Electronically Controllable Dual-Mode Universal Biquadratic Filter Using Triple-Output OTAs

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Abstract

This article presents a dual-mode (voltage-mode and current-mode) universal biquadratic filter performing completely standard functions: low-pass, high-pass, band-pass, band-reject and all-pass function based on triple-output operational transconductance amplifiers (Triple-Output OTA). The features of the circuit are that the bandwidth quality factor and natural frequency can be tuned electronically via the input bias currents. The circuit description is very simple, consisting of merely 2 triple-output OTAs and 2 capacitors. The circuit can provide either the voltage-mode or current-mode filter without changing circuit topology. Additionally, each function response can be selected by suitably selecting input signals with digital method. Without any external resistors, the proposed circuit is very suitable to further develop...
into an integrated circuit. The PSPICE simulation results are depicted. The given results agree well with the theoretical anticipation. The maximum power consumption is approximately 1.64mW at ±1.5V supply voltages.

**Keywords**: Universal Filter, Dual-Mode, Triple-Output OTAs

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### Introduction

An analog filter is an important block and widely used for continuous-time signal processing. It can be found in many fields: for instance, communication, measurement and instrumentation and control systems [1-2]. One of most popular analog filters is a universal biquadratic filter since it can provide several functions. Nowadays, a universal filter working in current-mode has being more popular than voltage-mode one. Since the last decade, there has been much effort to reduce the supply voltage of analog systems. This is due to the command for portable and battery-powered equipment. Since a low-voltage operating circuit becomes necessary, the current-mode technique is ideally suited for this purpose. Actually, a circuit using the current-mode technique has many other advantages: for example, larger dynamic range, higher bandwidth, greater linearity, simpler circuitry and lower power consumption [3-4]. However, in present, the voltage-mode circuits are still used in some applications.

The OTA has received considerable attention as active components, because the transconductance can be adjusted electronically, especially suitable for analog circuits [5]. The flexibility of the devices to operate in both current and voltage-modes allows for a variety of circuit designs.

In many applications, voltage and current-mode circuits are used to be connected which causes some difficulties that can be overcame by using voltage-to-current and current-to-voltage converters at the interface of these circuits. During V-I interfacing, it is also possible to perform signal processing at the same time so that the total effectiveness of the electronic circuitry can be increased [6]. The literature surveys show that the dual-mode universal filter circuit using different high-performance active building blocks such as OTAs [7-9], current feedback op-amps (CFOAs) [10], current feedback amplifiers (CFAs) [11-12], Four-Terminal Floating Nullors (FTFNs) [6, 12-15] and current conveyors [16-20], have been reported. Unfortunately, these reported circuits suffer from one or more of following weaknesses:

- Excessive use of the active and/or passive elements [6, 10-13, 15-20].
- Require changing circuit topologies to achieve several functions [7-8, 11-13].
- Can not provide completely standard functions [6-7, 9, 11-12, 15-16, 18].
- Can not provide functions both in voltage and current-modes with the same topology [9, 11, 13, 15].
This work is arranged to propose a new voltage/current–mode universal biquadratic filter, emphasizing on use of triple-output OTAs. The features of proposed circuit are that: the proposed universal filter can provide completely standard functions both in voltage-mode and in current-mode without changing circuit topology by appropriately selecting the input signals: the circuit description is very simple, it consists of 2 triple-output OTAs and 2 capacitors, which is suitable for fabricating in monolithic chip: the filter does not require any external resistor. In addition, the natural frequency and the bandwidth can be tuned electronically by adjusting the bias currents. Its performances are illustrated by PSPICE simulations, they show good agreement as mentioned.

**Figure 1. DO-OTA (a) Symbol (b) Equivalent circuit**

Principle of operation

Triple-output operational transconductance amplifier (Triple-Output OTA)

An ideal triple-output OTA has infinite input and output impedances. The output current of a triple-output OTA is given by

\[
I_{O1} = I_{O2} = I_{O3} = g_m (V_1 - V_2).
\]

where \( g_m \) is the transconductance of the triple-output OTA. For a bipolar triple-output OTA, the transconductance can be expressed to be

\[
g_m = \frac{I_B}{2 V_T},
\]

where \( I_B \) and \( V_T \) are the bias current and thermal voltage, respectively. The symbol and the equivalent circuit of the triple-output OTA are illustrated in Fig. 1(a) and (b), respectively.

**Figure 2. Proposed dual-mode universal filter**
Proposed filter

The proposed dual-mode universal filter is shown in Fig. 2, where \( I_{B1} \) and \( I_{B2} \) are input bias currents of OTA \(_1\) and OTA \(_2\), respectively. They are used to control the corresponding parasitic resistances.

For voltage-mode case, where \( V_{in1} = V_{in2} = V_{in3} = 0 \), straightforwardly analyzing the filter in Fig. 2, the output voltage can be obtained to be

\[
V_o = \frac{s^2C_1V_{in1} + (sC_1g_m + g_mR_2)\cdot V_{in2} - sC_1g_m\cdot V_{in3}}{sC_1C_2 + sC_1g_m + g_mR_2}. \quad (3)
\]

From Eq. (3), \( V_{in1}, V_{in2}, \) and \( V_{in3} \) can be chosen as in Table I to obtain a standard function of the 2nd-order network. From Table I, it should be remarked that, in case of the LP, BR and AP, the circuit condition: \( R_{x1} = R_{x2} \) is required. Moreover, \( V_{in3} \) must be double of \( V_{in1} \) and \( V_{in2} \) in the case of AP. So to achieve this condition, the voltage amplifier which has gain of 2 is required.

<table>
<thead>
<tr>
<th>Filter Responses</th>
<th>Input selections</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>0 0 1</td>
</tr>
<tr>
<td>HP</td>
<td>1 0 0</td>
</tr>
<tr>
<td>BR (( g_{m1} = g_{m2} ))</td>
<td>1 1 1</td>
</tr>
<tr>
<td>AP (( g_{m1} = g_{m2} ))</td>
<td>1 1 2</td>
</tr>
<tr>
<td>LP (( g_{m1} = g_{m2} ))</td>
<td>0 1 1</td>
</tr>
</tbody>
</table>

For current-mode case, where \( V_{in1} = V_{in2} = V_{in3} = 0 \), straightforwardly analyzing the circuit in Fig. 2, the output current can be obtained to be

\[
I_o = \frac{(s^2C_1C_2 + sC_1g_m + g_mR_2)\cdot I_{in1} - sC_1g_m\cdot I_{in2} - g_mR_2\cdot I_{in3}}{s^2C_1C_2 + sC_1g_m + g_mR_2}. \quad (4)
\]

From Eq. (4), the magnitudes of input currents \( I_{in1}, I_{in2}, \) and \( I_{in3} \) can be chosen as in Table II to obtain a standard function of the network. The circuit of digital selection can be seen in [21].

<table>
<thead>
<tr>
<th>Filter Responses</th>
<th>Input selections</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (_o)</td>
<td>I (<em>{in1}) I (</em>{in2}) I (_{in3})</td>
</tr>
<tr>
<td>BP</td>
<td>1 0 0</td>
</tr>
<tr>
<td>HP</td>
<td>1 1 1</td>
</tr>
<tr>
<td>BR</td>
<td>1 0 1</td>
</tr>
<tr>
<td>AP</td>
<td>2 0 1</td>
</tr>
<tr>
<td>LP</td>
<td>0 1 0</td>
</tr>
</tbody>
</table>

From Eqs. (3)-(4), for dual-mode, the natural frequency \( (\omega_0) \) and quality factor \( (Q_0) \) of each filter response can be expressed to be

\[
\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad (5)
\]

\[
Q_0 = \sqrt{\frac{C_1g_{m2}}{C_2g_{m1}}}, \quad (6)
\]
Substituting the transconductance as depicted in Eq. (2), it yields

$$\omega_0 = \frac{1}{2V_T} \sqrt{\frac{I_{g1}I_{g2}}{C_1C_2}} \quad (7)$$

$$Q_0 = \frac{C_1I_{g2}}{C_2I_{g1}} \quad (8)$$

From Eqs. (7) and (8), by maintaining the ratio $I_{g1}$ and $I_{g2}$ to be constant, it can be remarked that the natural frequency can be adjusted by $I_{g1}$ and $I_{g2}$ without affecting the quality factor. In addition, bandwidth (BW) of the system can be expressed by

$$BW = \omega_0 = \frac{2I_{g1}}{C_1V_T} \quad (9)$$

We found that the bandwidth can be linearly controlled by $I_{g1}$. Moreover, it can be seen that the natural frequency can be adjusted orthogonally from the bandwidth by varying $I_{g2}$. Moreover, in current-mode case due to high output impedance, so it is easy cascading in current-mode but in voltage-mode the output impedance is quit low.

### Circuit sensitivities

The sensitivities of the proposed circuit can be found as

$$S_{c1,c2}^{\omega_0} = -\frac{1}{2}, \quad S_{I_{g1},I_{g2}}^{\omega_0} = \frac{1}{2}, \quad S_{I_{g1},I_{g2}}^{Q_0} = \frac{1}{2}, \quad (10)$$

and

$$S_{c2,I_{g1}}^{BW} = -1, \quad S_{I_{g1},I_{g2}}^{Q_0} = 1. \quad (12)$$

Therefore, all the active and passive sensitivities are equal or less than unity in magnitude.

#### Simulation results

To prove the performances of the proposed circuit, the PSPICE simulation program was used for the examinations. The PNP and NPN transistors
employed in the proposed circuit were simulated by respectively using the parameters of the PR200N and NR200N bipolar transistors of ALA400 transistor array from AT&T [22]. Fig. 3 depicts schematic description of the triple-output OTA used in the simulations. The circuit was biased with ±1.5V supply voltages. $C_1=C_2=1nF$ and $I_{B1}=I_{B2}=100\mu A$ are chosen.

Figure 4. Gain and phase responses of the biquad filter in voltage-mode for (a) BP (b) HP (c) BR (d) AP (e) LP
The results shown in Fig. 4 are the gain and phase responses of the proposed biquad filter in voltage-mode obtained from Fig. 2. It yields the natural frequency of 261.81kHz, while calculated value of this parameter from Eq. (7) is 612.45kHz. There are seen that the proposed filter in voltage-mode can provide low-pass, high-pass, band-pass, band-reject and all-pass functions dependent on selection as shown in Table I, without modifying circuit topology.

The gain and phase responses of the proposed biquad filter in current-mode are shown in Fig. 5. There are seen that the proposed filter in current-mode can also provide completely standard functions dependent on selection as shown in Table II. Fig. 6 shows gain responses of band-pass function where I_{b1} and I_{b2} are equally set to keep the ratio to be constant and changed for several values. It is found that pole frequency can be adjusted without affecting the quality factor, as depicted in Eqs. (7) and (8). Maximum power consumption is about 1.64mW.

**Conclusions**

The dual-mode universal biquadratic filter based on triple-output OTAs has been presented. The advantages of the proposed circuit are that: it performs low-pass, high-pass, band-pass, band-reject and all-pass functions dependent on an appropriate selection of three signals in dual-mode: the bandwidth and the natural frequency can be electronically controlled via input bias currents, it is easily modified to use in control systems using a microcontroller [3]. The circuit description comprises only 2 triple-output OTAs and 2 capacitors. With mentioned features, it is very suitable to realize the proposed circuit in monolithic chip to use in battery-powered, portable electronic equipments such as wireless communication system devices.

**References**


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