Current-mode and transimpedance-mode universal biquadratic filter using two current conveyors

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A current-mode and transimpedance-mode universal biquadratic filter with single input and multi-outputs using two current conveyors, four resistors and two grounded capacitors is presented. The proposed circuit can realize current-mode notch, highpass and bandpass responses, simultaneously. The current-mode lowpass and allpass responses can be obtained by interconnection of relevant output currents. Moreover, the transimpedance-mode highpass, bandpass, lowpass, notch and allpass filters can also be obtained, simultaneously, from the proposed circuit.

Keywords: Current conveyor; Current-mode filter; Transimpedance-mode filter

In analogue signal processing applications it may be desirable to have active filter with input currents and output currents or voltages, defined as current-mode or transimpedance-mode filters, respectively1–3. Current-mode analogue signal processing circuit techniques have been received considerable attention due to better linearity, wider bandwidth and larger dynamic range and the simplicity of implementation signal operations such as addition, subtraction and multiplication4–6. A transimpedance-mode filter is described as an interface circuit connecting a current-mode circuit to a voltage-mode circuit, one of the most important application areas of transimpedance-mode filters is the receiver baseband (BB) blocks of modern radio systems7.

If the filters employing grounded capacitors, it is attractive for monolithic IC implementation8. Because the current conveyor has a non-negligible output parasitic resistance on port x ($R_x$), when the x port of current conveyor is loaded by a capacitor, it leads to an improper transfer functions. Due to the effect of this parasitic resistance $R_x$ at the x port of current conveyor, the filters with x port loaded by a capacitor do not exhibit good performance at high frequency.

Several circuits realizing current transfer functions with single input and three outputs (SITO) have been presented in the literatures. By interconnection of relevant output currents, the lowpass, bandpass, highpass, notch and allpass filters can be obtained from the same circuit configuration. Each of the SITO current-mode universal biquads in Refs9–13 requires at least four active elements. Abuelma'atti and Khan14 proposed a current-mode SITO universal biquadratic filter circuit using three multiple outputs second-generation current conveyors (MOCCIIs), one OTA, two grounded resistors and three grounded capacitors. Each of the current-mode SITO universal biquad in Refs15–17 uses three MOCCIIs, two resistors and two grounded capacitors. However, some x ports of the MOCCIIs in Refs14–17 are connected to capacitors that degrade their high frequency performance. Each of the current-mode SITO universal biquads in Refs18,19 uses four current controlled conveyors and two floated capacitors. The current-mode SITO universal biquad in Horng et al.20 uses three MOCCIIs, four resistors and two grounded capacitors. However, it needs components matching condition in realizing the allpass response. Jerabek and Vrba21 present an interesting current-mode SITO universal biquad using three universal current conveyor (UCC), two resistors and two grounded capacitors. The current-mode SITO universal biquad22 using three MOCCIIs, five resistors and two grounded capacitors. The current-mode biquad23 uses two current controlled MOCCIIs, one current-controlled current amplifier and two grounded capacitors.

Several transimpedance-mode filters were presented24–25. However, only highpass, bandpass and...
lowpass filters can be simultaneously obtained in each circuit configuration. Abuelma‘atti et al.\textsuperscript{26} present a mixed-mode filter with multi-inputs and two outputs using seven CCIIs, eight resistors and two grounded capacitors. However, only one filter type can be obtained in each circuit realization. An interesting transimpedance-mode single input and five outputs universal biquad using three MOCCIIs, five resistors and two grounded capacitors were presented\textsuperscript{22}. Five kinds of standard filter functions can be simultaneously obtained from the same circuit configuration. However, the active and passive components used were not minimum.

In this paper, a new current-mode and transimpedance-mode universal biquadratic filter circuit with single current input terminal is presented. The proposed circuit requires two current conveyors, four resistors and two grounded capacitors. The current-mode notch, highpass and bandpass filters can be obtained simultaneously. The realizations of current-mode lowpass or allpass functions do not need additional current conveyors in either case as this can be simply achieved by connecting the appropriate nodes. Moreover, the transimpedance-mode highpass, bandpass, lowpass, notch and allpass filters can also be obtained, simultaneously, from the proposed circuit (the allpass filter needs component matching condition).

With respect to the current-mode universal biquads in Refs\textsuperscript{9-23}, the proposed circuit uses less active components. With respect to the current-mode universal biquads in Refs\textsuperscript{14-17}, the x ports of the current conveyors in the proposed circuit are connected to resistors. With respect to the current-mode universal biquads in Refs\textsuperscript{18,19}, the proposed circuit uses only grounded capacitors. With respect to the transimpedance-mode filters in Refs\textsuperscript{24,26}, the proposed circuit can realize five kinds of standard filter functions, simultaneously, and employing less active components. With respect to the transimpedance-mode filters in Refs\textsuperscript{22}, the proposed circuit employs less active and passive components.

Proposed Circuit

The circuit symbol of the MOCCII is shown in Fig. 1, which shows the two types of output terminals, the positive outputs represented by terminal z+ and the negative by terminal z-. The terminal characteristic of the MOCCII can be described by the following matrix equation:

One possible implementation of the MOCCII is shown in Fig. 2\textsuperscript{27}. The multiple current outputs can be easily implemented by simply adding output branches.

The circuit symbol of the multiple outputs differential voltage current conveyor (MODVCC) is shown in Fig. 3, which shows the two types of output terminals, the positive outputs represented by terminal z+ and the negative by terminal z-. The terminal characteristic of the MODVCC can be described by the following matrix equation:
One possible implementation of the MODVCC is shown in Fig. 4. The multiple current outputs can be easily implemented by simply adding output branches.

The proposed circuit comprises two current conveyors, four resistors and two grounded capacitors is shown in Fig. 5. The use of grounded capacitors is particularly attractive for integrated circuit implementation. The output voltages and currents for the circuit at Fig. 5 are given by the following equations:

\[
\begin{align*}
V_{o1} &= \frac{G_1 G_2}{s^2 C_1 C_2 G_3 + sC_2 G_1 G_2 + G_1 G_2 G_3} I_{in} \quad \ldots (3) \\
V_{o2} &= \frac{s^2 C_2 G_1}{s^2 C_1 C_2 G_3 + sC_2 G_1 G_2 + G_1 G_2 G_3} I_{in} \quad \ldots (4) \\
V_{o3} &= \frac{-s^2 C_1 C_2}{s^2 C_1 C_2 G_3 + sC_2 G_1 G_2 + G_1 G_2 G_3} I_{in} \quad \ldots (5) \\
V_{o4} &= \frac{-s^2 C_1 C_2}{s^2 C_1 C_2 G_3 + sC_2 G_1 G_2 + G_1 G_2 G_3} I_{in} \quad \ldots (6) \\
V_{o5} &= \frac{s^2 C_1 C_2 - sC_2 G_1 G_2 + G_1 G_2}{s^2 C_1 C_2 G_3 + sC_2 G_1 G_2 + G_1 G_2 G_3} I_{in} \quad \ldots (7)
\end{align*}
\]

The resonance angular frequency \(\omega_o\) and the quality factor \(Q\) are given by

\[
\omega_o = \sqrt{\frac{1}{C_1 C_2 R_1 R_2}} \quad \ldots (11)
\]

and

\[
Q = \frac{1}{R_1} \sqrt{\frac{C_1 C_2 R_1 R_2}{C_2}} \quad \ldots (12)
\]

From Eqs (3)-(6) it can be seen that the transimpedance-mode lowpass, notch, bandpass, and highpass filters are obtained from \(V_{o1}\), \(V_{o2}\), \(V_{o3}\) and \(V_{o4}\), respectively. If \(R_4 = R_3\), a transimpedance-mode
The relationship of the terminal voltages and currents of MODVCC can be rewritten as

\[
\begin{bmatrix}
\alpha_1(s) & 0 & 0 & 0 & 0 & ... & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & v_{i1} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & v_{i2} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & i_x \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & v_{i+1} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & v_{i+2} \\
... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ... & ...
\end{bmatrix}

\]

where \( \alpha_ka(s) \) represents the frequency transfer function of the internal voltage follower and \( \beta_kb(s) \) represent the frequency transfer function of the internal current follower of the \( k \)-th current conveyor. They can be approximated by first order lowpass functions, which can be considered to have a unity value for frequencies much lower than their corner frequencies.\(^{28}\) If the circuit is working at frequencies much lower than the corner frequencies of \( \alpha_ka(s) \) and \( \beta_kb(s) \), then \( \alpha_ka(s) = \alpha_ka = 1 - \varepsilon_{kav} \) and \( \varepsilon_{kav} (|\varepsilon_{kav}| << 1) \) denotes the voltage tracking error from \( y_i \) terminal to \( x \) terminal of the \( k \)-th current conveyor and \( \beta_kb(s) = \beta_kb = 1 - \varepsilon_{kbi} \) and \( \varepsilon_{kbi} (|\varepsilon_{kbi}| << 1) \) denotes the current tracking error of the \( k \)-th current conveyor. The denominator of the non-ideal output voltage function for Fig. 5 becomes

\[
D(s) = s^2C_1C_2G_3 + sC_2G_1G_2\alpha_2\beta_2x_{\beta_2} + G_1G_2G_3\alpha_2\beta_1x_{\beta_1} \ldots (17)
\]

The resonance angular frequency \( \omega_o \) and the quality factor \( Q \) are given by

\[
\omega_o = \frac{\alpha_1\alpha_2\beta_1\beta_2}{C_1C_2R_1R_2} \ldots (18)
\]

\[
Q = \frac{1}{R_1\alpha_2\beta_2} \frac{1}{C_2\alpha_2\beta_1} \ldots (19)
\]

The active and passive sensitivities of \( \omega_o \) and \( Q \) are

\[
-S^a_o = S^b_o = S^a_o = S^a_o = S^b_o = -1
\]

\[
-S^a_o = S^b_o = S^a_o = S^b_o = -1
\]
all of which are small.

**Influence of Parasitic Elements**

A non-ideal MODVCC model is shown in Fig. 6. It is shown that the real MODVCC has parasitic resistors and capacitors from the y1, y2 and z terminals to the ground, and also, a series resistor at the input terminal x. The non-ideal MOCII model can also be obtained from Fig. 6 by deleting y2 terminal. Taking into account the non-ideal current conveyors and assuming the circuits are working at frequencies much lower than the corner frequencies of \( \alpha_{\alpha} \) and \( \beta_{\beta} \), namely, \( \alpha_{\alpha} \equiv \beta_{\beta} \equiv 1 \). Moreover, in practical current conveyors, the external resistors can be chosen to be much smaller than the parasitic resistors at the y and z terminals of current conveyors and much greater than the parasitic resistors at the x terminals of current conveyors, i.e., \( R_y, R_z \gg R_k \gg R_x \). The external capacitances \( C_1 \) and \( C_2 \) can be chosen to be much greater than the parasitic capacitances at the y terminals and z terminals of the current conveyors are equal, i.e., \( C_y \equiv C_z \). Under these conditions, the output voltages and currents of Fig. 5 become

\[
V_{o1} \approx \frac{sC_1G_1G_2G_4'}{s^2C_1' C_2' C_3' + sC_1' C_2' C_4'(G_3 + 2G_4')} I_{in}
+ sC_1' C_2' C_3' G_4' + sC_1' C_2' G_2' G_4' + G_2' G_4' G_4'
\]

\[
V_{o2} \approx \frac{sC_1' C_2' C_3' + sC_2' C_3' G_4'}{s^2C_1' C_2' C_3' + sC_2' C_3' C_4'(G_3 + 2G_4')} I_{in}
+ sC_1' C_2' C_3' G_4' + sC_2' C_3' G_2' G_4' + G_2' G_4' G_4'
\]

where \( C_1' = C_1 + C_{z1} + C_{y2} \), \( C_2' = C_2 + C_{z1} + C_{z2} + R_x' = R_1 + R_x \), \( R_2' = R_2 + R_{x2} \), \( G_1' = G_3 + G_{z12} \), \( G_2' = G_4 + G_{z23} \), \( G_a = G_{z1} + G_{z2} \), \( G_b = G_{z11} + G_{z21} \).

In Eqs (20)-(27), undesirable factors are yielded by the non-idealities of the current conveyors. The effect of capacitance \( C_z \) become non-negligible at very high frequencies, the conductances \( G_a \) and \( G_b \) become non-negligible at very low frequencies. To minimize the effects of the current conveyors’ non-idealities, the operation angular frequency should be restricted to the following conditions.
\[ \omega \ll \min \left\{ \frac{G_{\text{b}} G'_{G}}{C_z^2}, \sqrt{\frac{G_{\text{a}} G_{\text{d}}}{C_z C_1 C_2' (G_3' + 2G_4')}}, \frac{G_{\text{b}} G_0}{C_z} \right\} \quad \ldots (28) \]

\[ \omega \gg \max \left\{ \frac{G_{\text{b}}}{C_z^2}, \frac{C_1' G_0 + C_2' G_6}{C_1' C_2'}, \sqrt{\frac{G_{\text{a}} G_0}{C_1' C_2'}} \right\} \quad \ldots (29) \]

Moreover, application of the Routh-Hurwitz test to the denominator of Eq. (20) shows that \( C_z \) may cause the root with positive real part. According to this test, the roots of the denominator will keep in left-half s-plane if

\[
C_z < \min \left\{ \frac{C_1' G_3'(G_3' + 2G_4')}{G_1' G_2'}, \frac{C_1' C_2' G_3' (G_3' + 2G_4')}{C_1' G_3' (G_3' + 2G_4')^2 + C_2' G_1' G_2' G_4'} \right\} \quad \ldots (30)
\]

It is not difficult to satisfy this condition, since the external capacitances \( C_1 \) and \( C_2 \) can be chosen much greater than \( C_z \).

**Simulation Results**

HSPICE simulations with 0.18 \( \mu \)m level 49 MOSFET from TSMC were carried out to demonstrate the feasibility of the proposed circuit in Fig. 5. The MOCCII was realized by the CMOS implementation in Fig. 2. The MODVCC was realized by the CMOS implementation in Fig. 4. The aspect ratios of the PMOS and NMOS transistors are \( W/L = 9\mu/0.9\mu \) and \( W/L = 4.5\mu/0.9\mu \), respectively. Figures 7 (a), (b), (c), (d) and (e) represent the simulated frequency responses for the transimpedance-mode lowpass \( (V_{o1}) \), notch \( (V_{o2}) \), bandpass \( (V_{o3}) \), highpass \( (V_{o4}) \) and allpass \( (V_{o5}) \) filters.
Fig. 7 (e) – Simulation results of the proposed transimpedance-mode filters: (a) lowpass filter, (b) notch filter, (c) bandpass filter, (d) highpass filter and (e) allpass filter.

Fig. 8 – Simulated frequency responses for the bandpass filter ($V_{o3}$) of Fig. 5 designed with $C_1 = C_2 = 10 \text{ pF}$ and $R_1 = R_2 = R_3 = R_4 = 10 \text{ k}\Omega$. The supply voltages are $V^+ = +0.9 \text{ V}$, $V^- = -0.9 \text{ V}$, $V_{b1} = V_{b2} = -0.38 \text{ V}$, $V_{b3} = 0.38 \text{ V}$. Figure 8 represents the simulated frequency responses for the bandpass filter ($V_{o3}$) of Fig. 5 as the resistor $R_3$ in $Q$ is varied designed with: $C_1 = C_2 = 10 \text{ pF}$ and $R_1 = R_2 = R_3 = R_4 = 10 \text{ k}\Omega$. The non-idealities may be due to the ignored parasitic elements of the conveyors.

In Fig. 9, total harmonic distortion (THD) of the current bandpass signals ($I_{o2}$) are given at 1.58 MHz operation frequency designed with: $C_1 = C_2 = 10 \text{ pF}$ and $R_1 = R_2 = R_3 = R_4 = 10 \text{ k}\Omega$. Figure 9 shows the transient analysis of the current bandpass signal ($I_{o2}$) for various temperature (0°C, 27°C, 100°C) where sinusoidal signal with 3.1623 μA amplitude; 1.58 MHz was applied to the filter input.

Conclusions
A current-mode and transimpedance-mode universal biquadratic filter with single current input terminal using one MOCCII, one MODVCC, four resistors and two grounded capacitors is presented. The new circuit offers several advantages, such as using minimum active and passive components, five kinds of standard transimpedance-mode filter functions can be obtained simultaneously, five kinds of standard current-mode filter functions can be obtained from the same circuit configuration, very
low filter sensitivities, the use of grounded capacitors and direct incorporation of the parasitic resistance at the x terminal of the current conveyor as a part of the main resistance.

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References