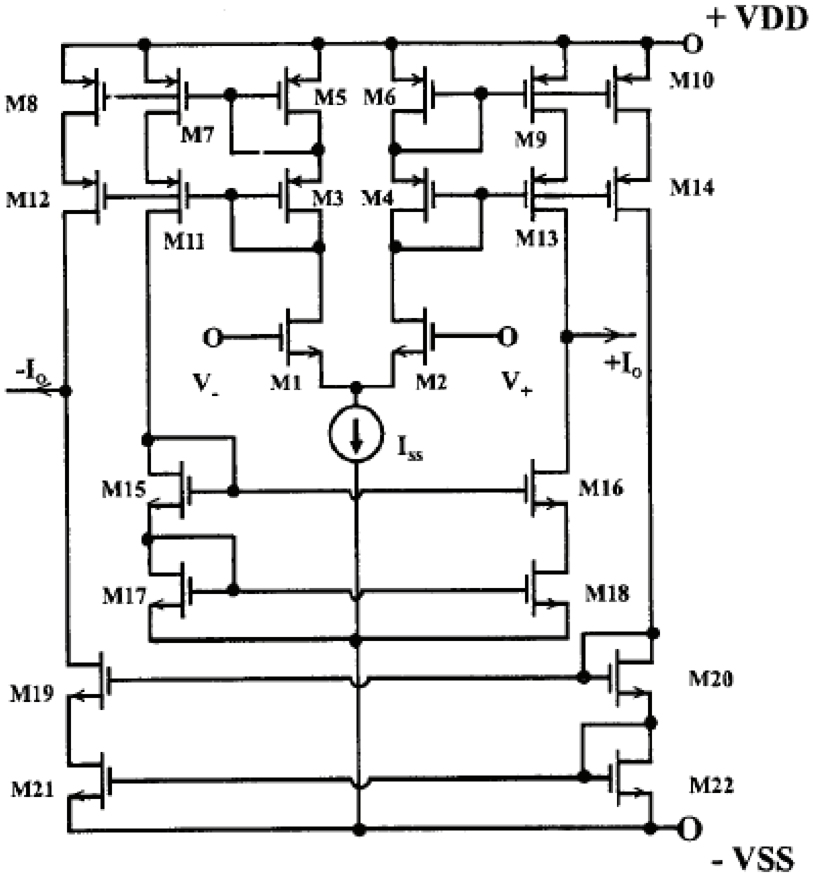

Fig. 3. CMOS cascade DO-OTA structure used for SPICE simulations.

For all simulations the capacitances of C1 and C2 are taken as C1 = C2 = 50 pF.

The biasing current of the OTAs is chosen as Iss = 500uA which yields an OTA transconductance of 450uA/V

Theoretical and simulation results of oscillation frequency obtained for proposed oscillator topologies

Topology	Theory	Simulation with actual CMOS DO-OTAs
Fig. 1a	1.342 MHz	1.297 MHz
Fig. 1b	1.433 MHz	1.358 MHz
Fig. 1c	1.488 MHz	1.431 MHz
Fig. 1d	1.472 MHz	1.37 MHz
Fig. 1e	1.433 MHz	1.355 MHz
Fig. 1f	1.433 MHz	1.365 MHz
Fig. 1g	1.433 MHz	1.36 MHz
Fig. 1h	1.433 MHz	1.35 MHz
Fig. 1i	1.537 MHz	1.509 MHz

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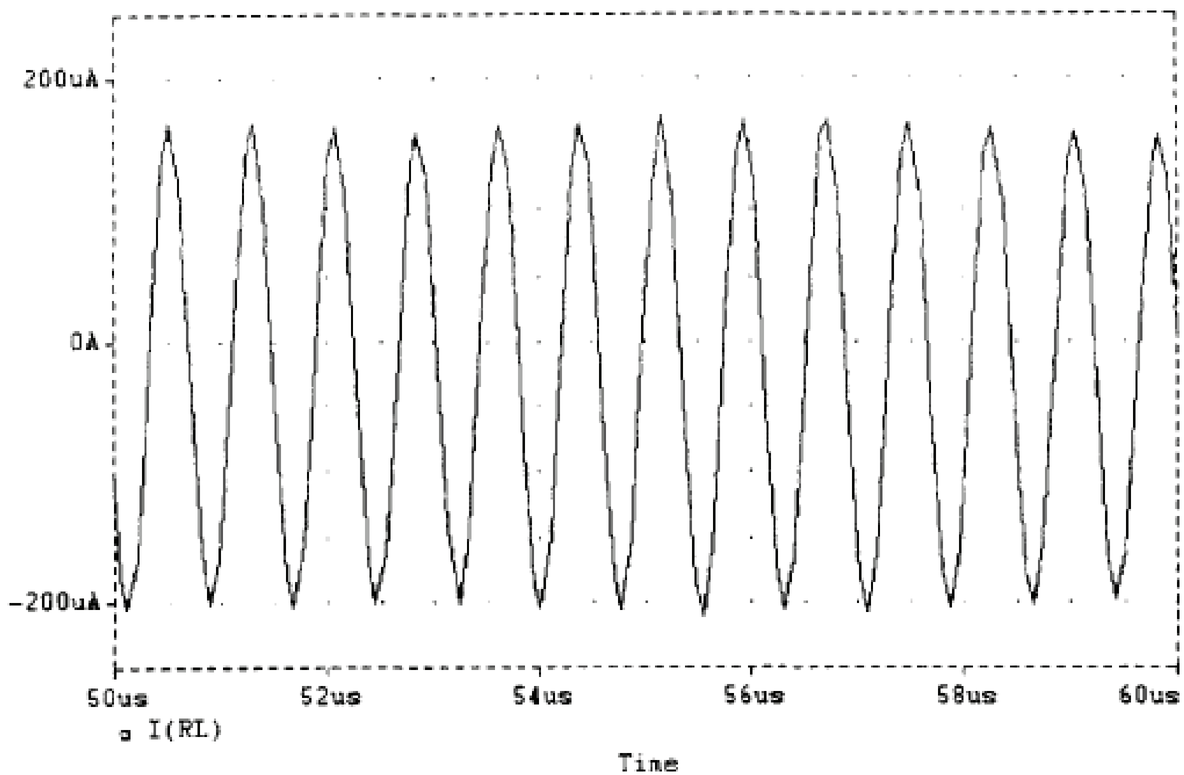
Realization of DO-OTA-C oscillators



Simulated waveform for output current of oscillator topology illustrated in Fig. 1a, $C_1 = C_2 = 50$ pF, $R_L = 1000\ \Omega$.

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Realization of DO-OTA-C oscillators

SPICE simulation results of output current and output voltage performed for different load resistance values

Fig. 1a	$I_{OUT_{pp}}$	$V_{OUT_{pp}}$	Frequency
$R_L = 1\,\Omega$	376.255 μA	376.255 μV	1.297 MHz
$R_L = 1\,k\Omega$	372.208 μA	372.208 mV	
$R_L = 10\,k\Omega$	398.098 μA	3.98098 V	
Fig. 1b			
$R_L = 1\,\Omega$	616.392 μA	616.392 μV	1.358 MHz
$R_L = 1\,k\Omega$	709.969 μA	709.968 mV	
$R_L = 10\,k\Omega$	668.157 μA	6.6815 V	
Fig. 1c			
$R_L = 1\,\Omega$	656.413 μA	656.413 μV	1.431 MHz
$R_L = 1\,k\Omega$	649.716 μA	649.716 mV	
$R_L = 10\,\Omega$	602.833 μA	6.0283 V	
Fig. 1d			
$R_L = 1\,\Omega$	1006.509 μA	1006.509 μV	1.37 MHz
$R_L = 1\,k\Omega$	1007.313 μA	1007.313 mV	
$R_L = 5\,k\Omega$	975.762 μA	4.8788 V	
Fig. 1e			
$R_L = 1\,\Omega$	718.012 μA	718.012 μV	1.355 MHz
$R_L = 1\,k\Omega$	720.880 μA	720.880 mV	
$R_L = 10\,k\Omega$	688.346 μA	6.8835 V	

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Realization of DO-OTA-C oscillators

Fig. 1f			
$R_L = 1\,\Omega$	731.044 μA	731.451 μV	1.365 MHz
$R_L = 1\,k\Omega$	774.261 μA	774.261 mV	
$R_L = 10\,k\Omega$	747.489 μA	7.4761 V	
Fig. 1g			
$R_L = 1\,\Omega$	714.922 μA	714.922 μV	1.36 MHz
$R_L = 1\,k\Omega$	736.624 μA	736.624 mV	
$R_L = 10\,k\Omega$	699.877 μA	6.796 V	
Fig. 1h			
$R_L = 1\,\Omega$	679.074 μA	679.074 μV	1.35 MHz
$R_L = 1\,k\Omega$	704.037 μA	704.037 mV	
$R_L = 10\,k\Omega$	675.921 μA	6.7592 V	
Fig. 1i			
$R_L = 1\,\Omega$	642.317 μA	642.317 μV	1.509 MHz
$R_L = 1\,k\Omega$	650.343 μA	650.343 mV	
$R_L = 10\,k\Omega$	576.071 μA	5.7607 V	

Realization of FTFN-Based Current-Mode Oscillators

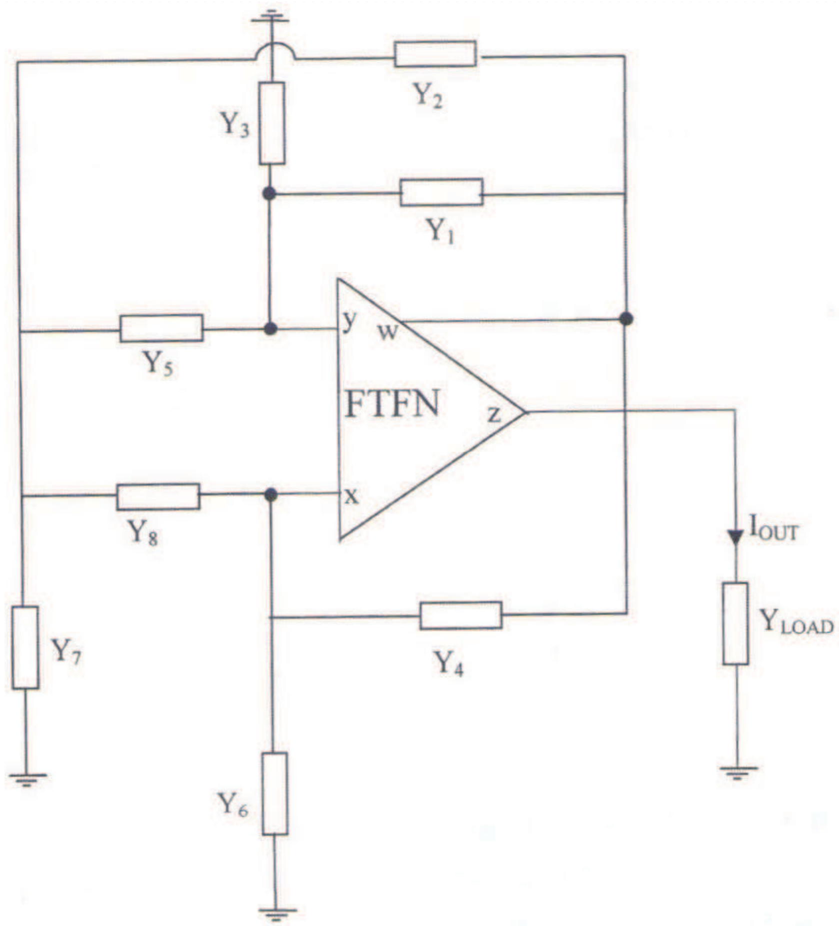
- **Current-Mode High Output Impedance Sinusoidal Oscillator Configuration Employing Single FTFN**
- a new oscillator configuration providing high output impedance,
- employing single FTFN, five resistors and two capacitors.

The proposed circuits permit

- Noninteractive control of oscillation frequency and
- oscillation condition,
- low active and passive sensitivities

Current-Mode Analog Circuit Design

Realization of FTFN-Based Current-Mode Oscillators



$$
\begin{aligned}
&Y_1Y_6(Y_2+Y_5+Y_7+Y_8)+Y_1Y_7Y_8+Y_2Y_5Y_6\\
&\quad -Y_3Y_4(Y_2+Y_5+Y_7+Y_8)\\
&\quad -Y_4Y_5Y_7-Y_2Y_3Y_8=0 \qquad (2)
\end{aligned}
$$

The general form of the proposed oscillator configuration.

Current-Mode Analog Circuit Design

Realization of FTFN-Based Current-Mode Oscillators

Taking the FTFN non-idealities into consideration, the port relations

$$V_x = \beta V_y \quad I_{o2} = \alpha I_{o1}$$

where $\beta = 1 - \varepsilon_v$, ε_v ($|\varepsilon_v| \ll 1$) denotes voltage tracking error and $\alpha = 1 - \varepsilon_i$, $\varepsilon_i(|\varepsilon_i| \ll 1)$ denotes current tracking error of the FTFN respectively.

$$\begin{aligned}
&\beta[Y_1Y_6(Y_2 + Y_5 + Y_7 + Y_8) + Y_1Y_7Y_8 + Y_2Y_5Y_6] \\
&\quad - Y_3Y_4(Y_2 + Y_5 + Y_7 + Y_8) - Y_4Y_5Y_7 - Y_2Y_3Y_8 \\
&\quad - (\beta - 1)[Y_4(Y_1Y_2 + Y_1Y_5 + Y_1Y_8 + Y_1Y_7 \\
&\quad + Y_2Y_5 + Y_5Y_8) \\
&\quad + Y_8(Y_1Y_2 + Y_1Y_5 + Y_2Y_5)] = 0
\end{aligned}$$

Current-Mode Analog Circuit Design

Realization of FTFN-Based Current-Mode Oscillators

- From equation (2) many oscillators can be derived.
- In this study two subsets of possible circuits are presented.
- Table 1 shows the selected passive elements for single resistance controlled oscillators.
- It is clearly observed from Table 1 for all proposed oscillators, oscillation condition and oscillation frequency can be independently adjusted by a resistor.

Table 1. Oscillation condition and oscillation frequency of single resistance-controlled oscillators (2C-5R).

No.	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Oscillation Condition	Oscillation Frequency
1	G_1	G_2	—	G_4	G_5	G_6	C_7	C_8	$C_8G_1G_6 + C_7G_1G_6 = C_7G_5G_4$	$\omega_0 = \sqrt{\frac{G_6(G_1G_2+G_1G_5+G_2G_5)}{C_7C_8G_1}}$
2	G_1	G_2	G_3	—	G_5	G_6	C_7	C_8	$C_7G_1G_6 + C_8G_1G_6 = C_8G_3G_2$	$\omega_0 = \sqrt{\frac{G_6(G_1G_2+G_1G_5+G_2G_5)}{C_7C_8G_1}}$
3	—	C_2	G_3	G_4	G_5	G_6	G_7	C_8	$C_8G_3G_4 + C_2G_3G_4 = C_2G_6G_5$	$\omega_0 = \sqrt{\frac{G_4(G_3G_7+G_5G_7+G_3G_5)}{C_2C_8G_3}}$
4	G_1	C_2	G_3	G_4	G_5	—	G_7	C_8	$C_8G_3G_4 + C_2G_3G_4 = C_8G_1G_7$	$\omega_0 = \sqrt{\frac{G_4(G_3G_7+G_5G_7+G_3G_5)}{C_2C_8G_3}}$
5	—	G_2	G_3	G_4	C_5	G_6	C_7	G_8	$C_5G_3G_4 + C_7G_3G_4 = C_5G_2G_6$	$\omega_0 = \sqrt{\frac{G_3(G_2G_8+G_4G_8+G_2G_4)}{C_5C_7G_4}}$
6	G_1	G_2	G_3	G_4	C_5	—	C_7	G_8	$C_5G_3G_4 + C_7G_3G_4 = C_7G_1G_8$	$\omega_0 = \sqrt{\frac{G_3(G_2G_8+G_4G_8+G_2G_4)}{C_5C_7G_4}}$
7	G_1	C_2	—	G_4	C_5	G_6	G_7	G_8	$C_2G_1G_6 + C_5G_1G_6 = C_5G_4G_7$	$\omega_0 = \sqrt{\frac{G_1(G_7G_8+G_6G_8+G_6G_7)}{C_2C_5G_6}}$
8	G_1	C_2	G_3	—	C_5	G_6	G_7	G_8	$C_2G_1G_6 + C_5G_1G_6 = C_2G_3G_8$	$\omega_0 = \sqrt{\frac{G_1(G_7G_8+G_6G_8+G_6G_7)}{C_2C_5G_6}}$

Current-Mode Analog Circuit Design

Realization of FTFN-Based Current-Mode Oscillators

Table 2 shows the selected passive elements of single frequency oscillators in which the number of resistors is reduced by one compared to the oscillators in Table 1.

Table 2. Oscillation condition and oscillation frequency of single frequency oscillators (2C-4R).

No.	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8	Oscillation Condition	Oscillation Frequency
1	G_1	G_2	G_3	—	—	G_6	C_7	C_8	$C_8G_1G_6 + C_7G_1G_6 = C_8G_3G_2$	$\omega_0 = \sqrt{\frac{G_2G_6}{C_8C_7}}$
2	—	C_2	G_3	G_4	G_5	G_6	—	C_8	$C_2G_3G_4 + C_8G_3G_4 = C_2G_5G_6$	$\omega_0 = \sqrt{\frac{G_4G_5}{C_2C_8}}$
3	—	G_2	G_3	G_4	C_5	G_6	C_7	—	$C_5G_3G_4 + C_7G_3G_4 = C_5G_2G_6$	$\omega_0 = \sqrt{\frac{G_2G_3}{C_8C_7}}$
4	G_1	C_2	G_3	—	C_5	G_6	—	G_8	$C_2G_1G_6 + C_5G_1G_6 = C_2G_3G_8$	$\omega_0 = \sqrt{\frac{G_1G_8}{C_2C_5}}$
5	G_1	—	—	G_4	G_5	$G_6 + C_6$	C_7	—	$C_6G_1G_5 + C_7G_1G_6 = C_7G_4G_5$	$\omega_0 = \sqrt{\frac{G_6G_5}{C_6C_7}}$
6	G_1	C_2	G_3	—	—	C_6	G_7	G_8	$C_6G_1G_8 + C_6G_1G_7 = C_2G_3G_8$	$\omega_0 = \sqrt{\frac{G_8G_7}{C_2C_6}}$
7	G_1	—	—	G_4	C_5	$G_6 + C_6$	G_7	—	$C_5G_1G_6 + C_6G_1G_7 = C_5G_4G_7$	$\omega_0 = \sqrt{\frac{G_6G_7}{C_5C_6}}$
8	G_1	—	G_3	$G_4 + C_4$	—	—	C_7	G_8	$C_4G_3G_8 + C_7G_3G_4 = C_7G_1G_8$	$\omega_0 = \sqrt{\frac{G_4G_8}{C_4C_7}}$

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Experimental Results and Discussions

- To confirm theoretical analysis, all the proposed circuits were experimentally tested.

- SPICE simulations were performed for the proposed circuits.

- The FTFN circuit was constructed with two AD844 IC of Analog Devices as shown in Fig. 3.

- The supply voltages were taken as VDD = 10V and VSS .=- 10 V.

- As an example, the experimental wave-form of second circuit in Table 1 is shown in Fig. 4.

- The passive elements of the oscillator were chosen as R1 = R2= R5 = R6 = 10 kOhm, R3 = 5kOhm, C7 = C8 = 1nF and the oscillation frequency was measured as 28 kHz.

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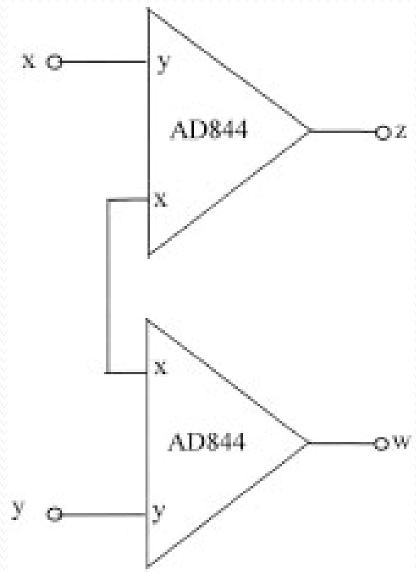
Realization of an FTFN with commercial AD844 IC (used as positive type CCII).



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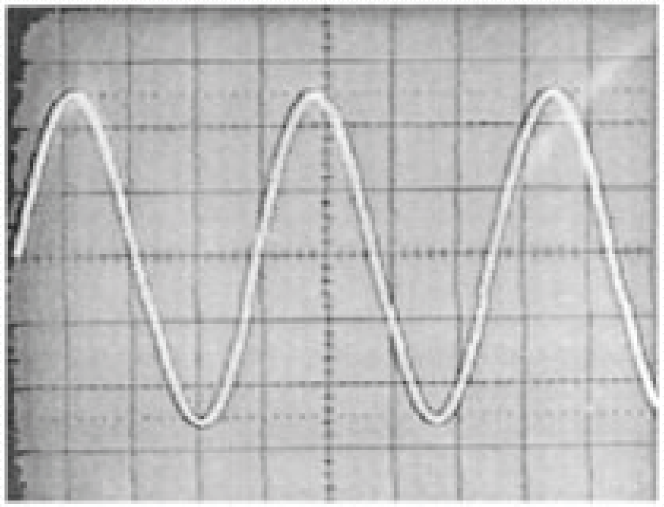
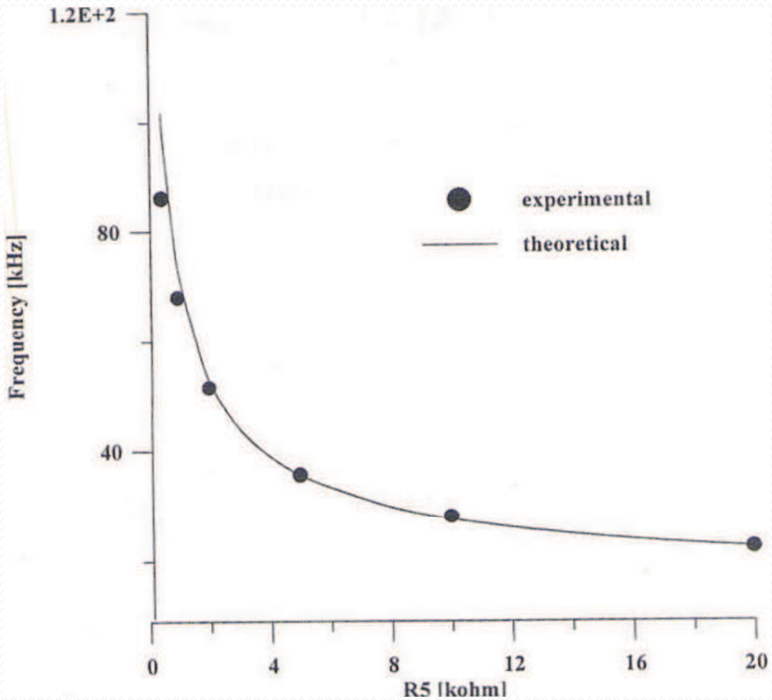


Experimental wave-form of the second circuit in Table 1 vertical: 1 div.0.1 mA, horizontal: 1 div.10).



Variation of the oscillation frequency with R5 of the second oscillator circuit given in Table 1.

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