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CFOA-based mixed-mode first-order universal filter implemented with commercially available ICs

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This paper introduces a mixed-mode first-order universal filter, which is implemented using commercially available integrated circuits. The proposed filter comprises three current feedback operational amplifiers (CFOAs) as commercially available ICs, along with three resistors and one capacitor as passive components. The three standard responses of a first-order filter, i.e., lowpass, highpass, and allpass responses, can be accomplished simultaneously with a single proposed structure. Additionally, it can operate in all four modes of operation, including voltage mode, transadmittance mode, current mode, and transimpedance mode. The circuit enables pole-frequency tunability through a single resistor. A non-ideal analysis considering the CFOA tracking errors and parasitic elements was also investigated. A simple application of the proposed filter for implementing a quadrature oscillator is suggested. To confirm the performance of the filter, the simulation results using PSPICE software were performed.

Keywords: current feedback operational amplifier (CFOA), mixed-mode circuit, first-order filter, commercially available IC, quadrature oscillator (QO)

1 Introduction

Analog signal processing circuits play an important role in modern electronic, instrumentation, and communication systems. Active filters are necessary circuits widely used for noise suppression and frequency selection. In particular, first-order universal active filters have attracted significant research interest since they serve as fundamental structures for synthesizing higher-order filters, automatic control systems, phase shifters, oscillators, etc. The capability to realize all three standard first-order filtering functions, namely lowpass (LP), highpass (HP), and allpass (AP), from a single circuit structure offers noteworthy design flexibility and reduces overall system complexity [1-39].

In modern analog system designs, input and output signals can be in the form of either voltage or current, depending on the architecture of the interacting systems. Hence, the operational modes of active filters are classified into four categories such as voltage mode (VM), transadmittance mode (TAM), current mode (CM), and transimpedance mode (TIM). Over the past decade, the conventional filters have been designed to operate in a single mode [1-35]. This approach, however, introduces interface challenges and increases power consumption when connecting filter circuits to other systems that require a different signal, as additional signal converters (e.g., voltage-to-current or current-to-voltage converters) are necessary. To avoid this issue, mixed-mode universal filters capable of all four possible modes of operation within a single topology have developed as a superior alternative, significantly reducing component count, decreasing power consumption, and enhancing system integration. These features improve signal-processing flexibility, simplify system design, and enhance overall circuit integration. In [36-39], the reported topologies are capable of operating in all four possible modes. The only work reported in [36] that can operate in mixed mode using a commercially available IC is mentioned. Conversely, other developed filters utilize transistor-level architectures to perform active blocks, which include BJT-based structures [2, 8, 10, 16] and MOS-based structures [4-6, 9, 12-15, 17-18, 20, 22-32, 34-39]. However, there are no off-the-shelf IC counterparts available for such specific active elements.

This study introduces a mixed-mode first-order universal filter based on current feedback operational amplifiers (CFOAs) as active elements to meet the demand for cost-effective, practical, and high-performance filtering solutions. This CFOA element is a kind of readily off-the-shelf IC, especially the AD844. The pro-

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posed filter comprises three CFOAs, three resistors, and a single capacitor. With a single topology, the filter can successfully realize all three standard filtering responses (LP, HP, and AP) beyond all four operational modes (VM, TAM, CM, and TIM). Furthermore, it features independent tuning of the pole frequency through a single resistor. The passband gains of the TAM and TIM modes can be independently adjusted without disturbing the pole frequency. The viability and performance of the proposed circuit are verified through PSPICE simulations using the AD844 macro model provided from Analog Devices. To illustrate its practical utility, an application in a quadrature oscillator realization is also implemented and simulated.

The remainder of this paper is structured as follows: Section 2 describes the proposed mixed-mode filter circuit. Section 3 presents a simulation verification. Section 4 presents the practical application of the filter in a quadrature oscillator. Finally, section 5 is a conclusion to the paper.

2 CFOA and mixed-mode first-order filter

Figure 1 shows the current feedback operational amplifier (CFOA), available commercially as the AD844 IC from Analog Devices [40], that is used as the active building block. This device consists of four terminals, and its terminal relationships can be expressed as follows:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \\ v_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \beta & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}, \quad (1)$$

where β, α, and γ are the input-voltage, input-current, and output-voltage tracking errors, respectively. All of these parameters are ideally equal to unity and therefore have no influence on the performance of the circuit.

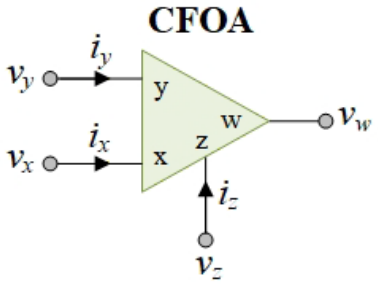


Fig. 1. Circuit symbol of the CFOA

Figure 2 shows the mixed-mode first-order universal filter. The design of the filter is implemented with three CFOAs, three resistors, and one capacitor. Analyzing the circuit by using equation (1) and disregarding the effect of tracking errors ($\beta = \alpha = \gamma = 1$), the operation of the proposed circuit in VM, TAM, CM, and TIM is detailed as follows.

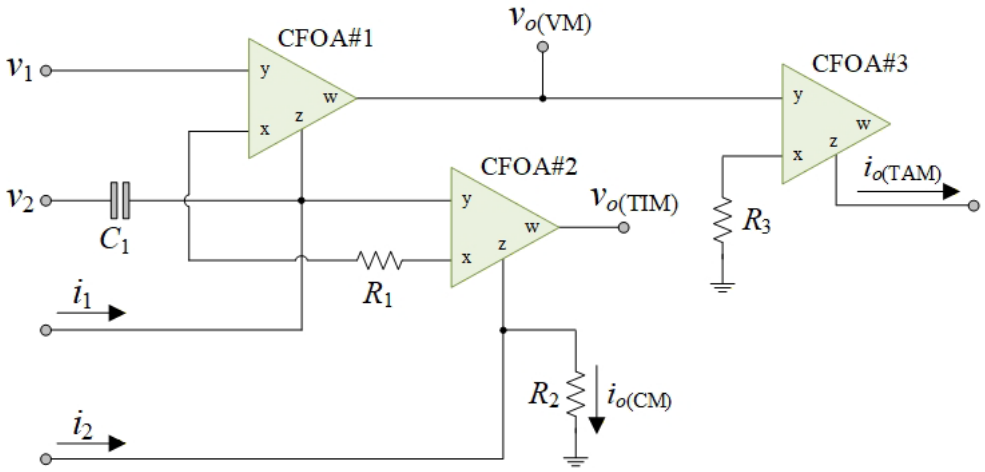


Fig. 2. Proposed mixed-mode first-order universal filter

2.1 Voltage mode and transadmittance mode

To accomplish the VM and TAM first-order filter, all input currents are set as 0 (open circuit). By applying the input voltages v_1 and v_2, the transfer functions for VM and TAM operation are obtained as follows:

$$v_{o(\mathrm{VM})} = \frac{(sR_1C_1)v_2+v_1}{D(s)}, \tag{2}$$

$$i_{o(\mathrm{TAM})} = \left(\frac{1}{R_3}\right)\left[\frac{(sR_1C_1)v_2+v_1}{D(s)}\right], \tag{3}$$

$$D(s) = sR_1C_1 + 1. \tag{4}$$

As presented in Eqns. (2) to (4), Tab. 1 shows the proper selection of the input in order to accomplish a LP, HP, and AP responses in VM and TAM.

Table 1. Input signal conditions and passband gains for VM and TAM filters in Fig. 2

Filtering function	v_1	v_2	Passband gain VM	Passband gain TAM
LP	v_{in}	0	1	$1/R_3$
HP	0	v_{in}	1	$1/R_3$
AP	$-v_{in}$	v_{in}	1	$1/R_3$

2.2 Current mode and transimpedance mode

The input voltages are kept grounded ($v_1 = v_2 = 0$) while suitable current input signals are applied. The proposed circuit in Fig. 2 can be operated in CM and TIM, with the following transfer function:

$$i_{o(\mathrm{CM})} = \frac{(sR_1C_1+1)i_2+i_1}{D(s)}, \tag{5}$$

$$v_{o(\mathrm{TIM})} = (R_2)\left[\frac{(sR_1C_1+1)i_2+i_1}{D(s)}\right]. \tag{6}$$

From Eqns. (5) and (6), the LP, HP, and AP responses with the appropriate input signal selections are found as in Tab. 2.

Table 2. Input signal conditions and passband gains for CM and TIM filters in Fig. 2

Filtering function	i_1	i_2	Passband gain CM	Passband gain TIM
LP	i_{in}	0	1	R_2
HP	$-i_{in}$	i_{in}	1	R_2
AP	$-2i_{in}$	i_{in}	1	R_2

In all of the four operational modes, the pole frequency ω_p of the proposed filter in Fig. 2 can be determined as:

$$\omega_p = 2\pi f_p = \frac{1}{R_1C_1}. \tag{7}$$

Equations (2)-(6) indicate that the passband gains in VM and CM are found as unity. On the other hand, the passband gains in TAM and TIM are represented as $1/R_3$ and R_2, respectively. It can be further noted that the passband gain in both TAM and TIM can be independently controlled from the ω_p value.

2.3 Non-ideal analysis

Considering the β_i, α_i, and γ_i of the i-th CFOA (i = 1, 2, 3), the transfer functions of the proposed filter are modified as follows:

$$v'_{o(\mathrm{VM})} = (\gamma_1)\left[\frac{(sR_1C_1)v_2+(\beta_1\alpha_1)v_1}{D'(s)}\right], \tag{8}$$

$$i'_{o(\mathrm{TAM})} = \left(\frac{\beta_3\alpha_3\gamma_1}{R_3}\right)\left[\frac{(sR_1C_1)v_2+(\beta_1\alpha_1)v_1}{D'(s)}\right], \tag{9}$$

$$i'_{o(\mathrm{CM})} = \frac{(sR_1C_1+\beta_2\alpha_1)i_2+(\beta_2\alpha_2)i_1}{D'(s)}, \tag{10}$$

$$v'_{o(\mathrm{TIM})} = (\gamma_2R_2)\left[\frac{(sR_1C_1+\beta_2\alpha_1)i_2+(\beta_2\alpha_2)i_1}{D'(s)}\right], \tag{11}$$

$$D'(s) = sR_1C_1 + \beta_2\alpha_1. \tag{12}$$

From Eqns. (8)-(12), the pole frequency is also modified as:

$$\omega'_p = 2\pi f'_p = \frac{\beta_2\alpha_1}{R_1C_1}. \tag{13}$$

Based on the non-ideal parameters, it may be determined that the pole frequency of the proposed filter slightly deviates from the theoretical value. However, the resistor R_1 may be adjusted to cause the pole frequency to converge to the theoretical finding.

2.4 Effect of parasitic impedances

Figure 3 shows the CFOA with its parasitic impedances. By analyzing the filter in Fig. 2 while considering the parasitic impedances, the non-ideal pole frequency in this case was found as:

$$\omega''_p = 2\pi f''_p = \frac{R_{z1}+R_T}{R_{z1}R_TC_T}, \tag{14}$$

where $R_T = R_1 + R_{x1} + R_{x2}$ and $C_T = C_1 + C_{z1} + C_{z2}$. (15)

Therefore, by adopting the following component selections, it may considerably reduce the impact of parasitic elements:

$$R_1 \gg R_{x1} + R_{x2}$$
$$max\{R_1\} \ll R_{z1}$$
$$C_1 >> (C_{z1} + C_{y2}) \quad (16)$$

Additionally, the presence of these parasitic elements has reduced the effective frequency range of the filter by introducing two undesirable dominant poles. The following non-ideal pole frequencies of the proposed filter are described as follows:

$$\omega_1 = \frac{1}{(R_{z1}//R_T)C_T}, \quad (17)$$

$$\omega_2 = \frac{1}{R_{w1}C_{y3}} \quad (18)$$

The filter circuit should operate at a frequency between ω_1 and ω_2 in order to obtain a proper frequency operation. Consequently, the following condition for the useful frequency operation of the proposed filter circuit was established as follows:

$$\omega_1 << \omega << \omega_2 \quad (19)$$

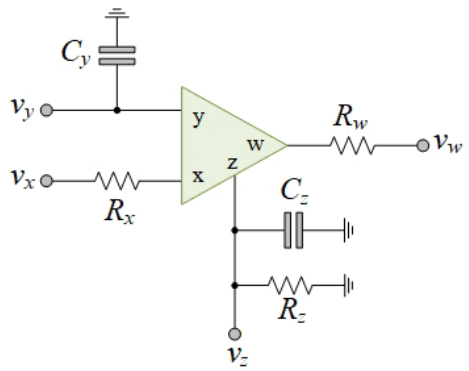


Fig. 3. Equivalent circuit of the CFOA including its parasitic elements

2.5 Sensitivity analysis

The sensitivity performance of the proposed mixed-mode first-order universal filter was also investigated. The active and passive sensitivities of the pole frequency with respect to active and passive components can be obtained as:

$$S_{R_1}^{\omega_p'} = S_{C_1}^{\omega_p'} = -1, S_{R_2}^{\omega_p'} = S_{R_3}^{\omega_p'} = 0, \quad (20)$$

$$S_{\beta_2}^{\omega_p'} = S_{\alpha_1}^{\omega_p'} = 1, \quad (21)$$

and $$S_{\beta_1}^{\omega_p'} = S_{\beta_3}^{\omega_p'} = S_{\alpha_2}^{\omega_p'} = S_{\alpha_3}^{\omega_p'} = 0. \quad (22)$$

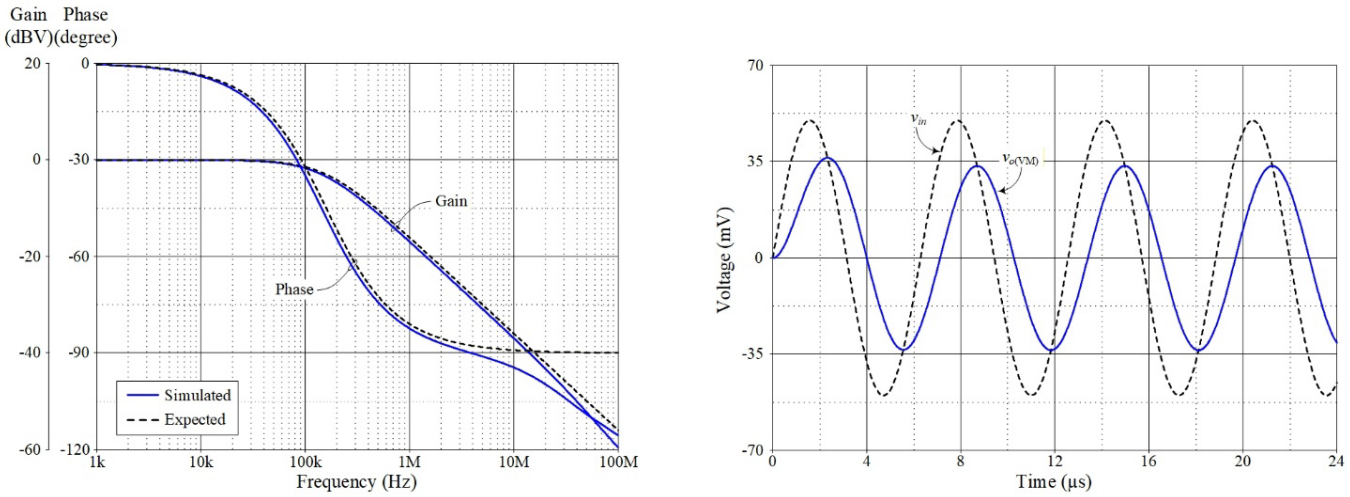
It can be observed that all sensitivities are not greater than unity in magnitude. Hence, the proposed filter exhibits low sensitivity performance with respect to both the CFOA non-ideal tracking parameters and the passive components.

3 Simulation verifications

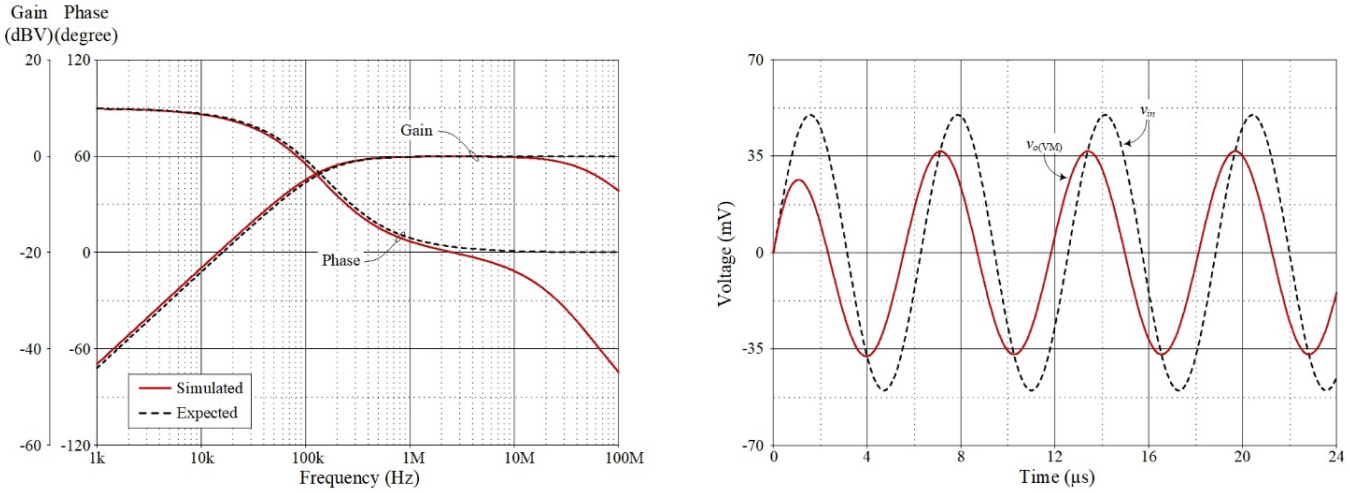
To verify the performance of the proposed filter in Fig. 2, PSPICE simulation using a AD844 macro model provided by Analog Devices was performed [40]. The supply voltages were set as ±5 V.

The expected and simulated results of the proposed filter in VM, TAM, CM, and TIM are shown in Figs. 4-7, respectively. The results were simulated using $R_1 = R_2 = R_3 = 1$ kΩ and $C_1 = 1$ nF. Under these component values, the pole frequency of $f_p = 159.15$ kHz is obtained. The simulated total power consumption of the circuit was determined to be 0.186 W.

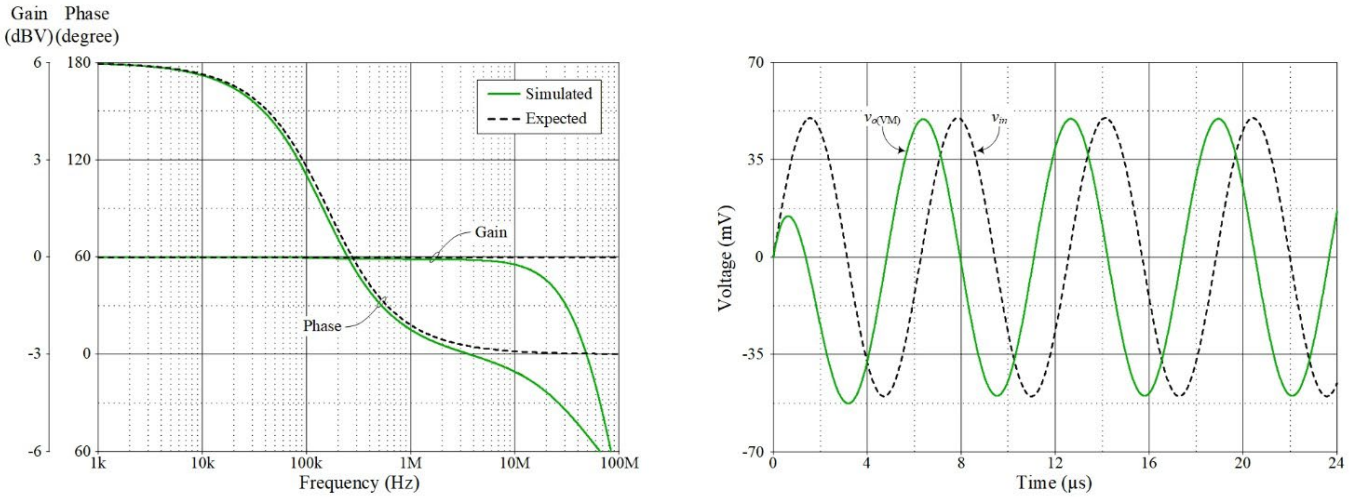
Figure 8 shows the proposed VM filter, which operates with the ambient temperature varying between –40 °C and 80 °C. Figure 9 presents the results of a Monte Carlo (MC) analysis of the VM AP filter with a 5% tolerance for all passive components. The analysis indicates that a low sensitivity to random variations in component values, yielding a mean frequency of 143.14 kHz and a standard deviation of 5.92 kHz, in contrast to a nominal pole frequency of 159.15 kHz. Figure 10 shows the tunability property of the pole frequency when R_1 is varied from 4 kΩ to 2 kΩ and then to 0.5 kΩ. In this configuration, the measured pole frequencies are 38.74 kHz, 75.57 kHz, and 263.28 kHz, compared to the theoretical values of 39.79 kHz, 79.58 kHz, and 318.31 kHz, respectively. As indicated in Tab. 3, the pole frequency can be independently tuned by adjusting R_1. The deviation observed at lower R_1 values can be primarily attributed to the internal parasitic resistances R_{x1} and R_{x2} of the CFOAs. According to Eqn. (16), the selection of an external resistance such that $R_1 >> R_{x1} + R_{x2}$ effectively minimizes this error.



(a)

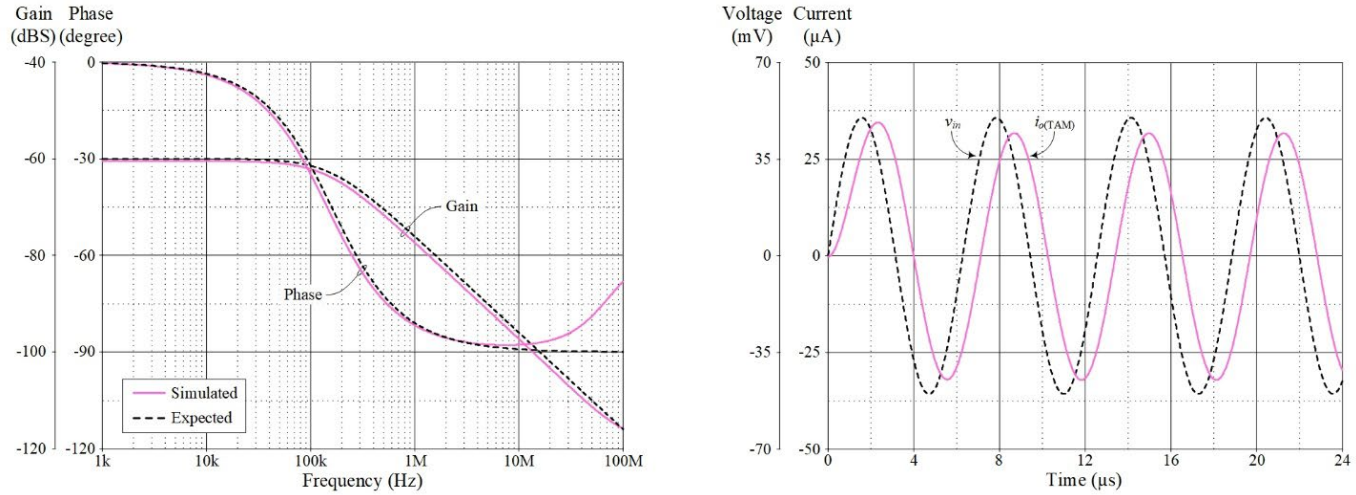


(b)

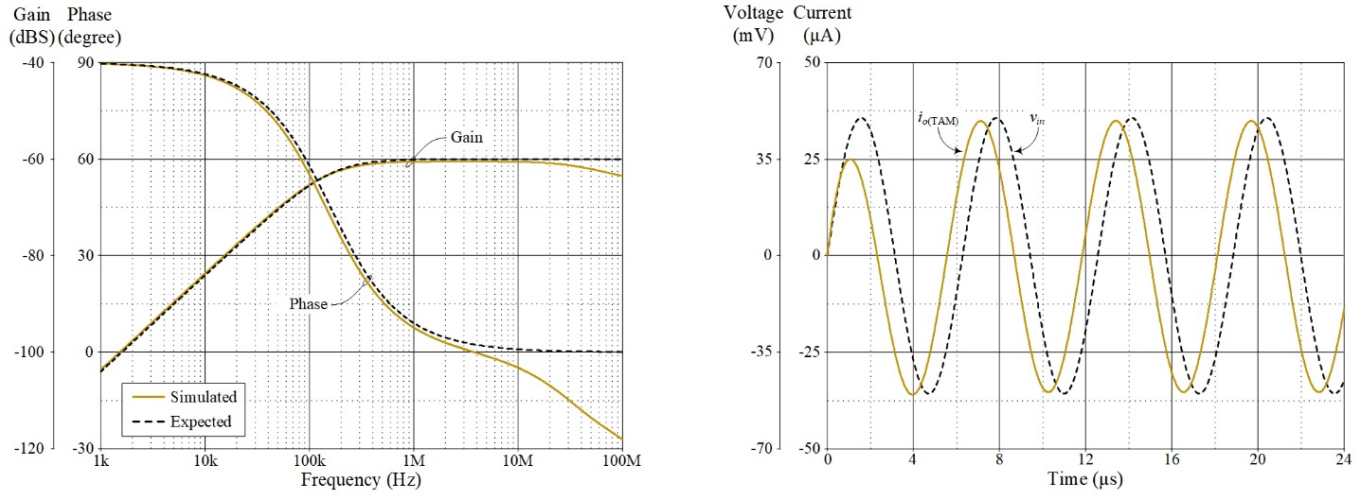


(c)

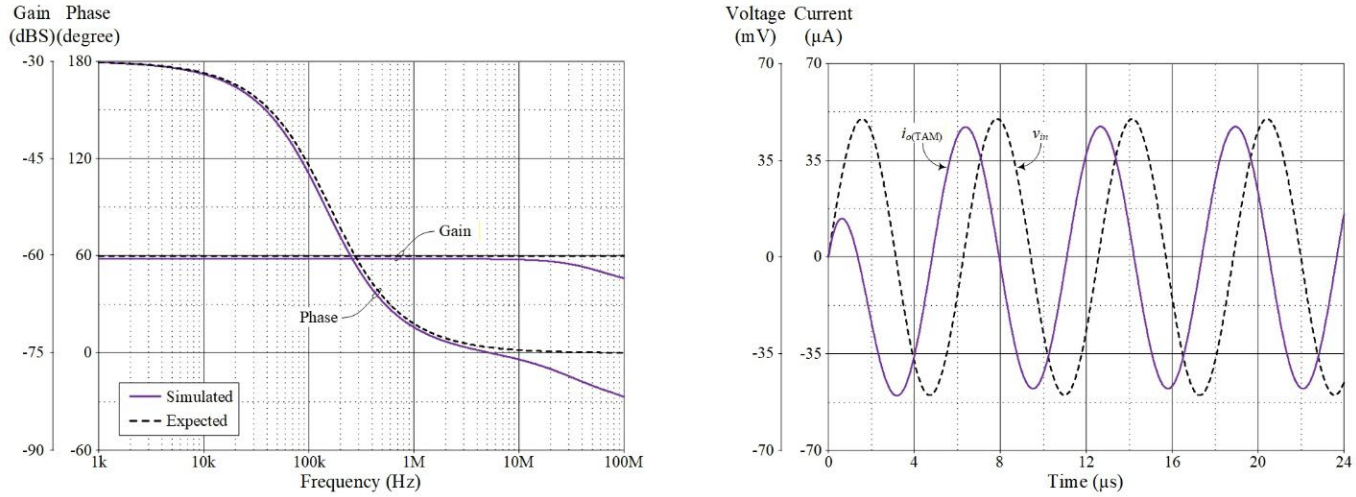
Fig. 4. Frequency- and time-domain responses of the proposed filter in VM: (a) LP; (b) HP; (c) AP



(a)

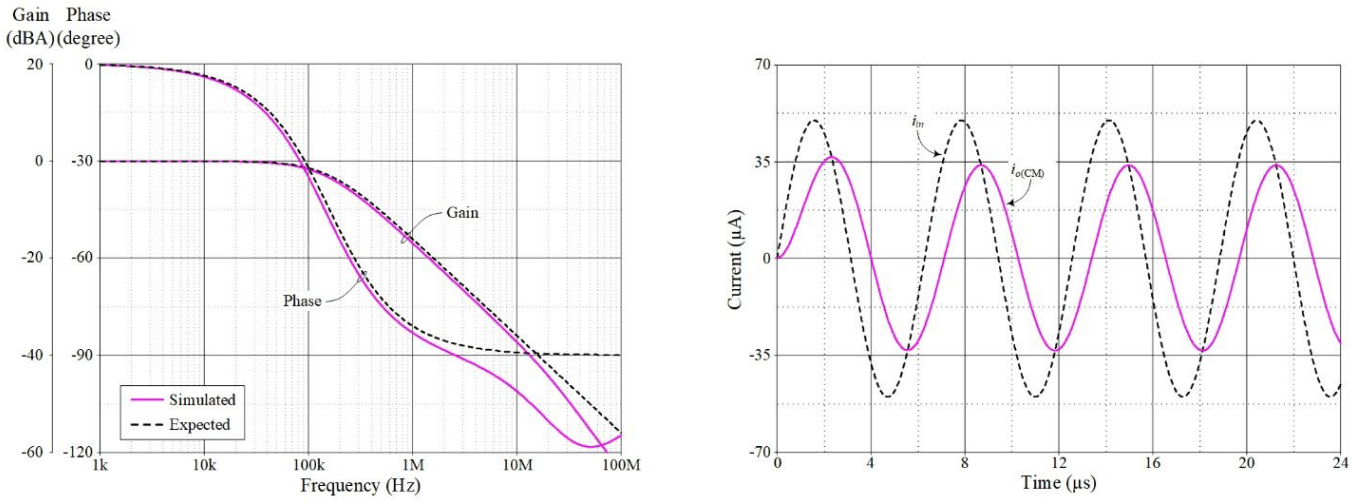


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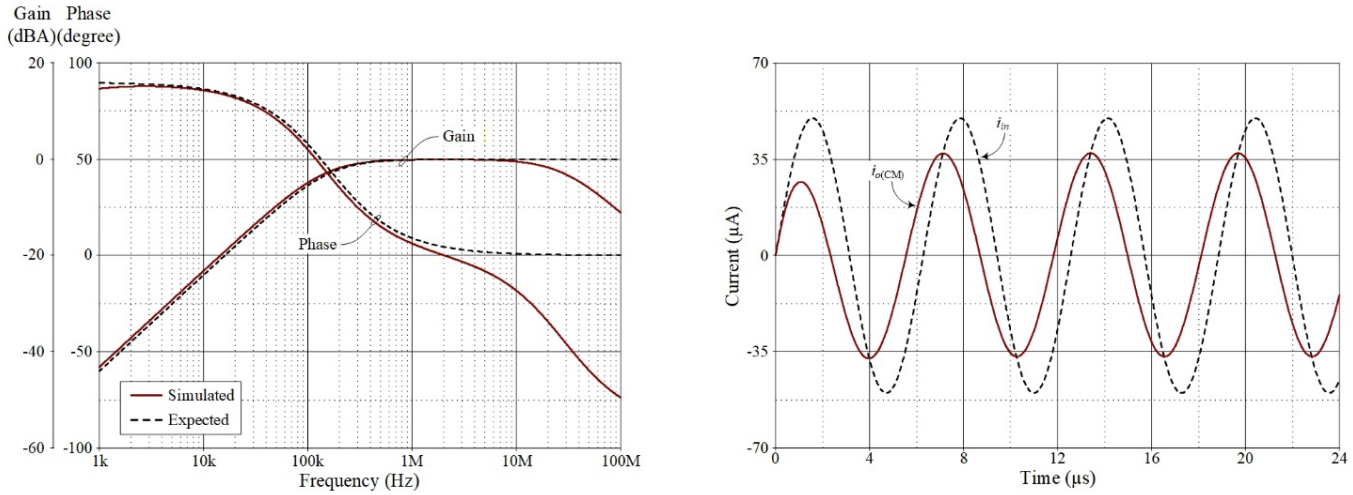


(c)

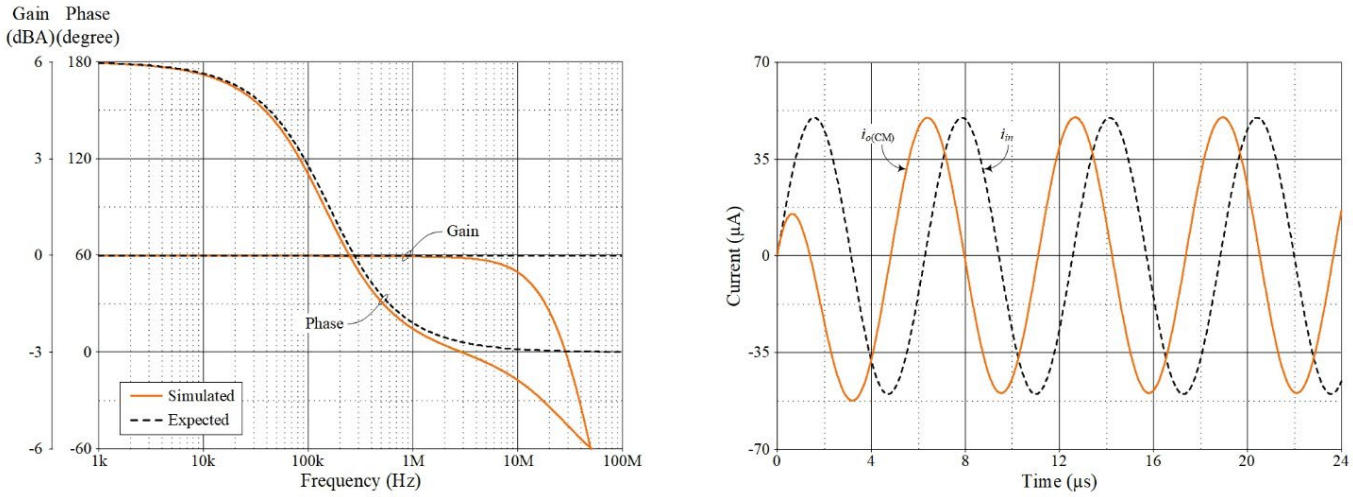
Fig. 5. Frequency- and time-domain responses of the proposed filter in TAM: (a) LP; (b) HP; (c) AP



(a)

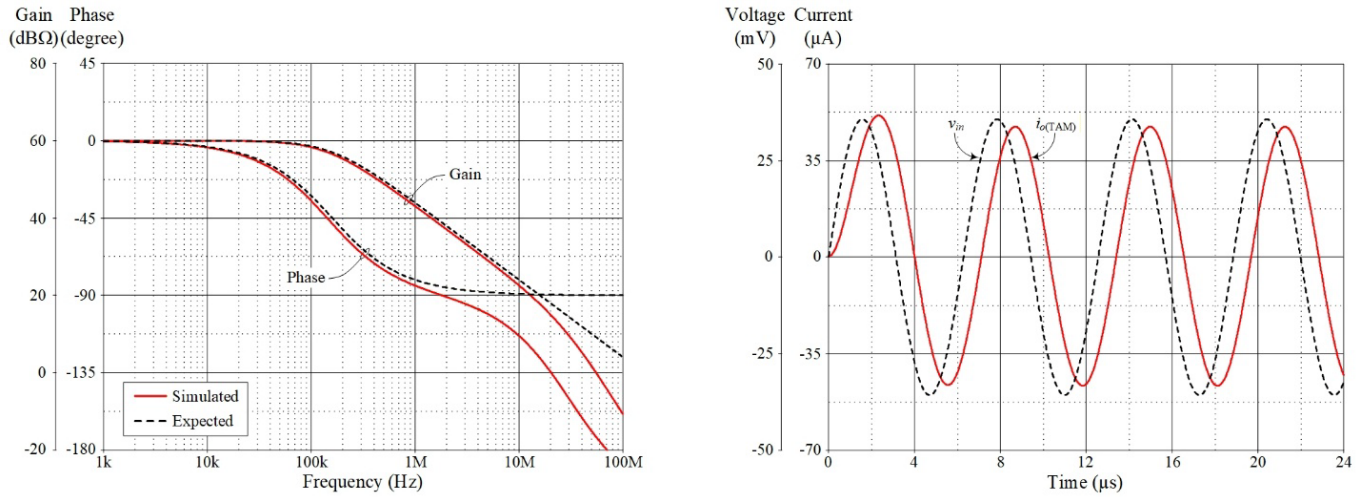


(b)

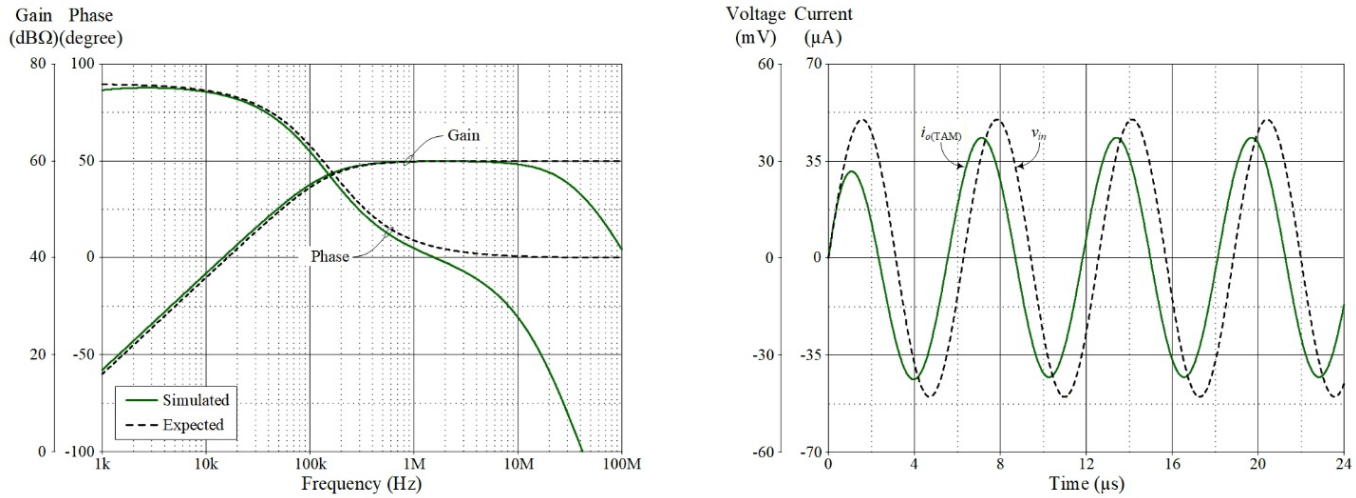


(c)

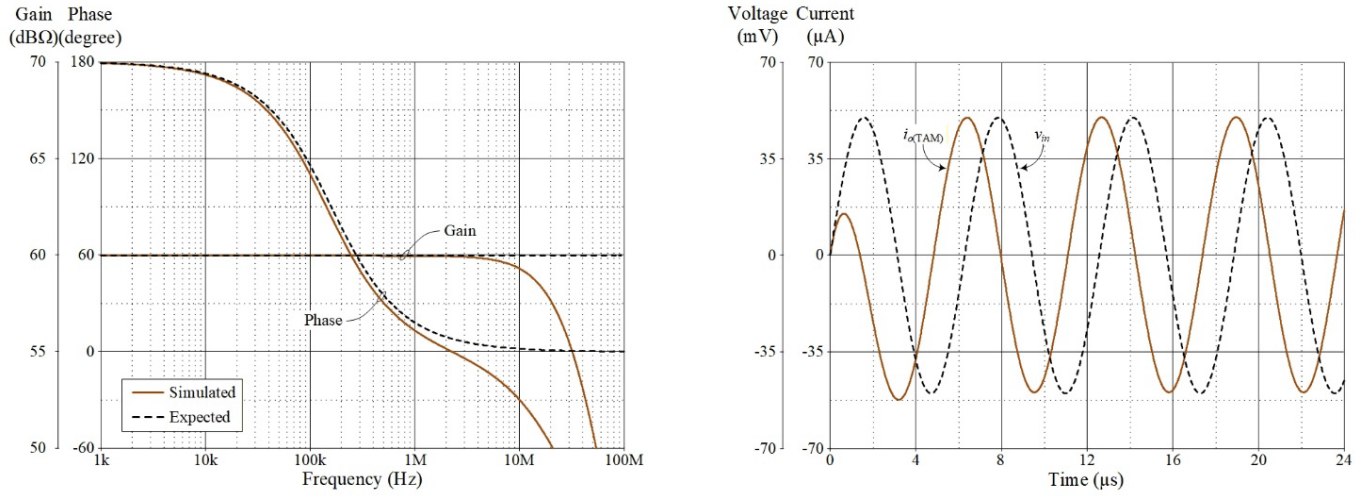
Fig. 6. Frequency- and time-domain responses of the proposed filter in CM: (a) LP; (b) HP; (c) AP.



(a)



(b)



(c)

Fig. 7. Frequency- and time-domain responses of the proposed filter in TIM: (a) LP; (b) HP; (c) AP.

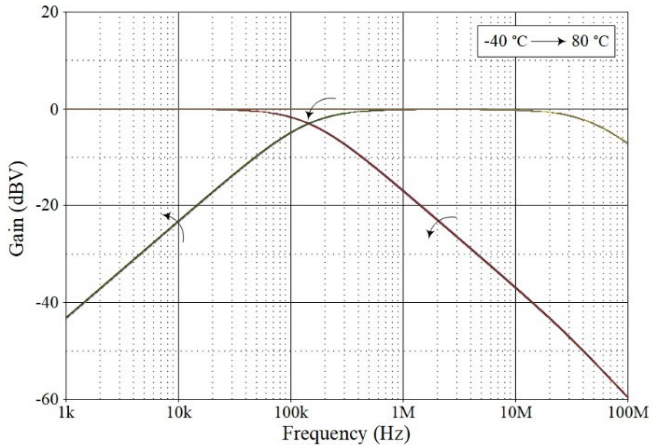


Fig. 8. Frequency-domain responses of the proposed VM filter at temperatures between –40 °C and 80 °C

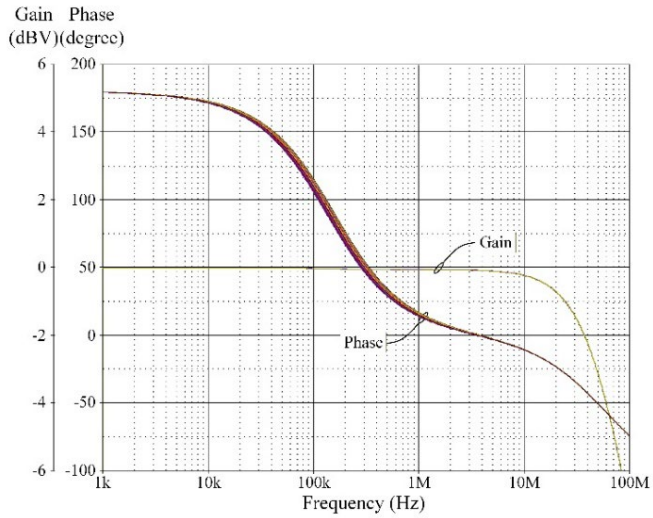


Fig. 9. Monte-Carlo analysis of the proposed VM AP

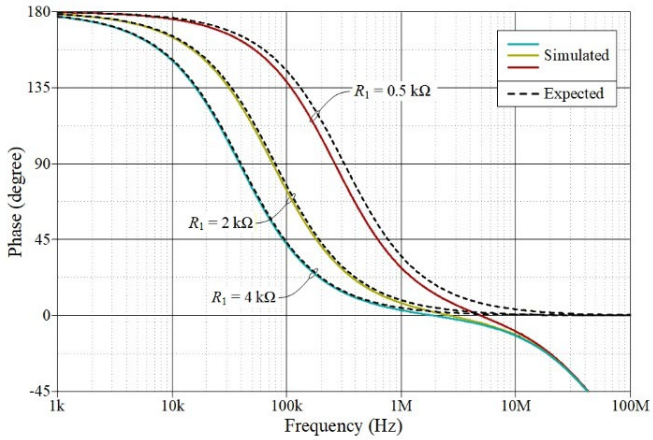


Fig. 10. Tunability of f_p for the proposed VM AP

Table 3. Theoretical and simulated values of pole frequency f_p recorded from Fig. 10

R_1 (kΩ)	Theoretical f_p (kHz)	Simulated f_p (kHz)	Error (%)
0.5	263.28	318.31	20.9
2	75.57	79.58	5.31
4	38.74	39.79	2.71

4 Application to quadrature oscillator

The quadrature oscillator (QO) shown in Fig. 11 has been designed using the proposed filter in Fig. 2. The characteristic function of the suggested QO equation can be expressed as:

$$s^2 + s\left(\frac{1}{R_1C_1} - \frac{1}{R_{o1}C_{o1}}\right) + \frac{1}{R_1R_{o2}C_1C_{o2}} = 0, \quad (23)$$

where the oscillation condition (OC) and the oscillation frequency (OF) are derived by:

$$\text{OC:} \quad \frac{1}{R_1C_1} = \frac{1}{R_{o1}C_{o1}}, \quad (24)$$

$$\text{OF:} \omega_{osc} = 2\pi f_{osc} = \frac{1}{\sqrt{R_1R_{o2}C_1C_{o2}}}. \quad (25)$$

Moreover, the relationship between the two quadrature output voltages (v_{oc1} and v_{oc2}) is given by

$$v_{oc1} = (sR_{o1}C_{o1})v_{oc2}. \quad (26)$$

The component values used in the simulation are $R_1 = R_2 = R_3 = R_{o1} = R_{o2} = 1$ kΩ, $C_1 = C_{o1} = C_{o2} = 1$ nF. Thus, the output waveforms of the suggested QO are shown in Fig. 12. The simulated waveforms exhibit a phase difference of 89.43°, which is close to the expected 90°.

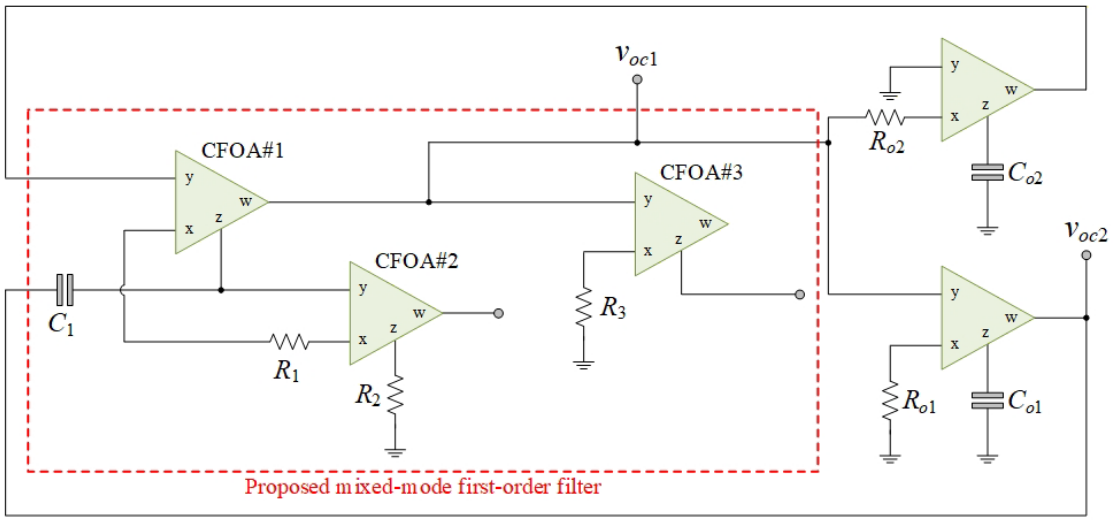


Fig. 11. Quadrature oscillator realization using the proposed VM filter

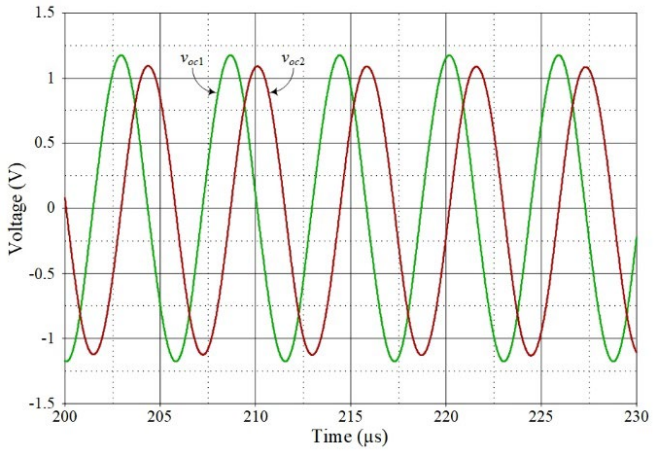


Fig. 12. Output waveforms of the QO in Fig. 11

5 Conclusions

This paper has proposed a mixed-mode first-order universal filter using three CFOAs, three resistors, and one capacitor. The proposed filter is capable of functioning as lowpass, highpass, or allpass filters responses in all possible modes: voltage mode (VM), transadmittance mode (TAM), current mode (CM), and transimpedance mode (TIM), all without modifying its structure. The pole frequency ω_p can be adjusted using a single resistor. Additionally, the passband gains in both TAM and TIM are independently controlled from the ω_p value through a single resistor. The non-ideal and sensitivity analyses of the proposed filter are also determined. The performance and theoretical validity of the proposed filter were verified through PSPICE simulations. The applicability of the proposed filter was demonstrated through a quadrature oscillator design. Future work will involve hardware prototyping to confirm the physical viability of the design. Future work will focus on implementing a simple breadboard or PCB design and conducting experimental hardware testing to further validate the proposed filter design.

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