Research Article

CDBA-Based Universal Biquad Filter and Quadrature Oscillator

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The voltage-mode universal biquadratic filter and sinusoidal quadrature oscillator based on the use of current differencing buffered amplifiers (CDBAs) as active components have been proposed in this paper. All the proposed configurations employ only two CDBAs and six passive components. The first proposed CDBA-based biquad configuration can realize all the standard types of the biquadratic functions, that is, lowpass, bandpass, highpass, bandstop, and allpass, from the same topology, and can also provide orthogonal tuning of the natural angular frequency (ω_o) and the bandwidth (BW) through separate virtually grounded passive components. By slight modification of the first proposed configuration, the new CDBA-based sinusoidal quadrature oscillator is easily obtained. The oscillation condition and the oscillation frequency are independently adjustable by different virtually grounded resistors. The sensitivity analysis of all proposed circuit configurations is shown to be low. PSPICE simulations and experimental results based upon commercially available AD844-type CFAs are included, which confirm the workability of the proposed circuits.

1. INTRODUCTION

Current-mode universal active components have two distinct advantages: they provide wide bandwidths and high slew rate. On the other hand, many of today's analog signal processing applications require voltage-mode operation. Therefore, it is advantageous to implement current-mode active elements in voltage-mode circuits [1].

Recently, a current differencing buffered amplifier (CDBA) that is one of the current-mode components has been introduced [2]. It can offer advantageously features such as high slew rate, free from parasitic capacitance, wide bandwidth, and simple implementation [3]. Since the CDBA consists of a unity-gain current differential amplifier and a unity-gain voltage amplifier, this element would be suitable for the implementation of voltage and current-mode signal processing applications. As far as the applications of the CDBA are concerned, various voltage-mode filters [2, 4–8] and oscillators [1, 9, 10] have been reported in literature. Only few can perform both biquadratic filter and oscillator in the same circuit configuration [1]. However, it is restricted for only bandpass filter function design and cannot be realized by another type of the standard biquadratic function

characteristics. Moreover, it generates a single-phase output voltage when it performs as a sinusoidal oscillator. There is no CDBA-based circuit configuration, which can realize the universal biquad filter and quadrature oscillator both in the same circuit configuration.

Thus, the voltage-mode universal biquadratic filter and sinusoidal quadrature oscillator using two CDBAs, four virtually grounded resistors, and two capacitors are described in this paper. The first proposed CDBA-based biquad filter can realize lowpass (LP), bandpass (BP), highpass (HP), bandstop (BS), and allpass (AP) biquadratic functions without changing the circuit topology. The filter also provides an orthogonal control of the natural angular frequency (ω_o) and the bandwidth (BW). Moreover, a CDBA-based sinusoidal quadrature oscillator circuit can be realized by slightly modifying the first proposed CDBAs-based circuit configuration. All passive components used in the circuit realization are really and virtually grounded, which is insensitive to the effects of the stray capacitance. The oscillation condition and the frequency of oscillation can be controlled independently through different virtually grounded resistors. In addition, the sensitivity analysis shows that all of the proposed circuits have low-sensitivity performance. PSPICE simulation
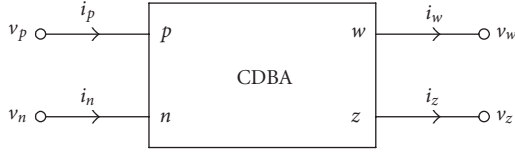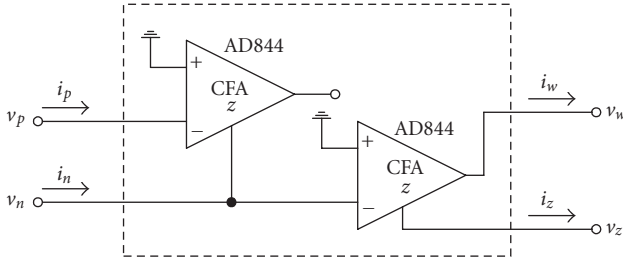
FIGURE 1: CDBA symbol.

FIGURE 2: Implementation of CDBA using two CFAs (AD844s).

and experimental results using commercially available active component AD844 are also included to verify the theoretical analysis.

2. CURRENT DIFFERENCING BUFFERED AMPLIFIER (CDBA)

The circuit symbol of the CDBA is shown in Figure 1, where p and n are the positive and negative current input terminals, respectively, z is the current output terminal, and w is the voltage output terminal. Its current and voltage characteristics can be described by the following matrix equations [1, 2]:

$$
\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix}.
\tag{1}
$$

According to the above set of describing equations, the terminal z behaves as a current source that takes the difference of currents at the inputs, and the terminal w behaves as a voltage source that copies the output voltage at the z terminal. Thus, the CDBA can be considered as a collection of a noninverting and an inverting current-mode, and noninverting voltage-mode unity-gain cells, which can be realized by a cascade connection of a current substractor and a voltage follower. Although the CDBA can be realized by using several well-known circuit techniques, one possible practical implementation is given in Figure 2 [4, 11].

3. PROPOSED CDBA-BASED UNIVERSAL BIQUAD

Figure 3 shows the proposed voltage-mode universal biquadratic filter, which consists of only two CDBAs, four virtual-grounded resistors, and two capacitors. By straight-
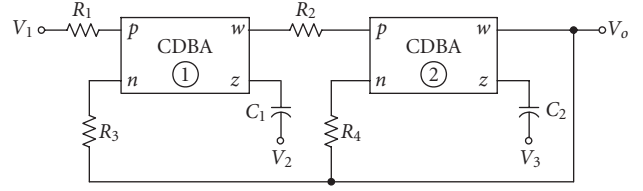

FIGURE 3: Proposed CDBA-based universal biquad filter.

forward analysis, the single output voltage function realized by this configuration is found to be

$$
V_o = \frac{s^2 V_3 + (s/R_2 C_2) V_2 + (1/R_1 R_2 C_1 C_2) V_1}{s^2 + (s/R_4 C_2) + (1/R_3 R_2 C_1 C_2)}.
\tag{2}
$$

From (2), by choosing the component values of $R_1 = R_3$ and $R_2 = R_4$, we can see that

1. if $V_1 = V_{in}$ (an input voltage signal), and $V_2 = V_3 = 0$ (grounded), the LP response can be realized with the passband gain $H_{LP} = 1$;
2. if $V_2 = V_{in}$ and $V_1 = V_3 = 0$, the BP response can be realized with the passband gain $H_{BP} = 1$;
3. if $V_3 = V_{in}$ and $V_1 = V_2 = 0$, the HP response can be realized with the passband gain $H_{HP} = 1$;
4. if $V_1 = V_3 = V_{in}$ and $V_2 = 0$, the BS response can be realized with the passband gain $H_{BS} = 1$;
5. if $V_1 = -V_2 = V_3 = V_{in}$, the AP response can be realized with the passband gain $H_{AP} = 1$.

Clearly, the proposed filter can be used as a voltage-mode three-input single-input universal filter that can realize all the standard types of the biquad filter functions.

Also from (2), the natural angular frequency (ω_o), the bandwidth (BW), and the quality factor (Q) in all cases are given by

$$
\begin{aligned}
\omega_o &= \frac{1}{\sqrt{R_A R_B C_1 C_2}}, \\
BW &= \frac{1}{R_B C_2}, \\
Q &= \sqrt{\frac{R_B C_2}{R_A C_1}},
\end{aligned}
\tag{3}
$$

where $R_A = R_1 = R_3$ and $R_B = R_2 = R_4$. Note that the filter parameters ω_o and BW are adjustable properly by the virtual-grounded resistor R_A or the capacitor C_1, and by the virtual-grounded resistor R_B or the capacitor C_2, in that order.

Taking the nonidealities of the CDBA into account, the relationship of the terminal currents and voltages given in (1) can be rewritten as

$$
\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & \alpha_p & -\alpha_n \\ \beta & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix},
\tag{4}
$$

where $\alpha_p = 1 - \varepsilon_p$ and $\varepsilon_p (|\varepsilon_p| \ll 1)$ is the current-tracking error from p terminal to z terminal, $\alpha_n = 1 - \varepsilon_n$

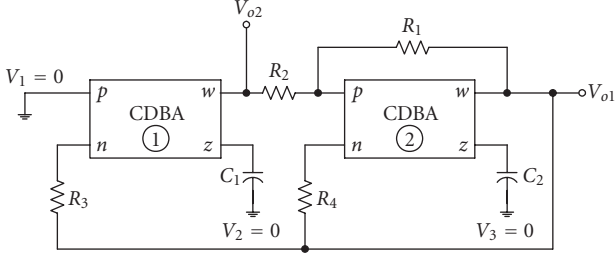FIGURE 4: Proposed CDBA-based sinusoidal quadrature oscillator.

FIGURE 5: Frequency characteristics for LP, BP, and HP responses of the proposed circuit of Figure 3.

and ε_n ($|\varepsilon_n| \ll 1$) is the current-tracking error from n terminal to z terminal, and $\beta = 1 - \varepsilon_v$ and ε_v ($|\varepsilon_v| \ll 1$) is the voltage-tracking error from z terminal to w terminal of the CDBA. Therefore, including these nonidealities into the voltage transfer function, the modified filter parameters are derived as

$$H_{\text{LP}} = \frac{\alpha_{p1}}{\alpha_{n1}}, \qquad H_{\text{BP}} = \frac{\alpha_{p2}\beta_1}{\alpha_{n2}}, \qquad H_{\text{HP}} = \beta_2,$$

$$\omega_o = \sqrt{\frac{\alpha_{p2}\alpha_{n1}\beta_1\beta_2}{R_A R_B C_1 C_2}},$$

$$\text{BW} = \frac{\alpha_{n2}\beta_2}{R_B C_2},$$

$$Q = \frac{1}{\alpha_{n2}}\sqrt{\frac{\alpha_{p2}\alpha_{n1}\beta_1 R_B C_2}{\beta_2 R_A C_1}},$$

(5)

where α_{pi}, α_{ni}, and β_i are the parameters α_p, α_n, and β of the ith CDBA ($i = 1, 2$).

The active and passive sensitivities of this universal filter are shown as follows:

$$S_{\alpha_{p1}}^{H_{\text{LP}}} = -S_{\alpha_{n1}}^{H_{\text{LP}}} = 1, \qquad S_{\alpha_{p2}}^{H_{\text{BP}}} = -S_{\alpha_{n2}}^{H_{\text{BP}}} = S_{\beta_1}^{H_{\text{BP}}} = 1, \qquad S_{\beta_2}^{H_{\text{HP}}} = 1,$$

$$S_{\alpha_{p2}}^{\omega_o} = S_{\alpha_{n1}}^{\omega_o} = S_{\beta_1}^{\omega_o} = S_{\beta_2}^{\omega_o} = \frac{1}{2},$$

$$S_{\alpha_{n2}}^{\text{BW}} = S_{\beta_2}^{\text{BW}} = 1,$$

$$S_{\alpha_{p2}}^{Q} = S_{\alpha_{n1}}^{Q} = S_{\beta_1}^{Q} = -S_{\beta_2}^{Q} = \frac{1}{2}, \qquad S_{\alpha_{n2}}^{Q} = -1,$$

$$S_{R_1}^{\omega_o} = S_{R_2}^{\omega_o} = S_{R_3}^{\omega_o} = S_{R_4}^{\omega_o} = S_{C_1}^{\omega_o} = S_{C_2}^{\omega_o} = -\frac{1}{2},$$

$$S_{R_2}^{\text{BW}} = S_{R_4}^{\text{BW}} = S_{C_2}^{\text{BW}} = -1,$$

$$S_{R_1}^{Q} = -S_{R_2}^{Q} = S_{R_3}^{Q} = -S_{R_4}^{Q} = S_{C_1}^{Q} = -S_{C_2}^{Q} = -1.$$

(6)

It is clearly observed from (6) that all of the sensitivities are low.

4. PROPOSED CDBA-BASED QUADRATURE OSCILLATOR

From the first configuration of Figure 3, by setting $V_1 = V_2 = V_3 = 0$ V (grounded) and connecting the resistor R_1 between the t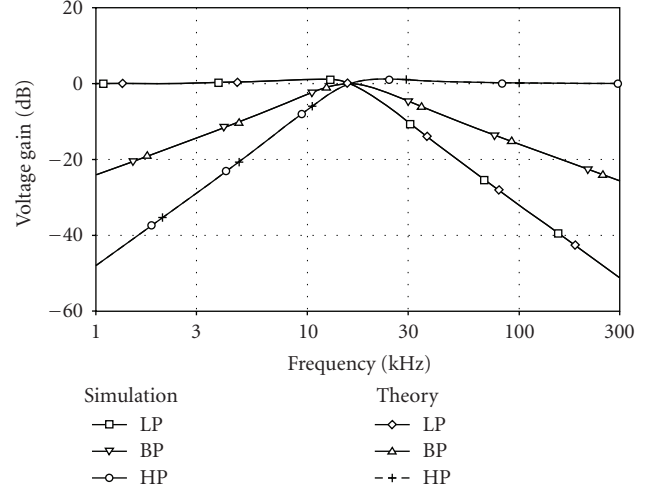erminals p and w of the CDBA2, the second proposed CDBA-based sinusoidal quadrature oscillator can be obtained as shown in Figure 4. In this case, the characteristic equation of the second proposed configuration can be given by

$$s^2 C_1 C_2 + s C_1 \left(\frac{1}{R_4} - \frac{1}{R_1}\right) + \left(\frac{1}{R_2 R_3}\right) = 0. \qquad (7)$$

The oscillation condition and the oscillation frequency (ω_o) of this configuration can be obtained, respectively, as

$$R_1 = R_4,$$

$$\omega_o = \frac{1}{\sqrt{R_2 R_3 C_1 C_2}}. \qquad (8)$$

Note from (8) that the oscillation condition of the proposed oscillator of Figure 4 can be adjusted by R_1 or/and R_4 without affecting the oscillation frequency ω_o. The ω_o can be adjusted by R_2 or/and R_3. Therefore, the oscillation condition and the oscillation frequency of the proposed oscillator circuit can be controlled independently.

From the configuration of Figure 4, the relationship between two quadrature output voltages V_{o1} and V_{o2} can be expressed as

$$\frac{V_{o2}}{V_{o1}} = -\frac{1}{s R_3 C_1}, \qquad (9)$$

where the phase shift is $\phi = 90°$. This guarantees that the proposed oscillator circuit provides the quadrature outputs V_{o1} and V_{o2}.

Taking into account the nonideal CDBAs in Figure 4, the characteristic equation becomes

$$s^2 C_1 C_2 + s C_1 \beta_2 \left(\frac{\alpha_{n2}}{R_4} - \frac{\alpha_{p2}}{R_1}\right) + \left(\frac{\alpha_{p2}\alpha_{n1}\beta_1\beta_2}{R_2 R_3}\right) = 0. \qquad (10)$$
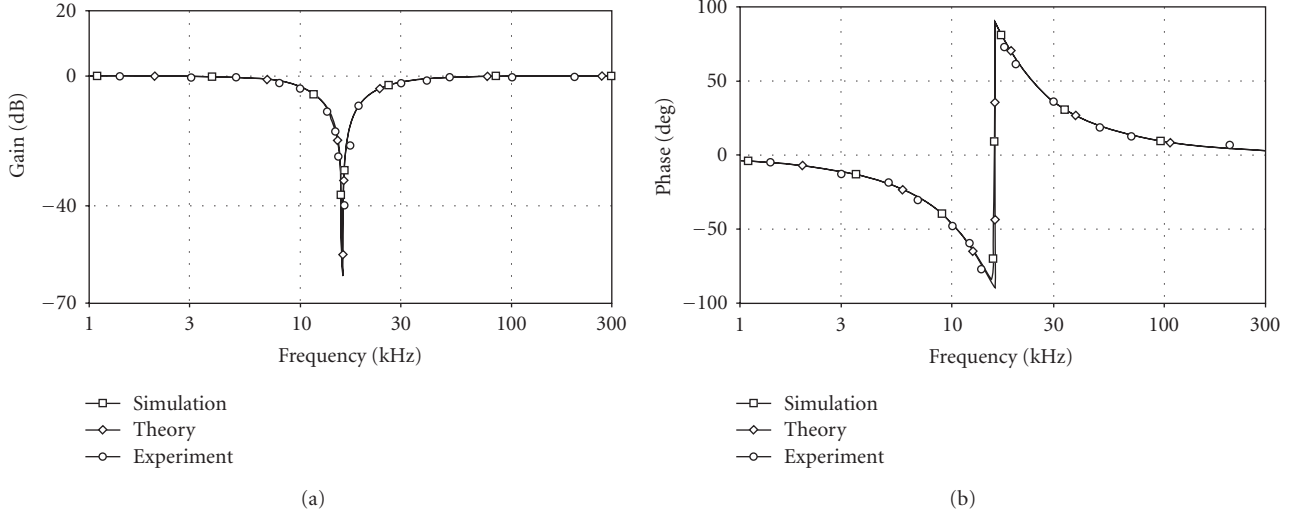
(a)

(b)

Figure 6: Frequency responses of the BS filter, (a) gain response and (b) phase response.
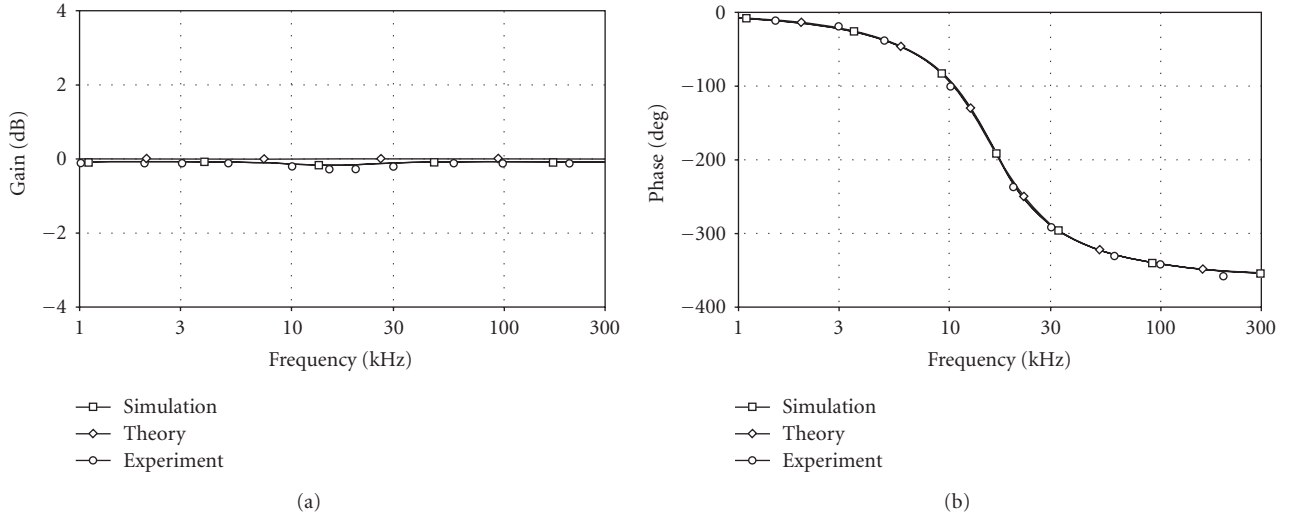

(a)

(b)

Figure 7: Frequency responses of the AP filter, (a) gain response and (b) phase response.

The modified oscillation condition and the oscillation frequency (ω_o) in this case are obtained as

$$\alpha_{n2}R_1 = \alpha_{p2}R_4, \tag{11}$$

$$\omega_o = \sqrt{\frac{\alpha_{p2}\alpha_{n1}\beta_1\beta_2}{R_2R_3C_1C_2}}. \tag{12}$$

It should be noted from (11) and (12) that the oscillation condition and ω_o of the proposed quadrature oscillator are altered slightly by the effects of the CDBA current- and voltage-tracking errors. However, they can still be controlled independently.

Sensitivities calculated from (12) using relative sensitivity formula are obtained as

$$\begin{aligned} S^{\omega_o}_{\alpha_{p2}} = S^{\omega_o}_{\alpha_{n1}} = S^{\omega_o}_{\beta_1} = S^{\omega_o}_{\beta_2} = \frac{1}{2}, \\ S^{\omega_o}_{R_2} = S^{\omega_o}_{R_3} = S^{\omega_o}_{C_1} = S^{\omega_o}_{C_2} = -\frac{1}{2}. \end{aligned} \tag{13}$$

The circuit has optimum sensitivity performance in the sense that all values are equal to 0.5 in magnitude.

5. SIMULATION AND EXPERIMENTAL RESULTS

In order to confirm the theoretical analysis, all the proposed circuits given in Figures 3 and 4 have been simulated using the PSPICE program. In simulations, the CDBA circuit was constructed with two AD844 ICs of analog devices, as shown in Figure 2. The model parameters of AD844 were taken from the built-in library (AD844/AD), and the supply voltages were taken as ±12 V. Theoretical analysis and simulation results were also verified by experimental testing. For the experiments, the proposed circuits were constructed in laboratory using commercially available current feedback amplifier (CFA) AD844 ICs with the same components used in simulation.
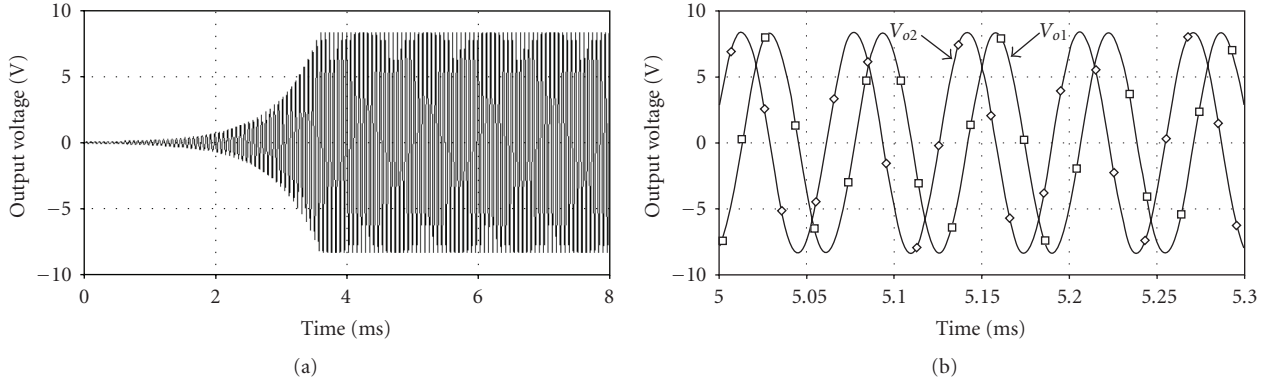
(a)

(b)

FIGURE 8: Simulated output waveforms V_{o1} and V_{o2} of the proposed oscillator of Figure 4, (a) at transient stage and (b) at steady stage.
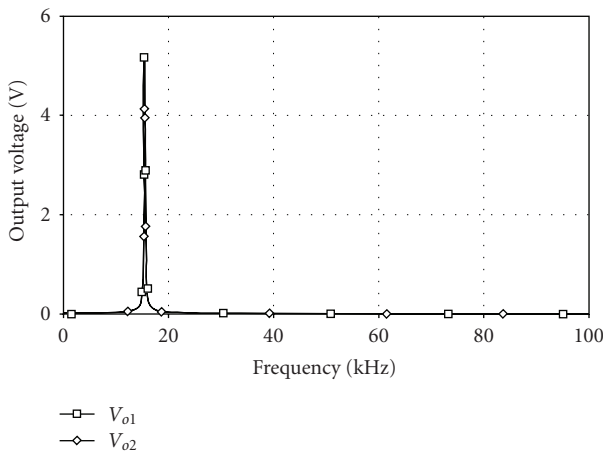

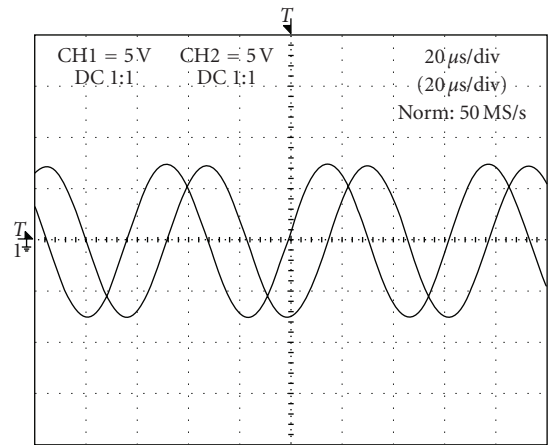FIGURE 9: Simulated frequency spectrums of the proposed oscillator of Figure 4.

FIGURE 10: Experimental output waveforms V_{o1} and V_{o2} of the proposed oscillator of Figure 4.

Figure 5 shows the simulated frequency characteristics for the LP, BP, and HP filter functions of the proposed CDBA-based multifunction biquad circuit in Figure 3 with the theory frequency responses. The passive component values were chosen as $R_1 = R_2 = R_3 = R_4 = 10\,k\Omega$ and $C_1 = C_2 = 1\,nF$, which is designed to obtain a universal filter with a natural angular frequency of $f_o = \omega_o/2\pi \cong 15.91\,kHz$ and the quality factor of $Q = 1$. With the same setting, the simulation and experimental results for the gain and phase responses of the BS and AP filters verifying theory values are, respectively, depicted in Figures 6 and 7. It appears from all figures that the simulation and experimental results are in excellent agreement with the theoretical values.

As an example to demonstrate the workability of the proposed CDBA-based quadrature oscillator circuit in Figure 4, the following passive component values were chosen as $R_1 = R_2 = R_3 = 10\,k\Omega$ and $C_1 = C_2 = 1\,nF$. The simulated quadrature output waveforms V_{o1} and V_{o2} of the oscillator are illustrated in Figure 8, where the value of $R_4 \cong 10.5\,k\Omega$ was chosen to be slightly larger than R_1 to ensure that the oscillations will start. The simulated frequency was measured as 15.37 kHz, which is lower than the theoretical value of

15.91 kHz, owing to the parasitic elements R_x, z, and C_z of the AD844 [12, 13]. Figure 9 shows the simulated frequency spectrums of the quadrature outputs, giving the total harmonic distortion (THD) less than 2.95%. The results of the THD analysis obtained from the simulations are summarized in Table 1.

Figure 10 shows the experimental output waveforms V_{o1} and V_{o2} of Figure 4, and the oscillation frequency f_o was measured as 15.52 kHz. The controllability of f_o through R_2 without influencing the oscillation condition is shown in Figure 11.

6. CONCLUSION

In this paper, a voltage-mode universal biquad filter using two CDBAs, four virtually grounded resistors, and two capacitors has been presented. By appropriately connecting input voltage terminals, the proposed CDBA-based biquadratic filter can realize all the standard types of the biquadratic filter functions. The filter permits orthogonal adjustment of the parameters ω_o and BW. Furthermore, a CDBA-based quadrature oscillator can be obtained easily by

TABLE 1: Total harmonic distortion analysis of the proposed CDBA-based quadrature oscillator of Figure 4.

Harmonic no.	Frequency (Hz)	Fourier component	Normalized component	Phase (Deg)	Normalized phase
1	1.592E + 04	8.264E + 00	1.000E + 00	1.232E + 02	0.000E + 00
2	3.183E + 04	2.023E − 01	2.447E − 02	1.357E + 02	1.249E + 01
3	4.775E + 04	9.652E − 02	1.168E − 02	1.680E + 02	4.563E + 01
4	6.366E + 04	6.915E − 02	8.368E − 03	1.418E + 02	1.854E + 01
5	7.958E + 04	1.405E − 02	1.701E − 03	−1.206E + 02	−2.438E + 02
	DC component = −1.699764E − 01				
	Total harmonic distortion = 2.948440E + 00 PERCENT				
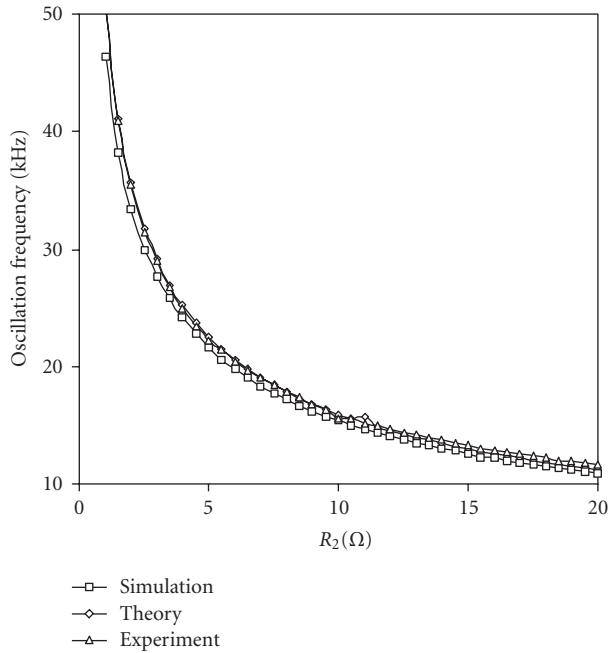
FIGURE 11: Variation of the oscillation frequency of Figure 4 obtained by varying the value of R_2.

slightly modifying the proposed CDBA-based biquad filter. Its oscillation condition and oscillation frequency can be controlled separately via different virtually grounded resistors. In addition, the sensitivities of all proposed circuits are shown to be low. It is shown that the simulation and experimental results conform very well to the theoretical conclusions.

ACKNOWLEDGMENTS

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