Current-Mode and Transimpedance-Mode Biquadratic Filter Circuit Using Five OTAs

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Abstract—A current-mode and transimpedance-mode biquadratic filter circuit with single current input terminal using five operational transconductance amplifiers and two grounded capacitors is presented. The proposed circuit can realize current-mode highpass, bandpass and lowpass responses, simultaneously. The current-mode notch and allpass responses can be obtained by interconnection of relevant output currents. Moreover, the transimpedance-mode highpass, bandpass and lowpass filters can also be obtained, simultaneously, from the proposed circuit. The resonance angular frequency and quality factor can be orthogonally adjusted.

Index Terms—Active filter; Operational transconductance amplifier; Biquadratic, Frequency response, Analog signal processing.

I. INTRODUCTION

Operational transconductance amplifiers (OTAs) are attractive active elements in the implementation of active circuits. The OTAs based circuits offer resistorless filter structures. This is because of the OTA’s small signal transconductance parameter (g_m) is utilized for realizing the time-constant of the filter [1-4]. As this parameter (g_m) is controlled though an appropriate dc current/voltage, the resulted filter structures have the capability of the electronic tuning of their frequency characteristics. Active filters with input currents and output currents are defined as current-mode filters. Active filters with input currents and output voltages are defined as transimpedance-mode filters. Current-mode or transimpedance-mode filters have many applications in analogue signal processing [5-8].

Current-mode analogue signal processing circuit techniques are attractive because of their better linearity, wider bandwidth, larger dynamic range and the simplicity of implementation signal operations such as addition, subtraction and multiplication [9-13]. A transimpedance-mode filter is used as an interface circuit connecting a current-mode circuit to a voltage-mode circuit. The receiver baseband (BB) blocks of modern radio systems is one of the most important application areas of transimpedance-mode filters [14]. Current-mode active filters with high output impedences are attractive because they can be directly connected in cascade to implement higher order filters without loading problem [15-16]. On the other hand, from the point of view of integrated circuit fabrications and reducing parasitic capacitances, the use of only grounded capacitors is beneficial [17].

Several mixed-mode biquadratic filters using OTAs have been reported [18-23]. However, because the current-mode types of these circuits require two or three current input signals in the realizations of some filter functions, other current followers are needed to duplicate the input current signal for these situations. This solution is sensitive to the precision of providing these copies because of parasitic zeros, which appear in the transfer functions. Moreover, the use of additional input current signals will add parasitic capacitors and resistors into the main circuit, which will degrade the performance of these circuits.

In 1998, Wu and El-Masry proposed a current-mode biquadratic filter using three OTAs [24]. However, a capacitor it used is not grounded. In 2005, Bhaskar et al. proposed two current-mode biquadratic filters each using four OTAs [25]. However, the resonance angular frequency and quality factor of the first circuit cannot be orthogonally controllable. The allpass filter realization of the second circuit require matching condition.

In this paper, a new current-mode and transimpedance-mode biquadratic filter circuit is presented. The proposed circuit requires five OTAs and two grounded capacitors. The proposed circuit has single current input terminal, three current output terminals and three voltage output terminals. The current-mode highpass, bandpass and lowpass filters can be obtained simultaneously. The realizations of current-mode notch or allpass functions do not need additional components in either case as this can be simply achieved by connecting the appropriate nodes. Moreover, the transimpedance-mode highpass, bandpass and lowpass filters can also be obtained, simultaneously, from the proposed circuit.

II. PROPOSED CIRCUIT

The OTA is a differential voltage-controlled current source with transconductance gain g_m, which can be characterized by $I_{out} = g_m (V_+ - V_-)$. The circuit symbol of the multi-output OTA is shown in Fig. 1 which shows the two types of output current terminals, the positive output represented by terminal “+” and the negative by terminal “-”.

Fig. 1 Multi-output OTA circuit symbol.
The output currents can be expressed as

\[ I_{o1} = \frac{s^2C_1C_2g_5}{s^2C_1C_2g_5 + sC_2g_1g_4 + g_1g_2g_3}I_{in} \]  
\[ I_{o2} = \frac{-sC_2g_4}{s^2C_1C_2g_5 + sC_2g_1g_4 + g_1g_2g_3}I_{in} \]  
\[ I_{o3} = \frac{g_2g_3}{s^2C_1C_2g_5 + sC_2g_1g_4 + g_1g_2g_3}I_{in} \]

From (4)-(6) it can be seen that a current-mode highpass output signal can be obtained at \( I_{o1} \), a current-mode inverting bandpass current signal can be obtained at \( I_{o2} \) and a current-mode lowpass signal can be obtained at \( I_{o3} \). A current-mode notch signal is easily obtained by connecting the \( I_{o1} \) and \( I_{o3} \) output terminals. Let \( I_{notch} = I_{o1} + I_{o3} \), we obtain the current-mode notch output current:

\[ I_{notch} = \frac{s^2C_1C_2g_5 + g_1g_2g_3}{s^2C_1C_2g_5 + sC_2g_1g_4 + g_1g_2g_3}I_{in} \]

Similarly, by connecting the \( I_{o1} \), \( I_{o2} \) and \( I_{o3} \) output terminals \( (I_{allpass} = I_{o1} + I_{o2} + I_{o3}) \), a current-mode allpass output current can be obtained by

\[ I_{allpass} = \frac{s^2C_1C_2g_5 - sC_2g_1g_4 + g_1g_2g_3}{s^2C_1C_2g_5 + sC_2g_1g_4 + g_1g_2g_3}I_{in} \]

Since the output impedances of \( I_{o1} \), \( I_{o2} \) and \( I_{o3} \) are high, the high output impedances make the output currents easy to be connected to next stage without any buffer.

In all the above cases, the resonance angular frequency \( \omega_0 \) and the quality factor \( Q \) are given by

\[ \omega_0 = \frac{g_1g_2g_3}{\sqrt{C_1C_2g_5}} \]  
\[ Q = \frac{1}{g_4 \sqrt{C_1g_3g_5}} \]

From (9) and (10) one can see that resonance angular frequency and quality factor can be orthogonally adjusted. The active and passive sensitivities of \( \omega_0 \) and \( Q \) are

\[ S_{\omega_0}^{o1}g_{1}g_{2}g_{3} = -S_{\omega_0}^{o1}C_{1}C_{2}g_{5} = \frac{1}{2}, \]  
\[ S_{g_{4}}^{Q}C_{2}g_{1}g_{3} = -S_{g_{4}}^{Q}C_{1}g_{2}g_{5} = \frac{1}{2}, S_{g_{4}}^{Q} = -1. \]  
all of which are small.

### III. Simulation Results

The current-mode filters were simulated using HSPICE with 0.18\( \mu \)MOSFET from TSMC. The CMOS OTA implementation is shown in Fig. 2. The aspect ratios of the MOS transistors were chosen as in Table 1. Fig. 4 (a), (b) and (c) represent the simulated frequency responses for the current-mode highpass (\( I_{o1} \)), bandpass (\( I_{o2} \)) and lowpass (\( I_{o3} \)) filters of Fig. 3, respectively, designed with \( f_0 = 266.92 \text{ KHz} \), \( Q = 0.79643 \), \( C_1 = C_2 = 100 \text{ pF} \), \( g_1 = g_2 = g_4 = 167.7129 \text{ \mu S} \), and \( g_2 = g_3 = 133.5715 \text{ \mu S} \). The supply voltages are \( V_{DD} = +1.25 \text{ V} \), \( V_{SS} = -1.25 \text{ V} \). The bias voltage \( V_b \) of each OTA are
-0.6V, -0.65V, -0.6V, -0.6V, -0.65V, respectively. The power dissipation is 0.62mW. Fig. 5 represents the simulated frequency responses for the current-mode notch filter of Fig. 3, designed connecting the highpass ($I_{o1}$) and lowpass ($I_{o3}$) output terminals. Fig. 6 represents the simulated frequency responses for the current-mode allpass filter of Fig. 3, designed connecting the highpass ($I_{o1}$), bandpass ($I_{o2}$) and lowpass ($I_{o3}$) output terminals.

Fig. 7 represents the frequency responses for the current-mode bandpass filter of Fig. 3 as the conductance $g_4$ in $Q$ is varied with $C_1 = C_2 = 100$ pF, $g_1 = g_3 = 167.7129$ μS, and $g_2 = g_5 = 133.5715$ μS. Fig. 8 shows the square wave response of the filter of Fig. 3 with 40 μA-pp input at $I_{in}$ and $I_{o1}$, $I_{o2}$ and $I_{o3}$ outputs which confirms the stability of Fig. 3. To observe the incompatibility of passive components on the filter’s performances, a Monte-Carlo analysis is performed by selecting the values of capacitors $C_1$ and $C_2$ to 100 pF with a 10% Gaussian deviation for 100 simulation runs for a 266.92 kHz pole frequency. The Monte-carlo simulations of magnitude response and phase response for bandpass ($I_{o2}$) filter are shown in Fig. 9. Figure 10 (a), (b) and (c) shows the magnitude frequency responses of $I_{o1}$, $I_{o2}$ and $I_{o3}$ outputs, respectively, when the temperature was changed from −20 to 85 °C.
Fig. 7 Simulation results of the proposed current-mode bandpass filter in Fig. 3 design with $C_1 = C_2 = 100 \, \text{pF}$, $g_1 = g_3 = 167.7129 \, \mu\text{S}$, and $g_2 = g_5 = 133.5715 \, \mu\text{S}$, “- - -”, ideal curve; “o o o”, $g_4 = 167.7129 \mu\text{S}$; “+ + +”, $g_4 = 133.5715 \mu\text{S}$; “\n\n\n”, $g_4 = 103.3747 \mu\text{S}$; “***”, $g_4 = 72.1517 \mu\text{S}$.

Fig. 8 Stability tests of Fig 3. (a) Highpass filter ($I_{o1}$); (b) Bandpass filter ($I_{o2}$); (c) Lowpass filter ($I_{o3}$).

Fig. 9 Monte-Carlo analysis of (a) magnitude response and (b) phase response for current-mode bandpass filter ($I_{o2}$).
IV. CONCLUSIONS

A current-mode and transimpedance-mode biquadratic filter with single current input terminal, three current output terminals and three voltage output terminals using five OTAs and two grounded capacitors is presented. The new circuit offers several advantages, such as three 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 and the use of grounded capacitors. The current-mode filters also have the advantages of high output impedances.

REFERENCES


Table 1 Aspect ratios of the MOSFETs in Fig. 2.

<table>
<thead>
<tr>
<th>MOS transistors</th>
<th>Aspect ratio (W/L)</th>
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<tr>
<td>M₁-M₁₂</td>
<td>6.3/0.9</td>
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<tr>
<td>M₁₃, M₁₄</td>
<td>7.2/0.9</td>
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<tr>
<td>M₁₅-M₂₃</td>
<td>2.7/0.9</td>
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