Voltage-mode universal biquadratic filter and quadrature oscillator using CFAs

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Abstract: The paper presents a new voltage-mode universal biquadratic filter and a new quadrature oscillator using two current-feedback amplifiers (CFAs) with two capacitors and three resistors. The proposed circuit can work as both a voltage-mode universal biquadratic filter and a quadrature oscillator without changing the circuit configuration. As a voltage-mode universal biquadratic filter, the proposed circuit can be easily realized all five generic filtering functions by selecting three different input voltage signals. The proposed filter allows the orthogonal controllability of the quality factor and the resonance angular frequency. If there is no input voltage signal, the proposed configuration can work as a quadrature oscillator without changing the circuit topology. This proposed topology provides two quadrature voltage outputs. The oscillation condition and oscillation frequency are also independent adjustability. The experimental results show that the new voltage-mode universal biquadratic filter and quadrature oscillator are feasible.

Keywords: voltage-mode universal filter, quadrature oscillator, CFAs

Classification: Integrated circuits

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1 Introduction

In analog signal processing circuits, the current feedback amplifier (CFA) is an important active element to provide a constant bandwidth with independent of closed-loop gain and to enable a high slew-rate [1]. From analog devices [2], CFA is suitable for working with the commercially available integrated circuit chip, AD844. Moreover, CFA has low output impedance, which is easy to make the circuit cascaded without additional buffer.

Recently, many CFA based voltage-mode universal biquadratic filters [3, 4, 5, 6, 7, 8] and quadrature oscillators [9, 10, 11, 12, 13] have been reported in some technical literatures. However, all of them only provide one function, either a universal biquadratic filter [3, 4, 5, 6, 7, 8] or a quadrature oscillator [9, 10, 11, 12, 13]. For example, a versatile voltage-mode biquadratic filter with four inputs and three outputs based on three CFAs, three resistors and two capacitors has been proposed in 2005 [7]. The circuit permits the orthogonal controllability of the quality factor, $Q$, and the resonance angular frequency, $\omega_0$. The circuit achieves all standard types of the filtering functions by selecting four input voltages. However, the circuit needs to use three CFAs. Another voltage-mode universal biquadratic filter with five inputs and two outputs based on two CFAs, two capacitors and four resistors has been proposed in 2013 [8]. This circuit implements all standard filtering functions using the same circuit configuration, but it has too many component-matching requirements. Moreover, the characteristic parameters, $\omega_0$ and $Q$, cannot be controlled orthogonally. Third, a voltage-mode single-resistance-controlled sinusoidal quadrature oscillator and a voltage-mode universal biquadratic filter based on two CFAs, two/three resistors, and two capacitors has been proposed in 2009 [9]. Nevertheless, the voltage-mode universal filter and the quadrature oscillator need to be realized in the different configuration. Last but not least, two interesting quadrature sinusoidal oscillators based on two CFAs, two resistors, and two capacitors has been proposed in 2015 [10], but the oscillation condition and oscillation frequency cannot be controlled independently.

This paper proposes a new voltage-mode universal biquadratic filter and quadrature oscillator using two CFAs, two capacitors and three resistors. The proposed circuit has the following advantages: (i) one circuit with the same configuration has two functions, the voltage-mode universal filter and the quadrature oscillator, (ii) one filter realizes all five filtering responses in voltage-mode with low output impedance, (iii) no inverting input voltage is needed in voltage-
mode filter, (iv) the filter parameters, $\omega_0$ and $Q$, can be controlled orthogonally, (v) the quadrature oscillator uses two grounded capacitors, (vi) the two voltage quadrature signals have 90° phase difference, (vii) in quadrature oscillator, the oscillation condition and oscillation frequency are controlled independently, and (viii) the proposed circuit has low active and passive sensitivities.

Table I lists the feature comparison of the proposed circuit and the other previous reported CFA-based voltage-mode universal filters or quadrature oscillators. The proposed circuit can operate as a voltage-mode universal biquadratic filter or a quadrature oscillator with the same circuit configuration, which the previous works in Table I cannot achieve. Moreover, the proposed circuit is also better than the individual circuit in Table I by comparing with either the filter function or the oscillator function. For example in the filter function, the number of CFAs in the proposed circuit are less than that in the circuit of [7], the number of passive components in the proposed circuit are less than that in the circuit of [8], and the proposed circuit provides the orthogonal controllability of $Q$ and $\omega_0$, which the circuit of Fig. 3 in [9] does not provide. Another example in the oscillator structure, both two capacitors of the proposed circuit are grounded, but one capacitor in the circuit of Fig. 2 in [9] is floating. Also, the proposed circuit allows independent control of the oscillation condition and oscillation frequency, which the circuit in [10] does not allow.

### Table I. Comparison of the proposed circuit with recently reported CFA-based voltage-mode universal filters or quadrature oscillators.

| Related works | [7] | [8] | [9] Fig. 3 | [9] Fig. 2 | [10] | This work |
|---------------|-----|-----|------------|------------|------|----------|
| No. of CFAs   | 3   | 2   | 2          | 2          | 2    | 2        |
| No. of passive elements | 3R, 2C | 4R, 2C | 2R, 2C | 3R, 2C | 2R, 2C | 3R, 2C |
| (i) | no | no | no | no | no | yes |
| (ii) | yes | yes | yes | NA | NA | yes |
| (iii) | yes | yes | no | NA | NA | yes |
| (iv) | yes | no | no | NA | NA | yes |
| (v) | NA | NA | NA | no | yes | yes |
| (vi) | NA | NA | NA | yes | yes | yes |
| (vii) | NA | NA | NA | yes | no | yes |
| (viii) | yes | no | yes | yes | yes | yes |

2 Proposed voltage-mode universal biquadratic filter and quadrature oscillator

CFA consists of a second-generation current conveyor and a voltage buffer. Using standard notation, the relationship equations between the input and output of the CFA is $i_y = 0$, $v_y = v_y$, $i_z = i_x$ and $v_w = v_z$ [3]. The proposed circuit for both the voltage-mode universal biquadratic filter and the quadrature oscillator is shown in Fig. 1, which includes two CFAs, three resistors and two capacitors.
2.1 Voltage-mode universal biquadratic filter

The circuit in Fig. 1 can be the proposed voltage-mode universal biquadratic filter, if the input voltages, \( V_{i1}, V_{i2} \) and \( V_{i3} \), are added, the \( V_o2 \) output voltage signal can be expressed as:

\[
v_{o2} = \frac{s^2 v_{i1} - \left( \frac{s}{R_2 C_2} \right) v_{i2} + \left( \frac{1}{R_1 R_3 C_1 C_2} \right) v_{i3}}{s^2 + s \left( \frac{1}{R_1 C_2} - \frac{1}{R_2 C_2} \right) + \frac{1}{R_1 R_3 C_1 C_2}}
\]  

(1)

According to (1), five kinds of filters can be realized by adjusting the input voltage, \( V_{i1}, V_{i2} \) and \( V_{i3} \), as follows:

(i) lowpass (LP): \( V_{i1} = V_{i2} = 0 \), and \( V_{i3} = V_{in} \)

(ii) bandpass (BP): \( V_{i1} = V_{i3} = 0 \), and \( V_{i2} = V_{in} \)

(iii) highpass (HP): \( V_{i2} = V_{i3} = 0 \), and \( V_{i1} = V_{in} \)

(iv) bandstop (BS): \( V_{i2} = 0 \), and \( V_{i1} = V_{i3} = V_{in} \)

(v) allpass (AP): \( V_{i1} = V_{i2} = V_{i3} = V_{in} \), and \( R_2 = 2 R_1 \)

In summary, the proposed circuit can be used as a three-input and single-output voltage-mode universal filter, which realizes all kinds of the filter responses without any inverting-type input voltage. The resonance angular frequency \( \omega_o \), and quality factor \( Q \) of the proposed universal filter are given by

\[
Q = \frac{R_2}{R_2 - R_1} \sqrt{\frac{R_1 C_1}{R_3 C_2}}
\]

and

\[
\omega_o = \sqrt{\frac{1}{R_1 R_3 C_1 C_2}}
\]

(2)

From (2), the parameter \( Q \) can be independently tuned by \( R_2 \) without affecting \( \omega_o \). In other words, the \( \omega_o \) and \( Q \) parameters are orthogonal adjustability through \( R_3 \) and then \( R_2 \) in that order. The orthogonal adjustability is a desire property for designing and tuning flexibility of the biquadratic filters.

2.2 Voltage-mode quadrature oscillator

The circuit in Fig. 1 can be worked as the proposed voltage-mode quadrature oscillator, if all the input voltages, \( V_{i1}, V_{i2} \) and \( V_{i3} \), are zero, the characteristic equation of the Fig. 1 circuit can be expressed as:

\[
S^2 + S \left( \frac{1}{R_1 C_2} - \frac{1}{R_2 C_2} \right) + \frac{1}{R_1 R_3 C_1 C_2}
\]

(3)
The oscillation condition and oscillation frequency can be expressed as (4) and (5), respectively.

\[
R_2 \leq R_1 \tag{4}
\]

\[
\alpha_o = \frac{1}{\sqrt{R_1R_3C_1C_2}} \tag{5}
\]

The oscillation condition of the proposed voltage-mode quadrature oscillator can be adjusted by \(R_2\) independently. The oscillation frequency can be adjusted by \(R_3\) independently. Thus, both oscillation condition and oscillation frequency are adjustable independently. Since the output impedance of CFA is very small, the output impedance of the proposed voltage-mode quadrature oscillator is very small, which can be cascaded to the next stage easily. The voltage transfer function from \(V_{o1}\) to \(V_{o2}\) of the proposed voltage-mode quadrature oscillator is

\[
\frac{V_{o1}}{V_{o2}} = -\frac{1}{sC_1R_3} \tag{6}
\]

Under sinusoidal steady state, (6) can be changed as

\[
\frac{V_{o1}}{V_{o2}} = \frac{1}{\alpha_oC_1R_3} e^{j90^\circ} \tag{7}
\]

The phase difference, \(\phi\), between \(V_{o1}\) and \(V_{o2}\) is

\[
\phi = 90^\circ \tag{8}
\]

which ensure the voltages \(V_{o1}\) and \(V_{o2}\) in quadrature.

As indicated by (7), the magnitude ratios of the quadrature voltages given by \(\frac{1}{\alpha_oC_1R_3}\) are the dependent term of operating frequency. Thus, changing the oscillation frequency by \(R_3\) will change the magnitude ratios of the generated quadrature signals. However, the equal magnitude quadrature signals could be obtained by choosing the equal capacitors and changing \(R_3\) and \(R_1\) synchronously because of \(R_3 = R_1\), and then adjusting \(R_2\) to equal to \(R_1\) in order to satisfy the oscillation condition. In other words, the oscillation frequency and oscillation condition are orthogonal adjustability by adjusting \(R_3\) and/or \(R_1\) and then adjusting \(R_2\) in that order.

Considering the non-ideal CFA, the relationship equations between the input and output of the CFA can be rewritten as \(v_x = \beta v_y, i_z = a_i x\), and \(v_w = \gamma v_z\) [6], and the characteristic equation of the proposed voltage-mode quadrature oscillator in Fig. 1 becomes

\[
s^2 + s \left( \frac{1}{R_1C_2} - \frac{a_2}{R_2C_2} \right) + \frac{a_1}{R_1R_3C_1C_2} \tag{9}
\]

According (9), the non-ideal oscillation condition and oscillation frequency can be obtained as (10) and (11), respectively.

\[
R_2 \leq a_2 R_1 \tag{10}
\]

\[
\alpha_o = \frac{a_1}{\sqrt{R_1R_3C_1C_2}} \tag{11}
\]

where \(a_1\) and \(a_2\) are the tracking errors. They slightly change the oscillation condition and oscillation frequency, respectively.
A sensitivity study forms an important index of any active network. The formal definition of sensitivity is \( S^F = \frac{x}{F} \frac{\partial F}{\partial x} \), where \( F \) represents one of \( \omega_0 \) and \( x \) represents any passive elements or active parameters. Based on the sensitivity expression, the active and passive sensitivities of the proposed oscillator are given as

\[
S^\omega_0_{C_1} = \frac{S^\omega_0}{C_1} = \frac{S^\omega_0}{C_2} = \frac{S^\omega_0}{R_1} = \frac{S^\omega_0}{R_3} = \frac{1}{2}
\]

(12)

As indicated by (12), the active and passive sensitivities are less than unity.

### 3 Measurement results

The proposed voltage-mode universal biquadratic filter and quadrature oscillator has been validated by using a commercially available AD844-type of CFA with ±5 V DC power supply. The proposed filter is designed with \( C_1 = C_2 = 100 \text{ pF} \), \( R_1 = 2 \text{ k}\Omega \), \( R_2 = 4 \text{ k}\Omega \), \( R_3 = 8 \text{ k}\Omega \), and \( f_0 = 397.9 \text{ kHz} \). Fig. 2 shows the experimental frequency responses of the LP, HP, and BS filters and the center frequency of the BS experimental result is 391 kHz, which approximates the theoretical value within 1.73% of its error. Fig. 3 shows the experimental frequency responses of the...
BP and AP filters and the center frequency of the BP experimental result is 391 kHz, which approximates the theoretical value within 1.73% of its error. Fig. 4 shows the inverting BP sinusoidal input waveforms with 1 V (peak) and 397.9 kHz on channel 1, and its output response waveforms on channel 2. These waveforms validate the function of the proposed BP filter is good. The phase error of the inverting BP response is less than 3%.

The 1-dB power gain compression point (P1dB) represents the linearity of the proposed filter. Fig. 5 shows the measured P1dB of the BP filter with input power at the center frequency of 397.9 kHz. As shown in Fig. 5, the measured circuit has about 1 dB loss and the measured P1dB is about 8 dBm with respect to the input power. Fig. 6 shows the frequency spectrum of the BP filter at the center frequency of 397.9 kHz with 2 dBm input power. The total harmonic distortion (THD) in Fig. 6 is about 2.38%, which calculation includes the first harmonic through the ninth harmonic components.

The proposed oscillator is designed with $C_1 = C_2 = 400 \text{ pF}$ and $R_1 = R_2 = R_3 = 1 \text{ k}\Omega$, and the oscillation starts from $R_2 = 0.9 \text{ k}\Omega$. The theoretical oscillation...
frequency of this design is 398 kHz. Fig. 7 represents the oscilloscope output waveforms, $V_{o1}$ and $V_{o2}$, of the proposed oscillator. The quadrature relationship is further verified through the $X$–$Y$ plot of the two outputs in Fig. 8. Fig. 9 shows...
the frequency spectrum of the oscillator output voltage, $V_{o1}$. Fig. 10 shows the magnitude difference between the fundamental harmonic and the second harmonic. As we can see, the magnitude of the second harmonic is 40.15 dB, which is less than the magnitude of the fundamental harmonic. The measured oscillation frequency in Fig. 9 is 396.46 kHz, which is close to theoretical value and the error is only 0.39%. The THD in Fig. 9 is about 1.42%, which calculation includes the first harmonic through the ninth harmonic components. Obviously, the experimental results are consistent with the theoretical values.

Noise is a major concern in oscillators, even if introducing a small noise into an oscillator will still lead to dramatic changes in its frequency spectrum and timing properties. Fig. 11 shows how the phase noise is calculated using the Agilent phase noise measurement solution. The phase noise in the proposed oscillator is lower than $-105.09$ dBc/Hz (at 10 kHz offset). Fig. 12 shows the root mean square (RMS) jitter of the proposed oscillator, which is 3.4 ns at an operating frequency of 396.4 kHz.
4 Conclusions

The paper combines a new CFA-based voltage-mode biquadratic filter and a new quadrature oscillator in a single circuit. The proposed circuit utilizes two CFAs, three resistors, and two capacitors to realize both a universal biquadratic filter and a quadrature oscillator within the same circuit topology. The proposed voltage-mode biquadratic filter can bring out all five filtering functions without any inverting-input voltage. The resonance angular frequency, $\omega_0$, and quality factor, $Q$, of the proposed voltage-mode biquadratic filter are orthogonal controllability. The proposed quadrature oscillator has independent control of the oscillation condition and oscillation frequency. The phase difference of the two low output impedances of the proposed quadrature oscillator is 90°. The active and passive sensitivities are low.

The experimental results validate that the functions of the proposed filter and the proposed oscillator are excellent. Finally, the proposed universal biquadratic filter and quadrature oscillator can be used as a filter or an oscillator. Hence, in the applications of the wireless communications, baseband signal will need filters to filter out the undesirable bandwidth. In the test, the system can perform self-test by

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Fig. 11. The measured phase noise of the proposed oscillator.

Fig. 12. The measured RMS jitter of the proposed oscillator at an operating frequency of 396.4 kHz.
sinusoidal signal generated by the oscillator without additional external baseband signal. The cost of the circuit test can be reduced to enhance the ability of IC self-testing. Moreover, if integrated the proposed circuit, the costs of design, layout, tape-out, packaging, and testing can be reduced.