Single CDBA-Based Multifunction Filter Design
Tek CDBA Tabanlı Çok İşlevli Filtre Tasarımı

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***Abstract*— In this study, we proposed a second-order multifunction filter topology based on a current differencing buffered amplifier. With the proposed topology, five filter functions can be realized. Sensitivity and non-ideal state analyses of the proposed circuit have been performed. In addition to the proposed second-order multifunction filter topology, the third-order quadrature oscillator circuit was operated as the application circuit. In both circuits, the theoretical work and simulation results are in compliance. The proposed design has potential in the medical device design field.**

Keywords—analog integrated circuit, current differencing buffered amplifier, multifunction filter, oscillator.

***Özetçe*— Bu çalışmada, akım farkı tamponlu yükselticiye dayalı ikinci dereceden çok işlevli bir filtre topolojisi önerilmiştir. Önerilen topoloji ile beş filtre fonksiyonu gerçekleştirilebilir. Önerilen devrenin hassasiyet ve ideal olmayan durum analizleri yapılmıştır. Önerilen ikinci dereceden çok fonksiyonlu filtre topolojisine ek olarak, uygulama devresi olarak üçüncü dereceden dörtlü osilatör devresi çalıştırılmıştır. Her iki devrede de teorik çalışma ve simülasyon sonuçları uyum içindedir. Önerilen tasarım, tıbbi cihaz tasarımı alanında potansiyele sahiptir.**

Anahtar Kelimeler—analog tüm devre, akım farkı tampon yükselteç, çok fonksiyonlu süzgeç, osilatör.

I. Introduction

The operational amplifier (opamp) had a dominant function in the last centuries as an important active building block and there is a tremendous number of publications about the various circuit samples in the literature. Nonetheless, classical opamp-based devices show several disadvantages in their functioning performance resulting due to limited features, for example; slew rate ratio and bandwidth [1].

The universal active components which have current modes have two different advantages: they render wide bandwidths and a high-speed ratio. Then again, today's most analog signals work on applications that request the voltage mode style. Hence, it brings us advantageous, that using current-type active elements in the voltage mode circuits [2].

Lately, a Current Difference Buffered Amplifier (CDBA) has been introduced which is one of the existing mode components [3]. It has several advantages such as a high slew rate ratio, away from interference capacity, astray bandwidth, and simple application [4]. CDBA consists of both voltage and current differentials with a unity gain. So, this component is appropriate for the carrying out of both signal processing applications which are voltage and current modes.

In the literature, many applications based on CDBA were reported [5-18]. Also, several multifunction CDBA-based filters were presented in the literature. These filters can be assorted in four sections. One is; named single-input and single-output (SISO) [9, 14, 15] and the other is multi-input single-output (MISO) [10, 16, 17] and others are single input multi output (SIMO) and multi input multi output (MIMO) [11, 13, 18]. However, the filters which are used single active components are more useful due to the power dissipation. The single CDBA-based voltage mode structures which are proposed in the literature suffer from only a single filter response is contributed. Some of them don't have all filter types' responses which use only one CDBA. Some have large component propagation to achieve a high Q value, and the number of passive components is large as shown in Table 1.

The main contribution of this study is, realizing a single CDBA-based second-order multifunction filter topology with voltage mode and can realize five filter types.

II. Methods

A. Circuit Description of CDBA

The circuitry symbol of the CDBA is depicted in Fig. 1. The input terminals are represented by p and n terminals and the output terminals are w and z. As shown in Fig. 1, the difference of the currents from p and n terminals is called the output current and represented by z-terminal. The terminal p is noninverting and the terminal n is inverting terminal. The w terminal voltage is called output voltage because it follows the z terminal voltage. Input terminals are grounded internally so the input impedance of the p and n terminals is inwardly zero.

Table 1. Equivalence of the previously presented studies where LP is low-pass, HP is high-pass, BP is band-pass, BS is band-stop, and AP is all-pass.

<table>
<tr><th></th><th>CDBA</th><th>Filter Types</th><th>Filter Mode</th><th colspan="3">Resistor + Capacitor</th><th>Independent ω_0 and Q_0</th></tr>
<tr><td>[2]</td><td>2</td><td>LP,HP,BP,BS,AP</td><td>VM</td><td colspan="3">4+2</td><td>YES</td></tr>
<tr><td>[4]</td><td>2</td><td>LP,HP,BP</td><td>CM</td><td colspan="3">5+2</td><td>YES</td></tr>
<tr><td>[6]</td><td>1</td><td>BP</td><td>VM</td><td colspan="3">2+2,3+3,3+3,2+2</td><td>YES</td></tr>
<tr><td rowspan="5">[9]</td><td rowspan="5">1</td><td rowspan="5">LP,HP,BP</td><td></td><td>LP</td><td>HP</td><td>BP</td><td rowspan="5">NO</td></tr>
<tr><td>CM</td><td>3+2</td><td>2+3</td><td>2+3</td></tr>
<tr><td>VM</td><td>3+2</td><td>2+3</td><td>2+3</td></tr>
<tr><td>TIM</td><td>2+2</td><td>2+2</td><td>NA</td></tr>
<tr><td>TAM</td><td>3+2</td><td>3+2</td><td>3+2</td></tr>
<tr><td>[10]</td><td>1</td><td>LP,HP,BP,BS,AP</td><td>VM</td><td colspan="3">4+2</td><td>YES</td></tr>
<tr><td rowspan="2">[11]</td><td>3</td><td>LP, BP,BS</td><td>VM</td><td colspan="3">7+2</td><td rowspan="2">YES</td></tr>
<tr><td>3</td><td>HP,BP,AP</td><td>VM</td><td colspan="3">2+7</td></tr>
<tr><td rowspan="3">[13]</td><td>3</td><td>LP,BP</td><td rowspan="3">CM</td><td colspan="3">3+2</td><td>YES</td></tr>
<tr><td>3</td><td>HP</td><td colspan="3">3+2</td><td>YES</td></tr>
<tr><td>3</td><td>HP</td><td colspan="3">3+3</td><td>YES</td></tr>
<tr><td rowspan="5">[15]</td><td rowspan="5">2</td><td rowspan="5">LP,HP,BP,BS,AP</td><td rowspan="5">CM</td><td>LP</td><td colspan="2">4+2</td><td rowspan="5">Q_0</td></tr>
<tr><td>HP</td><td colspan="2">2+4</td></tr>
<tr><td>BP</td><td colspan="2">3+3</td></tr>
<tr><td>BS</td><td colspan="2">4+4</td></tr>
<tr><td>AP</td><td colspan="2">3+3</td></tr>
<tr><td>[16]</td><td>3</td><td>LP,HP,BP,BS</td><td>CM</td><td colspan="3">2+2</td><td>YES</td></tr>
<tr><td>[17]</td><td>1</td><td>LP,HP,BP,BS</td><td>VM</td><td colspan="3">4+4</td><td>YES</td></tr>
<tr><td rowspan="2">[18]</td><td>3</td><td>LP, BP, BS</td><td>VM</td><td colspan="3">4+2</td><td>YES</td></tr>
<tr><td>3</td><td>HP, BP, AP</td><td>VM</td><td colspan="3">2+4</td><td>YES</td></tr>
<tr><td rowspan="5">This study</td><td rowspan="5">1</td><td rowspan="5">LP,HP,BP,BS,AP</td><td rowspan="5">VM</td><td>LP</td><td colspan="2">3+2</td><td rowspan="5">NO</td></tr>
<tr><td>HP</td><td colspan="2">2+2</td></tr>
<tr><td>BP</td><td colspan="2">3+2</td></tr>
<tr><td>BS</td><td colspan="2">2+4</td></tr>
<tr><td>AP</td><td colspan="2">4+2</td></tr>
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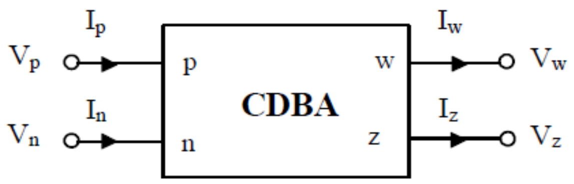

Figure 1. General two-port representation of the CDBA.

CDBA's port characteristics of are given by

$$\begin{bmatrix} Iz \\ Vw \\ Vp \\ Vn \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Vz \\ Iw \\ Ip \\ In \end{bmatrix} \tag{1}$$

CDBA can be performed using a few known circuitry techniques. Fig. 2 shows one possible practical implementation via CFA's.

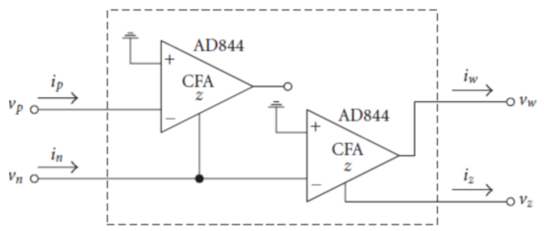

Figure 2. A CFA-based CDBA using AD844s.

AD844 is a commercially available device that can be used for the PSPICE simulation and experimental study. AD844 is an active component that also can be used to verify the theoretical study [18].

B. Proposed Voltage Mode CDBA-Based Multifunction Filter

The presented voltage-mode multifunction filter using single CDBA depicted in Fig. 3.

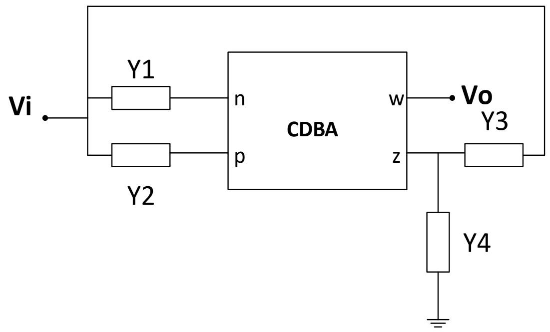

Figure 3. Single CDBA based Multifunction Filter.

Using routine analysis, the transfer function for the presented circuit is obtained as

$$\frac{V_0}{V_i} = \frac{Y_1 + Y_3 - Y_2}{Y_4 + Y_3} \tag{2}$$

With using the appropriate admittance values given in Table 2, the transfer functions for the five filters can be obtained. The ω_0, resonant angular frequency and Q_0, quality factor for the five filters function are listed in Table 3.

Table 2. Admittance Selection of Presented Multifunction Filter Topology

Response Type	Y_1	Y_2	Y_3	Y_4
AP $2(C_1G_2 + C_3G_1) = C_1G_1$	$Y_1 = \dfrac{1}{\dfrac{1}{G_1} + \dfrac{1}{sC_1}}$	$Y_2 = G_2 = \dfrac{G_1}{4}$	$Y_3 = sC_3$	$Y_4 = G_4 = G_2$
BP	$Y_1 = 0$	$Y_2 = \dfrac{1}{\dfrac{1}{G_2} + \dfrac{1}{sC_2}}$	$Y_3 = 0$	$Y_4 = G_4 + sC_4$
BS $(C_3G_1 + C_1G_2) = C_1G_1$	$Y_1 = \dfrac{1}{\dfrac{1}{G_1} + \dfrac{1}{sC_1}}$	$Y_2 = G_2 = \dfrac{G_1}{2}$	$Y_3 = sC_3 = \dfrac{sC_1}{2}$	$Y_4 = G_4$
HP	$Y_1 = \dfrac{1}{\dfrac{1}{G_1} + \dfrac{1}{s2C_1}}$	$Y_2 = sC_2 = sC_1$	$Y_3 = sC_3 = sC_1$	$Y_4 = G_4 + sC_4 = G_1 + sC_1$
LP	$Y_1 = \dfrac{1}{\dfrac{1}{2G_1} + \dfrac{1}{sC_1}}$	$Y_2 = G_2 = G_1$	$Y_3 = G_3 = G_1$	$Y_4 = G_4 + sC_4 = G_1 + sC_1$

Table 3. Filter Parameters.

Filter Type	ω0	Q0
AP	$\omega_0 = \sqrt{\frac{G_1G_4}{C_1C_3}}$	$Q = \frac{\sqrt{G_1G_4C_1C_3}}{C_3G_1 + C_1G_4}$
BP	$\omega_0 = \sqrt{\frac{G_2G_4}{C_2C_4}}$	$Q = \frac{\sqrt{G_4G_2C_2C_4}}{C_2G_4 + C_4G_2}$
BS	$\omega_0 = \sqrt{\frac{G_1G_4}{C_1C_3}}$	$Q = \frac{\sqrt{G_1G_4C_1C_3}}{C_3G_1 + C_1G_4}$
HP	$\omega_0 = \sqrt{\frac{G_1G_4}{2C_1(C_3 + C_4)}}$	$Q = \frac{\sqrt{2C_1G_1G_4(C_3 + C_4)}}{2C_1G_4 + G_1(C_3 + C_4)}$
LP	$\omega_0 = \sqrt{\frac{2G_1(G_4 + G_3)}{C_1C_4}}$	$Q = \frac{\sqrt{2C_1C_4G_1(G_4 + G_3)}}{2G_1C_4 + C_1(G_4 + G_3)}$

C. Sensitivity Analysis

For the BS filter configuration, the passive sensitivities of ω_0 and Q_0 can be derived as

$$S_{G_1}^{\omega_0} = S_{G_4}^{\omega_0} = \frac{1}{2}$$
$$S_{C_1}^{\omega_0} = S_{C_3}^{\omega_0} = -\frac{1}{2} \quad (3)$$

and

$$S_{G_1}^{Q} = \frac{1}{2}\frac{C_1G_4 - C_3G_1}{C_3G_1 + C_1G_4}$$
$$S_{G_4}^{Q} = \frac{1}{2}\frac{C_3G_1 - C_1G_4}{C_3G_1 + C_1G_4}$$
$$S_{C_1}^{Q} = \frac{1}{2}\frac{C_3G_1 - C_1G_4}{C_3G_1 + C_1G_4} \quad (4)$$
$$S_{C_3}^{Q} = \frac{1}{2}\frac{C_1G_4 - C_3G_1}{C_3G_1 + C_1G_4}$$

Similarly, for the other filter configurations, the passive sensitivities of ω0 and Q0 can be computed. It can be ascertained that filter topologies are insensitive to argument variance. For all responses, it can be seen that passive sensitivities are less than 0.5.

D. Non-Ideal Conditions

Due to the device mismatches some tracking errors can occur like voltage and current tracking errors in CMOS implementation of CDBA. It is important to taking these errors in count. Then the CDBA equations can be derived as

$$V_n = V_p = 0$$
$$I_z = \alpha_p I_p - \alpha_n I_n \quad (5)$$
$$V_w = \beta V_z$$

where

$$\alpha_p = (1-\varepsilon_p),\ \alpha_n = (1-\varepsilon_n) \text{ and } \beta = (1 - \varepsilon_v) \quad (6)$$

Adding into account the current and voltage tracking errors, the transfer functions of the proposed filter can be derived as

$$\frac{V_o}{V_i} = \frac{\beta(Y_3 + a_pY_2 - a_nY_1)}{Y_3 + Y_4} \quad (7)$$

The all five filter transfer functions can be expressed as

$$\left(\frac{V_0}{V_i}\right)_{BS} = \frac{\beta(s^2C_1C_3 + a_pG_1G_2)}{s^2C_1C_3 + s(G_1C_3 + G_4C_1) + G_1G_4}$$

$$\left(\frac{V_0}{V_i}\right)_{AP} = \frac{\beta\left(s^2C_1C_3 + s\left(G_1C_3 + a_pG_2C_1 - a_nC_1G_1\right) + a_pG_1G_2\right)}{s^2C_1C_3 + s(G_1C_3 + G_4C_1) + G_1G_4}$$

$$\left(\frac{V_0}{V_i}\right)_{LP} = \frac{\beta\left(s\left(G_3C_1 + a_pG_2C_1 - a_n2C_1G_1\right) + 2G_1G_3 + 2a_pG_1G_2\right)}{s^2C_1C_4 + s(C_1(G_3 + G_4) + 2G_1C_4) + 2G_1(G_3 + G_4)} \quad (8)$$

$$\left(\frac{V_0}{V_i}\right)_{HP} = \frac{\beta\left(s^2\left(2C_1C_3 + a_p2C_1C_2\right) + s\left(C_3G_1 + a_pC_2G_1 - 2a_nG_1C_1\right)\right)}{s^22C_1(C_3 + C_4) + s(2C_1G_4 + G_1(C_3 + C_4)) + G_1G_4}$$

$$\left(\frac{V_0}{V_i}\right)_{BP} = \frac{\beta a_psC_2G_2}{s^2C_2C_4 + s(G_2C_4 + G_4C_2) + G_2G_4}$$

III. Simulation Results

CMOS implementation of the CDBA [14] is given in Fig. 4 was used for testing the workability of the given multifunction filter. The SPICE simulations were done via 0.18 µm MOSIS CMOS process parameters. Vdd and Vss were taken ±0.9 V. Based on this parameter set, gate oxide thickness is given as $T_{ox} = 4.1 \times 10^{-9}$ m. Thus the oxide dielectric constant is $\mathcal{E}_{ox} = 3.46 \times 10^{-11}$ F/m, and oxide capacitance is found as $C_{ox} = 8.43 \times 10^{-3}$ F. Electron mobility, µn, is 282.8 cm^2 / V.s for MOSIS 0.18 µm technology.

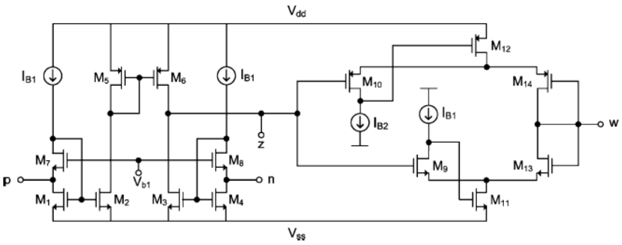

Figure 4. A CMOS structure of the CDBA [14].

For the simulations the resistor and the capacitor values are given in the Table 4. The theoretical resonant frequency can be found as $f_0 \approx$ 159.1 KHz with these passive element values. The simulated resonant frequency is equal to $f0 \approx$ 158.4 KHz, which is very close to the theoretical one. Fig. 5 depicted simulation results for all five filter types. Fig. 6 depicted the gain and phase diagrams of the all-pass filter. All of these filter types have different application areas in the literature [19-22].

Table 4. Passive component values for the filter types

Filter Type	Resistors	Capacitors
AP	R_1=10K R_2=R_4=40K.	C_1=100pF, C_3=25pF
BP	R_2= R_4=10K.	C_2=C_4=100pF
BS	R_1=20K, R_2=R_4=10K.	C_1=100pF, C_3=50pF
HP	R_1= R_4=10K.	C_1=C_2=C_3=C_4 =100pF
LP	R_1= R_2=R_3=R_4=10K.	C_1=100pF, C_3=100pF

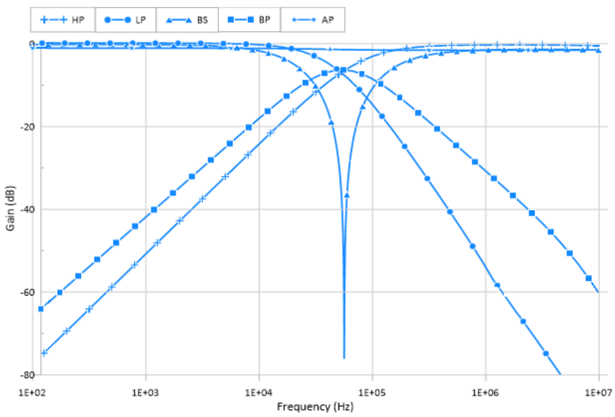

Figure 5. Simulation results of the proposed multifunction filter.

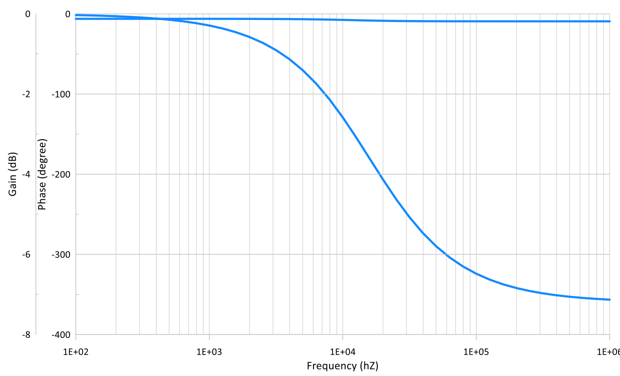

Figure 6. The gain and phase diagrams of the proposed all-pass filter.

A. An Application Example: Third-Order Quadrature Oscillator

For an application example for the proposed multifunction filter topology, a third order quadrature oscillator design was performed (Fig. 7). The presented structure is obtained by forming a closed loop by connecting the CDBA based second order low pass filter and CDBA based integrator with cascade connection. By the third order quadrature oscillator circuit, a sinusoidal waveform with 90° phase difference signal can be obtained. Since the output of this quadrature oscillator circuit structure has low impedance, the synthesized circuit can be connected without additional circuit as a cascade. Thus, there is no difficulty in adapting to analog signal processing circuits.

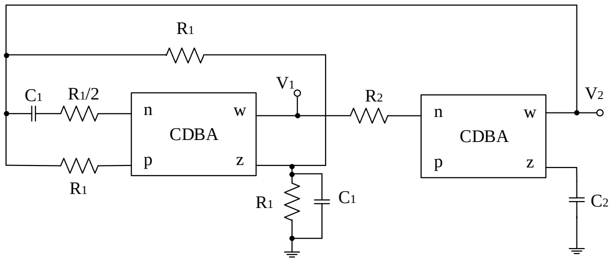

Figure 7. Third-order quadrature oscillator circuit.

The quadrature oscillator equation is given as

$$\frac{4G_1G_1}{s^2C_1C_1 + s4C_1G_1 + 4G_1G_1} * -\frac{G_2}{sC_2} = 1 \qquad (9)$$

As a result of mathematical operations, the proposed oscillator characteristic function of the circuit is obtained as

$$s^3C_1^2C_2 + s^2 4C_1G_1C_2 + s4G_1^2C_2 + 4G_1^2G_2 = 0 \qquad (10)$$

The oscillation condition can be found from the characteristic function in

$$(C_1^2C_2)(4G_1^2G_2) = (4C_1G_1C_2)(4G_1^2C_2)$$
$$C_1G_2 = 4C_2G_1 \qquad (11)$$

The oscillation frequency can be calculated as

$$W_o = \sqrt{\frac{4G_1^2G_2}{4C_1C_2G_1}} = \sqrt{\frac{G_1G_2}{C_1C_2}}$$
$$f_o = \frac{1}{2\pi R_1R_2C_1C_2} \qquad (12)$$

Fig. 8 shows the time response of this example design.

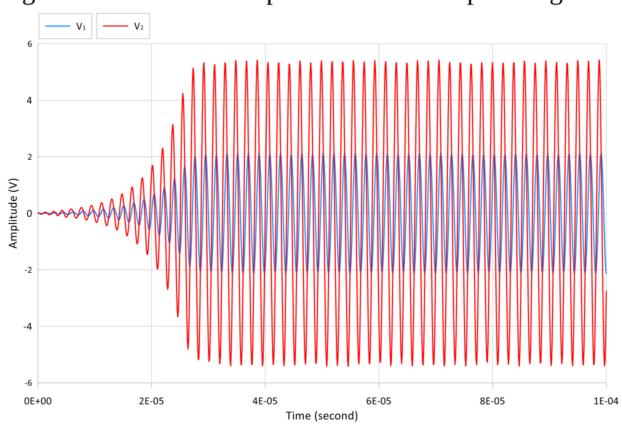

Figure 8. Time response of the third order quadrature oscillator example.

IV. Conclusion

In this study, a novel single CDBA-based voltage mode multifunction filter topology is presented. The proposed topology can be used to synthesize all five filters named LP, HP, BP, BS, and AP with appropriate choices of admittance. The proposed multifunction topology is an appropriate selection for high-quality factor application. Passive sensitivities are low for the proposed topology. Full-scale SPICE simulations were made to behold the execution of the proposed topology. Obtained theoretical and the implications of the simulation are in good conformity. For testing the workability of the proposed filter, the third-order quadrature oscillator was constructed and simulation results are in good agreement with the theoretical study. This design can be used in various fields including medical devices.

Author Contributions

This study is the part of I. Karacan's M.Sc. thesis and A. Gokcen is the thesis advisor.

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