Current-Processing Current-Controlled Universal Biquad Filter

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Abstract. This paper presents a current-processing current-controlled universal biquad filter. The proposed filter employs only two current controlled current conveyor transconductance amplifiers (CCCCTAs) and two grounded capacitors. The proposed configuration can be used either as a single input three outputs (SITO) or as three inputs single output (TISO) filter. The circuit realizes all five different standard filter functions i.e. low-pass (LP), band-pass (BP), high-pass (HP), band-reject (BR) and all-pass (AP). The circuit enjoys electronic control of quality factor through the single bias current without disturbing pole frequency. Effects of non-idealities are also discussed. The circuit exhibits low active and passive sensitivity figures. The validity of proposed filter is verified through computer simulations using PSPICE.

Keywords
Current-mode, analog signal processing, universal filters, electronic control.

1. Introduction

Current-mode circuits have become quite popular for a variety of applications, due to their potential advantages over the voltage-mode circuits. These advantages are high current swing under low supply voltage, reduced distortions, low input impedance, high output impedance, lesser sensitivity to switching noise, better ESD immunity, higher slew rate and larger bandwidth [1], [2]. Current-mode filters are among the most important building blocks for analog signal processing and hence received a lot of attention. These find applications in communication, measurement, instrumentation and control systems. Many current-mode filters have been realized in the past, based on the different current-mode active elements such as second generation current conveyor (CCII), current controlled current conveyor (CCCII), current controlled current conveyor transconductance amplifier (CCCCTA) etc. [3-30]. CCII based universal filters [3-6], [27] have several advantages such as wider dynamic range, wider bandwidth, higher slew rate and low power consumptions but suffer from non availability of electronic control over circuit parameters. On the other hand, CCCII based current-mode filters [9-11, 13-21, 23-26] offers wider range of electronic control over the circuit parameters. CCCCTA is relatively new active element [28] and has received considerable attention as current-mode active element, because its transconductance and parasitic resistance can be adjusted electronically. As a result CCCCTA based realizations do not need external resistors in practical applications. This device can be operated in both current and voltage-modes, providing flexibility. All these advantages make the CCCCTA a promising choice for realizing active filters [29-32]. Current-mode active filters have been broadly classified as single input three output (SITO) [3-7, 9-22, 26-27, 29-30] or three input single output (TISO) [23-28] filters. The SITO current-mode filters can realize second order LP, HP, BR and AP responses simultaneously, without changing the connection of the input current signal and without imposing any restrictive conditions on the input signal. The TISO current-mode filters can realize all the standard filter function through appropriate selection of the signals. Unfortunately these reported circuits [3-30] suffer from one or more of the following drawbacks:

- Use of large number of active and/or passive elements [3-6, 9-23, 25-27, 30].
- Non availability of standard filter functions [7, 9, 12, 14, 16-17, 29].
- Non availability of explicit current outputs [7, 9, 12, 16-17, 29].
- Use of floating passive elements [13, 17-18].
- Requirement of inverted input current signal(s) and/or multiple copy of input current signal(s) to realize AP filter function [24-25, 28].

Notwithstanding the above drawbacks, it may be noted that most of these current-mode filters fall in SITO or TISO category. However, the circuits reported in references [26-27] can be used as SITO as well as TISO filter, from the same configuration and realize all the standard filter functions. Moreover, the circuit in reference [26] uses three multi-output
The proposed current-processing universal biquad filter. In this design, it is to be noted that input current inversion is not required to realize the above standard filter functions. Only a simple current component matching condition is required to realize HP response. In addition, filter responses HP and AP requires additional copies of input current signals at the realizations. This solution requires an additional current follower to duplicate the input current signal. Moreover, the above proposed filter topology can also be used as single input three-output filter, if \( I_{in} = I_{in} = 0 \) and \( I_{i3} = I_{in} \). From (3) - (5), the following current transfer functions can be obtained:

\[
\frac{I_1}{I_{in}} = \frac{g_{m1} R_{X2} C_2 s}{D(s)}.
\]

\[
\frac{I_2}{I_{in}} = \frac{g_{m2} (I_{i0} + I_{i2}) C_2 s + I_{i0} g_{m2}}{D(s)}.
\]

\[
\frac{I_3}{I_{in}} = \frac{-C_1 C_2 R_{X2} s^2 + g_{m2}}{D(s)}.
\]

It can be seen from (7) - (9) that non-inverting BP, non-inverting LP and inverting BR filter responses are obtained from output currents \( I_1, I_2 \) and \( I_3 \), respectively. Inverting HP and AP filter responses can be easily obtained from the currents \( I_{i0} = I_2 + I_3 \) and \( I_{i0} = I_1 + I_3 \), respectively.
The pole frequency ($\omega_o$), the quality factor ($Q$) and bandwidth (BW) $\omega_o/Q$ of each filter can be expressed as

$$\omega_o = \frac{1}{V_f} \sqrt{I_{y2}I_{y2}} \frac{C_1C_2}{C_1C_2}, \quad Q = \frac{1}{g_{m1}} \left( \frac{C_1 g_{m2}}{C_1 R_{x2}} \right)^2,$$

$$BW = \frac{\omega_o}{Q} = \frac{1}{C_1 2V_f}.$$

Substituting intrinsic resistances and trans-conductance values as depicted in (2), the above equation yields

$$\omega_o = \frac{1}{V_f} \sqrt{I_{y2}I_{y2}} \frac{C_1C_2}{C_1C_2}, \quad Q = \frac{1}{g_{m1}} \left( \frac{C_1 g_{m2}}{C_1 R_{x2}} \right)^2.$$

In (11), by maintaining $I_{B2} = I_{S2} = I_{S1}$, the pole frequency can be electronically adjusted by $I_{B2}$ and $I_{S2}$ without affecting the quality factor. It can also be noted that the quality factor can be electronically adjusted by $I_{S3}$ without affecting the pole frequency. In addition, bandwidth (BW) of the system can be expressed

$$BW = \frac{\omega_o}{Q} = \frac{1}{C_1 2V_f}.$$

Equation (12) shows that the BW can be linearly controlled by $I_{S1}$. From (11) - (12), it is clear that parameters $\omega_o$ and $Q$ can be simultaneously controlled electronically by adjusting bias currents, without disturbing the parameter $\omega_o/Q$. Moreover, it can also be noted that high $Q$ can be easily obtained using low value of $I_{S1}$ and higher values of $I_{S2}$ and $I_{B2}$.

3. Non-ideal Analysis

Taking the non-idealities of CCCCTA into account, the relationship of the terminal voltages and currents can be rewritten as follow:

$$V_{x2} = \beta \frac{V}{V} + I_{x1} R_{x1}, \quad I_{x1} = \alpha I_{x1}, \quad I_{-x1} = -\alpha I_{x1}, \quad I_{x2} = \gamma_p g_{m} V_{x2}, \quad I_{-x2} = -\gamma_n g_{m} V_{x2}$$

(13)

where $\beta = (1 - \epsilon_{d2})$, $\epsilon_{d2}$ ($|\epsilon_{d2}| < 1$) represents the voltage tracking error from $Y$ to $X$ terminal. $\alpha = (1 - \epsilon_{p}), \epsilon_{p}$ ($|\epsilon_{p}| < 1$) represents the current tracking error from $X$ to $+Z$ terminal. $\alpha_n = (1 - \epsilon_{n}), \epsilon_{n}$ ($|\epsilon_{n}| < 1$) represents the current tracking error from $X$ to $-Z$ terminal. $\gamma_p$ and $\gamma_n$ are the trans-conductance inaccuracy factor from $-Z$ to $O$ and $-Z$ to $-O$ terminal, respectively. The non-ideal analysis of the proposed filter in Fig. 2 yields the transfer functions as

$$\frac{[(\alpha_p I_{a2} + \alpha_n I_{a1})C_2 s + (I_{y2} \gamma_p g_{m} R_{x2}) I_{a2} \gamma_p g_{m} g_{n2}]}{D(s)}$$

(14)

where

$$D(s) = \frac{s^2 \alpha_p C_2 R_{x2} + \alpha_n \gamma_p g_{m} R_{x2} C_2 + \alpha_p \gamma_p g_{m} g_{n2}}{C_2 s^2},$$

where

$$(\alpha_p I_{a2} + \alpha_n I_{a1})C_2 s + (I_{y2} \gamma_p g_{m} R_{x2}) I_{a2} \gamma_p g_{m} g_{n2}$$

(15)

In this case, the $\omega_o$ and $Q$ are changed to

$$\omega_o = \left( \frac{\alpha_p \beta \gamma_p g_{m}}{C_1 C_2 R_{x2}} \right)^{\frac{1}{2}}, \quad Q = \left( \frac{\alpha_p g_{m1} \gamma_p g_{n2}}{C_1 R_{x2}} \right)^{\frac{1}{2}}.$$
Fig. 3. Internal topology of CCCCTA.

Tab. 1. The SPICE model parameters of HFA3096 mixed transistors arrays.

Fig. 4. Current gain responses of the LP, BP, BR, HP and AP of the proposed circuit in Fig. 2, with $I_{in1} = I_{in2} = 0$ and $I_{in3} = I_{in}$.

Fig. 5. Current gain and phase responses of TISO configuration of the proposed circuit in Fig. 2.
Fig. 6 shows magnitude responses of BP and BR (when \( I_{in} = 0 \) and \( I_{in} = I_{in} \)) functions where \( I_{12}, I_{22} \) and \( I_{32} \) were equally set and changed for several values, by keeping its ratio to be constant for constant \( Q = 2 \). Other parameters were chosen as \( I_{12} = 180 \mu A, \) and \( C_1 = C_2 = 0.2 \) nF. The pole frequency (in Fig. 6) was found to vary as 0.885 MHz, 1.76 MHz, 3.42 MHz and 5.04 MHz for four values of \( I_{12} = 30 \mu A, 60 \mu A, 120 \mu A \) and 180 \( \mu A \), respectively, which shows that pole frequency can be electronically adjusted without affecting the quality factor. Fig. 7 shows the magnitude responses of BR and BP (when \( I_{in} = 0 \) and \( I_{in} = I_{in} \)) functions for different values of \( I_{31} \), by keeping \( I_{11} = I_{21} = 45 \mu A, I_{22} = 180 \mu A, \) and \( C_1 = C_2 = 0.2 \) nF. The quality factor was found to vary as 20, 12, 6 and 2.94, by keeping constant pole frequency as 2.62 MHz for four values of \( I_{31} \) as 9 \( \mu A, 15 \mu A, 30 \mu A \) and 60 \( \mu A \), respectively. This shows that the quality factor can be electronically adjusted without affecting pole frequency by input bias current \( I_{31} \). The large signal behavior of the proposed circuit in Fig. 2 was also investigated by applying a 140 \( \mu A \) peak to peak input current sinusoidal signal at frequency 500 kHz. Fig. 8 shows the time domain sinusoidal current input and corresponding LP output signal of the proposed circuit of Fig. 2, with \( I_{22} = I_{33} = 0 \) and \( I_{11} = I_{in} \).

5. Concluding Discussion

A current-processing current-controlled universal SITO/TISO biquad filter employing two CCCCTAs and two grounded capacitors is proposed. It may be noted that a current-processing circuit manipulates input signals as current(s) and provides output signal(s) also as current(s). Current control is a feature that allows the circuit parameters to be tuned through external current sources. The proposed circuit may require input current buffers, so as to meet the low input impedance requirements. Moreover, additional transistors need to be employed to obtain copies of input currents to be inserted at different nodes, wherever, input signal is to be applied at more than one node. The proposed filter possesses the following advantages: (i) realization of LP, HP, BP, BR and AP responses in current form with the single input three output or three input single output in the same configuration; (ii) the employment of minimum number of grounded capacitors; (iii) low active and passive sensitivity performance; (iv) electronic control of \( Q \) through single bias current without disturbing \( \omega_0 \); (v) availability of explicit current outputs (i.e. high impedance output nodes) without requiring any additional active elements; (vi) enjoys high-Q feasibility by adjusting the bias current(s). With above mentioned features, the proposed circuit is good for implementation as monolithic chip for portable electronic equipments. The proposed circuit is validated through simulation results which agree quite well with theoretical ones as expected, whereas the difference between them arises from non-idealities.

Fig. 6. (a) BR and (b) BP responses of the proposed filter for different value of \( I_{12} = I_{22} = I_{32} \) when \( I_{22} = I_{33} = 0 \) and \( I_{11} = I_{in} \).

Fig. 7. (a) BR and (b) BP responses of the proposed filter for different value of \( I_{31} \) when \( I_{12} = I_{33} = 0 \) and \( I_{11} = I_{in} \).

Fig. 8. Time domain input and LP output (I2) waveforms of the proposed circuit in Fig. 2 when \( I_{22} = I_{33} = 0 \) and \( I_{11} = I_{in} \).
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