Systematic Synthesis and Practical Implementation of Electronic Controllable Quadrature Oscillator based on OTAs

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Abstract—This article presents a systematic design of quadrature oscillator employing operational transconductance amplifier (OTAs). The oscillator frequency and oscillation condition can be electronically/orthogonally control via input bias currents. The proposed technique is based on simulated active inductor and active negative resistor oscillator using OTAs and grounded capacitors that lead to simple structure, easy to design and suitable for IC fabrication. The PSPICE simulation and experimental results are depicted, and the given results agree well with the theoretical anticipation.

I. INTRODUCTION

An oscillator is an important building block which are frequently employed in electrical engineering works. A quadrature oscillator is widely used because the circuit provides two sine waves with 90° phase difference, as for example in telecommunications for quadrature mixers and single-sideband [1-2]. Presently, the current-mode technique has been more popular than the voltage-mode technique. This is due to the requirements in low-voltage environments such as portable and battery-powered equipment. The current—mode technique is ideally suited for this purpose. Today, there is a growing interest in synthesizing current-mode circuits because of their potential advantages such as larger dynamic range, higher signal bandwidth, greater linearity, simpler circuitry, and lower power consumption [3-6].

Many authors have proposed the quadrature oscillators but these reported circuits suffer from one or more of the following weaknesses:

- Lack of electronic adjustability [8-10].
- Excessive use of the active and/or passive elements [7].
- Use of floating capacitors, which is not convenient to further fabricate in IC [11-13].
- The oscillation conditions and oscillation frequencies cannot be independently controllable [8-10].

The operational transconductance amplifier (OTA) has received considerable attention as active components, because the transconductance can be adjusted electronically, which is especially suitable for analog circuits [14-17]. Its internal construction can be easily fabricated into IC architecture to be low-power and low-voltage applications. Consequently, it can be used in the wireless communication circuit and systems [18]. Especially, it can be commercially found, it is also appropriate for off-the-shelf design. The flexibility of the mentioned devices to operate in current-modes allows for a variety of circuit designs. Also, the application of the OTA has been practically useful for constructing current-mode circuits from a reduced number of active components [18-19].

The purpose of this paper is to introduce a quadrature oscillator, based on OTAs. The oscillator frequency and oscillation condition can be electronically/orthogonally control via input bias currents. The circuit description is very simple, consisting of merely one capacitor, one resistor, one negative resistor and one inductor. The last two elements can be practically realized by OTA-based simulations. The completely proposed quadrature oscillator comprises 3 OTAs, 2 grounded capacitors and 1 grounded resistor. By using only grounded elements, the proposed circuit is then suitable for IC architecture. The PSPICE simulation and experimental results are depicted, and the given results agree well with the theoretical anticipation.

II. PRINCIPLE AND OPERATION

A. The Operational Transconductance Amplifier (OTA)

An ideal OTA has infinite input and output impedances. The output current of an OTA is given by

\[ I_o = g_m (V_i - V_c), \]  

(1)

where \( g_m \) is the transconductance of the OTA. For a bipolar OTA, the transconductance can be expressed by

\[ g_m = \frac{I_b}{2V_T}, \]  

(2)

where \( I_b \) and \( V_T \) are the bias current and thermal voltage,
respectively. The symbol and the equivalent circuit of the OTA are illustrated in Figs. 1(a) and (b), respectively.

\[ \begin{align*}
V_{(+)}, V_{(-)} & \rightarrow I_B, I_O \\
\text{OTA} & \\
\text{(a)} \\
V_{in} \rightarrow I_O \\
R \leftrightarrow \text{OTA} & \\
\text{(b)}
\end{align*} \]

Figure 1. OTA (a) Symbol (b) Equivalent circuit.

B. Basic principle of the oscillator

The oscillator is designed by connecting in parallel of a capacitor, a positive inductor, a positive resistor and a negative resistor as shown in Fig. 2. From electrical network in Fig. 2, we will receive the characteristic equation as

\[ s^2 + \left( \frac{1}{R_i} - \frac{1}{R_2} \right) s + \frac{1}{LC} = 0. \]  (3)

From (3), the oscillation condition (OC) and oscillation frequency \( (\omega_{oc}) \) can be written as

\[ OC: \quad R_2 = R_i \]  (4)

and

\[ \omega_{oc} = \sqrt{\frac{1}{LC}}. \]  (5)

From (4) and (5), the oscillation condition and oscillation frequency can be adjusted independently. It means that the oscillation condition can be controlled by \( R_i \) and \( R_2 \), while the oscillation frequency can be tuned by \( L \) and \( C \).

C. Proposed quadrature oscillator

Based on the circuit topology in Fig. 2, it can be modified to avoid the use of practical inductor and to realize the negative resistor, where the electronic controllability can be fulfilled.

The inductor \( L \) and negative resistor \( R_2 \) can be realized by using the OTAs, as illustrated in Figs. 3 and 4, respectively. Straightforward analysis of the circuit in Figs. 3 and 4, the equivalent inductance and negative resistance values can be respectively expressed as follows:

\[ L_{eq} = \frac{C_2}{g_{m1}g_{m2}} \]  (6)

and

\[ R_{2eq} = -\frac{1}{g_{m3}}. \]  (7)

The completely proposed quadrature oscillator is shown in Fig. 5. The characteristic equation, oscillation condition (OC) and oscillation frequency \( (\omega_{oc}) \) can be written as

\[ s^2 + \left( \frac{1}{R_i} - \frac{g_{m3}}{C_1} \right) s + \frac{g_{m1}g_{m2}}{C_1C_2} = 0, \]  (8)
\[ R_2 = \frac{1}{g_m} \]  
\[ \omega_{osc} = \frac{g_m g_a}{C_1 C_2} \].

Substituting \( g_m = I_a / 2V_f \) as depicted in Eq. (2), it yields

\[ \omega_{osc} = \frac{1}{2V_f} \frac{I_a I_a}{C_1 C_2} \].

From (9), the oscillation condition can be achieved by setting

\[ I_{R_2} = \frac{2V_f}{R_2} \].

From (11) and (12), the oscillation condition can be adjusted independently from the oscillation frequency by \( I_{R_2} \) and \( R_2 \), while the oscillation frequency can be electronically adjusted by varying bias currents \( I_{R1} \) and \( I_{R2} \). This property is an appropriately important factor in the synthesis of the modern oscillators.

It should be noted that, in fact, the positive resistor \( R_1 \) can be simulated by employing OTA but its nonlinear characteristic will effect on the linearity of the oscillator network. That means that if it is used for realization of the sinusoidal oscillator, the output signals become triangular signal. By the way, the use of OTAs to simulate the inductance and negative resistance is adequate to make the oscillator to be fully controlled by electronic method, as explained in Eqs. (8)-(12).

From Fig. 2, the voltage transfer function from \( V_{O2} \) to \( V_{O1} \) is

\[ \frac{V_{O2}(s)}{V_{O1}(s)} = \frac{g_m}{s C_2} \].

Under sinusoidal steady state, (13) becomes

\[ \frac{V_{O2}(j\omega)}{V_{O1}(j\omega)} = \frac{g_m}{\omega C_2} e^{-i90^\circ}. \]

The phase difference \( \phi \) between \( V_{O2} \) and \( V_{O1} \) is

\[ \phi = -90^\circ. \]

Ensuring the voltages \( V_{O2} \) and \( V_{O1} \) to be in quadrature.

### III. SIMULATION AND EXPERIMENTAL RESULTS

To prove the performances of the proposed circuit, a PSPICE simulation was performed for examination. The circuit of Fig. 5 was constructed using the LM13700-type OTA. The circuit was biased with \( \pm 3 \) V supply voltages, where \( R_i = 1k\Omega \), \( C_1 = C_2 = 2nF \), \( I_{R1} = I_{R2} = 50\mu A \) and \( I_{R3} = 55\mu A \). Fig. 6 shows simulated output waveforms in a transient response, this confirms the output quadrature form. Fig. 7 depicts the simulated output spectrum, where the total harmonic distortion (THD) is about 6.57\% for oscillator frequency of 70kHz. Fig. 8 depicts the plots of the simulated relative to theoretical oscillation frequency for variations of the bias currents; \( I_{R1} \) and \( I_{R2} \) where \( C_1 \) and \( C_2 \) are identical values of 0.1nF, 1nF and 10nF. It is seen that the simulation results are in accordance with the theoretical analysis as shown in Eq. (11). The results of the \( V_{O1} \) total harmonic distortion analysis are summarized in Table 1.

![Image](image_url)

**Figure 6. The simulation results of output waveforms during a steady state.**

**Figure 7. The simulation result of output spectrum.**

**Figure 8. Oscillation frequencies relative to bias current \( I_{R1} \) \( I_{R2} \) for different capacitances.**

In addition, to verify the practical workability, the experimental response at a frequency of about 70kHz is also illustrated in Figs. 9 and 10, which are the quadrature output signals and output spectrum, respectively.
IV. CONCLUSIONS

The quadrature oscillator based on OTAs has been presented. The oscillator frequency and oscillation condition can be electronically/orthogonally controlled via input bias currents. The circuit description is very simple, consisting of 2 grounded capacitors, one resistor and 3 OTAs, the proposed circuit is then suitable for IC architecture. The performances of the proposed oscillator have been verified by the PSPICE simulation and experiment results. The given results agree well with the theoretical anticipation. Additionally, since this oscillator is synthesized from the standard basic principle, the quadrature oscillator can be realized by other modern active elements, for instance, current conveyer, CDBA, CDTA, CFA, and etc.

REFERENCES

| Total Harmonic Distortion Analysis of Vc3 of Oscillator in Fig. 5. |
|---|---|---|---|---|
| Harmonic No. | Frequency (Hz) | Fourier Component | Normalized Component | Phase (Deg) | Normalized Phase (Deg) |
| 1 | 7.00E+04 | 2.49E-02 | 1.00E+00 | 1.92E+01 | 0.00E+00 |
| 2 | 1.40E+05 | 1.24E-03 | 5.00E-02 | -1.68E+02 | -2.06E+02 |
| 3 | 2.10E+05 | 6.84E-04 | 2.74E-02 | -1.50E+02 | -2.08E+02 |
| 4 | 2.80E+05 | 5.06E-04 | 2.02E-02 | -1.72E+02 | -2.49E+02 |
| 5 | 3.50E+05 | 3.92E-04 | 1.57E-02 | -1.71E+02 | -2.67E+02 |
| 6 | 4.20E+05 | 3.22E-04 | 1.29E-02 | -1.70E+02 | -2.85E+02 |
| 7 | 4.90E+05 | 2.73E-04 | 1.09E-02 | -1.69E+02 | -3.04E+02 |
| 8 | 5.60E+05 | 2.38E-04 | 9.55E-03 | -1.68E+02 | -3.22E+02 |
| 9 | 6.30E+05 | 2.11E-04 | 8.47E-03 | -1.67E+02 | -3.40E+02 |
| 10 | 7.00E+05 | 1.90E-04 | 7.61E-03 | -1.66E+02 | -3.58E+02 |

DC Component = -2.807711E-05

TOTAL HARMONIC DISTORTION = 6.579937E+00 PERCENT

![Figure 9. Experimental results of quadrature oscillator.](image)

![Figure 10. The experimental result of output spectrum.](image)