A New Universal Biquad Using CDBAs

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Abstract— **A new universal filter configuration using a recently introduced active element, namely Current Differencing Buffered Amplifier is presented. Independent control over filter parameters, namely the natural frequency, quality factor and gain is achieved. The filter offers all the advantages of Current Differencing Buffered Amplifier, i.e. being free from parasitic capacitances, current-mode operation and simple implementation while keeping the compatibility with existing voltage-mode signal processing circuits. Detailed analysis of the non-idealities of the active element is included. Experimental results that verify the analytical results are included.**

Keywords— **Active Filters, Universal Filter**

I. Introduction

Recently, current-mode analog integrated circuits in CMOS technology have received considerable interest. Current-mode techniques can achieve considerable improvement in amplifier speed, accuracy and bandwidth overcoming the finite gain-bandwidth product associated with conventional operational amplifiers [1]. Traditionally, most analog signal processing operations have been accomplished employing the voltage as the signal variable. In order to maintain compatibility with existing voltage processing circuits, it is necessary to convert the input and output signals of a current-mode signal processor to voltage using transconductors. This has the disadvantage of increasing both the chip area and power dissipation. Universal filters are considered as a fundamental second-order building block in many analog applications that can be cascaded to realize higher order transfer functions. They are capable of providing highpass, bandpass, lowpass, bandstop and allpass responses using the appropriate choice of admittances with the same active element configuration. This paper explores implementing voltage-mode continuous-time universal filters using the Current Differencing Buffered Amplifier (CDBA) [2-6]. Thus it is possible to keep compatibility with existing signal processing circuits while taking advantage of the CDBAs current mode characteristics. Also since the CDBA is not slew limited in the same fashion as op amps, it can provide amplification of high frequency signals with the ease of using standard op amps in addition to a constant bandwidth virtually independent of the gain.

II. Circuit description

The CDBA is a new versatile four terminal analog building block represented symbolically as shown in Fig. 1 and is characterized by the following set of equations:

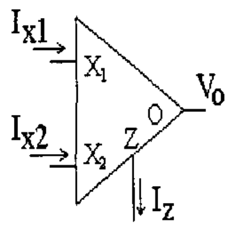

Fig. 1. The circuit symbol of CDBA

$$V_{X1} = V_{X2} = 0 \tag{1}$$

$$I_Z = I_{X1} - I_{X2} \tag{2}$$

$$V_O = V_Z \tag{3}$$

III. The Proposed Universal Filter

Although the CDBA can be constructed using existing analog building blocks like current followers and voltage buffers, these realizations include lots of redundancy [2,6]. However, compact CMOS realizations have been suggested to implement the CDBA recently [3,4]. The proposed filter topology using CDBA is shown in Fig 2. Routine analysis of the circuit yields

$$\frac{V_{out}}{V_{in}} = \frac{Y_1Y_6 - Y_1Y_7 + Y_4Y_5}{Y_1Y_2 + Y_3Y_4} \tag{4}$$

By appropriate selections of the two-terminals involved in the topology, one may obtain different multifunction filter circuits [7]. Among these specifications, some are given in Table I.

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Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
sC_1	sC_2+G_2	G_3	G_4	G_5	sC_6+G_6	G_7
sC_1+G_1	sC_2	G_3	G_4	G_5	sC_6	G_7
sC_1	sC_2	G_3	sC_4+G_4	G_5	sC_6	G_7

TABLE I

POSSIBLE SPECIFICATIONS FOR THE TOPOLOGY IN FIG.1

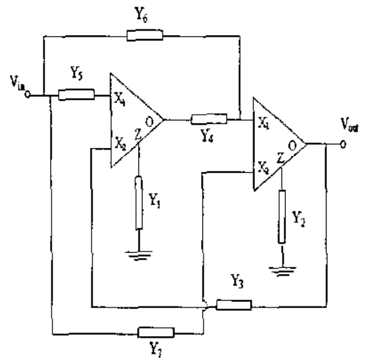

Fig. 2. The proposed Universal Filter Topology

As a design example, all filter responses corresponding to the first case are shown in Table II where the transfer function is given by:

$$\frac{V_{out}}{V_{in}} = \frac{\frac{C_6}{C_2}s^2 + \frac{(G_6-G_7)}{C_2}s + \frac{G_4G_5}{C_1C_2R_4R_5}}{s^2 + \frac{G_2}{C_2}s + \frac{G_3G_4}{C_1C_2}} \tag{5}$$

The natural angular frequency and the pole quality factor of the filter can be expressed by:

$$\omega_o = \sqrt{\frac{G_3G_4}{C_1C_2}} \tag{6}$$

and

$$Q = \frac{1}{G_2}\sqrt{\frac{C_2G_3G_4}{C_1}} \tag{7}$$

It is clear that the quality factor Q can be independently controlled by varying G_2 without affecting ω_o.

Filter Response	Realizability Condition
Highpass	$G_5 = G_6 = G_7 = 0$
Positive Bandpass	$C_6 = 0,\ G_5 = G_7 = 0$
Negative Bandpass	$C_6 = 0,\ G_5 = G_6 = 0$
Lowpass	$C_6 = 0,\ G_6 = G_7 = 0$
Allpass	$C_6 = C_2,\ G2 = G7,\ G_3 = G_5,\ G_6 = 0$
Bandstop	$C_6 = C_2,\ G_6 = G_7 = 0,\ G_3 = G_5$

TABLE II

THE REALIZATION OF DIFFERENT FILTER RESPONSES FOR THE FIRST CASE IN TABLE I

IV. NON-IDEAL ANALYSIS

The non-idealities related to the voltage and current following operations of CDBA can be modeled by the following equations:

$$V_O = \beta(s)V_Z = \frac{\beta_o}{1+\frac{s}{P_v}}V_Z \tag{8}$$

$$I_Z = \alpha(s)(I_{X1} - I_{X2}) = \frac{\alpha_o}{1+\frac{s}{P_i}}(I_{X1} - I_{X2}) \tag{9}$$

$\beta(s)$ and $\alpha(s)$ are the active non-idealities of the CDBA and are represented by single-pole transfer functions. P_v and P_i are the 3-dB cut-off frequencies of the voltage and current gains respectively. β_o and α_o represent the DC inaccuracies of these gains and they can be expressed as $\beta = 1-\epsilon_v$ and $\alpha = 1-\epsilon_i$ with $|\epsilon_v| \ll 1$ and $|\epsilon_i| \ll 1$ where ϵ_v and ϵ_i denote the voltage and current tracking errors respectively.

On the other hand, both the input terminals ($X1$ and $X2$) and output terminal (O) have fairly insignificant parasitics as they exhibit slight changes in their voltage being a virtual ground of a current follower or a low output impedance of a voltage buffer. Thus any response limitations incurred by capacitive time constants are eliminated, leading to circuits that are insensitive to the stray capacitances [6,8]. CDBA also suffers from having a high impedance node at the Z terminal between the voltage buffer and the differential current stage and voltage buffer. This leads to the presence of a parasitic capacitance, Cp, at that node and its effect should be included. Thus by having capacitor branches at the Z terminal (i.e. Y_1 and Y_2), the effect of the parasitic capacitance, C_p, can be compensated for by absorbing its effect in the integrated capacitances used. All design examples in Table I follow this condition.

Taking into account C_p and only the DC inaccuracies of CDBA's current and voltage gains (i.e. $P_v \approx \infty$, $P_i \approx \infty$, the characteristic polynomial in Eqn. (5) reduces to:

$$D(s) = s^2 + \frac{G_2}{C_2+C_p}s + \frac{\alpha_1\alpha_2\beta_1\beta_2G_3G_4}{(C_1+C_p)(C_2+C_p)} \tag{10}$$

From these relations, the natural angular frequency and the pole quality factor of the filter can be expressed by:

$$\omega_o = \sqrt{\frac{\alpha_1\alpha_2\beta_1\beta_2G_3G_4}{(C_1+C_p)(C_2+C_p)}} \tag{11}$$

$$Q = \frac{1}{G_2}\sqrt{\frac{\alpha_1\alpha_2\beta_1\beta_2(C_2+C_p)G_3G_4}{(C_1+C_p)}} \tag{12}$$

Thus it is clear that the active sensitivities are no more that unity in magnitude. Also the integrating capacitors, C_1 and C_2, can be chosen much larger than C_p in order to eliminate its effect. It is also possible to compensate the effect of C_p, by taking the design value, C_1 and C_2, of equal to its theoretical value minus C_p. Thus the effect of C_p is absorbed in the integrating capacitances and no additional elements for compensation are needed.

In the followings, the effects of the frequency dependencies of voltage and current $\beta(s)$ and $\alpha(s)$ are also studied. If we assume finite values for P_v and P_i in Eqns. (8,9) and neglect all the other non-idealities, the characteristic equation in Eqn. (5) becomes

$$D(s) = s^2 + \frac{\omega_o}{Q}s + \alpha_1(s)\alpha_2(s)\beta_1(s)\beta_2(s)\omega_o^2 \quad (13)$$

Assuming these non-idealities are same for both CDBA and making the following approximation

$$\frac{1}{(1+\frac{s}{P_v})^2(1+\frac{s}{P_i})^2} = \frac{1}{1+\frac{s}{P_{eq}}} \quad (14)$$

With

$$P_{eq} = \frac{2}{P_v} + \frac{2}{P_i}$$

And using Budak-Petrela's method [9], the following deviations can be deduced for natural frequency and pole-Q:

$$\frac{\triangle\omega_o}{\omega_o} \approx 0 \quad (15)$$

$$\frac{\triangle Q}{Q} \approx \frac{2Q^2}{\sqrt{4Q^2-1}}\frac{\omega_o}{P_{eq}} \quad (16)$$

Thus, the pole-Q increases for high-Q filters with high natural frequencies. Also, it should be noted that as in all the good active filters, the relative deviation of the natural frequency is approximately zero.

V. Experimental results

In order to verify the practical validity of the proposed filter, the presented topology with the specification given in the first case in Table I is bread boarded and tested. Among several experimental results verifying theoretical analysis, some are given in this section. In all the experiments, CDBAs are realized using the realization presented in [2] where, the active elements are implemented from commercially available CCIIs, AD844s [10] supplied under ± 5V.

The proposed filter is first designed to realize a lowpass and a highpass Butterworth type filter responses with a natural frequency of 200kHz. For this purpose, the passive component values are chosen as $R_2 = R_3 = R_4 = R_5$ =5.63k, C_1 = 200pF, C_2 = 100pF, for the lowpass response and $R_2 = R_3 = R_4$ =5.63k, C_1 = 200pF, C_2 = 100pF, C_6 = 100pF for the highpass responses. The characteristics for the lowpass response and the normalized highpass response are given in Fig. 3. For the actual highpass response, the magnitude in the passband is found to be slightly smaller than unity (approximately -0.8dB). However, one can easily verify that this deviation stems from the inaccuracy of the ratio $\frac{C_6}{C_2}$ due to the z-terminal parasitic capacitances C_z of CDBA. The capacitor C_z approximately has a value of 10pF and its effect could easily be minimized by appropriately changing the value of C_2. Nevertheless, the measured responses in Fig. 3 agree quite well with the theory. Second, we have designed a positive bandpass

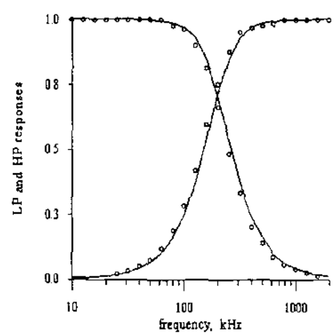

Fig. 3. The measured Lowpass and the Highpass Butterworth Filter responses with f_o=200kHz

filter with a natural frequency of 283kHz and Q of 10. For this purpose, the passive component values are chosen as $R_2 = R_4 = R_6$ = 5.63k, R_3 = 56k, $C_1 = C_2$ = 100pF. The slight deviation in the center frequency stems mainly from the parasitic capacitances at the z-terminal of CDBAs appearing in parallel with the capacitors C_1 and C_2 and increasing their theoretical values by approximately 10pF.

Third, we have realized an allpass filter with a natural frequency of 283kHz and Q of 1. This value of Q is useful when a second-order allpass circuit is used to linearize the phase of an nth-order lowpass filter [7]. In order to achieve this characteristic, the passive component values are chosen as $R_2 = R_3 = R_4 = R_5 = R_7$ =5.63k, $C_1 = C_2 = C_6$ = 100pF. The measured response is given in Fig. 4. The discrepancies of the magnitude response in the high-frequency region are mainly attributed to the inaccuracy of the ratio $\frac{C_6}{C_2}$ due to the Z-terminal parasitic capacitances of the

CDBAs, which appear in parallel with the capacitor C_2. However, by adjusting the value of the capacitor C_2, the error of the magnitude response at high frequencies can be reduced. Nevertheless, the measured frequency response verifies the practical validity of the proposed filter. Finally, in order to predict the

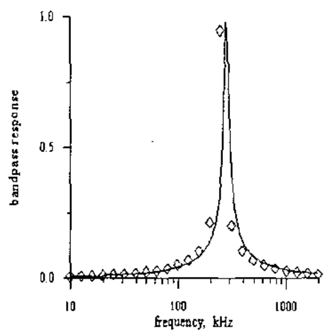

Fig. 4. The measured positive Bandpass response with f_o=283kHz and Q=10

frequency limitations of the filter, we have designed a positive bandpass filter with pole-Q of 10 and we have changed its center frequency from 133kHz to 1.2MHz. We have clearly observed the Q-enhancement effect as expected. In Table III, the designed and the actual values of pole-Q are given for some sample center frequencies and the relative deviations in these filter parameters are compared with those calculated from Eqn. (16). For the calculations of the pole-Q relative deviations, the non-idealities of AD844 are taken as given in [11]. As seen from these results, the relative deviations in pole-Q is close to the theoretical prediction and the actual operation frequency range of the filter conforms to that deduced from Eqn. (16). It should be also noted that for each case, the deviation in the center frequency remains very low conforming to the Eqn. 15.

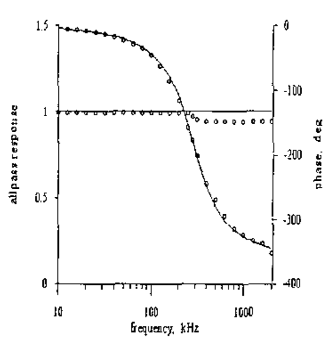

Fig. 5. The measured Allpass response with f_o=283kHz and Q=1

Designed		Measured		$\Delta Q/Q$ %	
f_o(kHz)	Q	f_o(kHz)	Q	measured	calculated
135	9.65	133	9.4	-2.62	2.34
257	9.65	253	9.8	1.52	6.28
471	9.65	470	13	24	13
1200	9.65	1180	20	107	96

TABLE III

THE MEASURED NATURAL ANGULAR FREQUENCIES AND CORRESPONDING POLE-QS

VI. Conclusion

In this work, a new circuit configuration for constructing universal filters using CDBAs is introduced from which six filter functions were derived. Detailed analysis of the limitations of the active element is included. The presented experimental results have shown that the proposed configuration's performance is a good option for realizing universal filters.

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