Research Article

Supplementary High-Input Impedance Voltage-Mode Universal Biquadratic Filter Using DVCCs

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To further extend the existing knowledge on voltage-mode universal biquadratic filter, in this paper, a new biquadratic filter circuit with single input and multiple outputs is proposed, employing three differential voltage current conveyors (DVCCs), three resistors, and two grounded capacitors. The proposed circuit realizes all the standard filter functions, that is, high-pass, band-pass, low-pass, notch, and all-pass filters simultaneously. The circuit enjoys the feature of high-input impedance, orthogonal control of resonance angular frequency (ω_o), and quality factor (Q) via grounded resistor and the use of grounded capacitors which is ideal for IC implementation.

1. Introduction

Analog filters are the basic building blocks and widely used for continuous-time signal processing. Application of analog filters employing current-mode active elements extends over a large number of fields [1]. The filter circuits may be used in phase-locked loop frequency modulation stereo demodulators, touch-tone telephone tone decoder, and cross-over networks in a three-way high fidelity loudspeaker [2, 3]. In the literature several voltage-mode biquadratic filters are presented which uses different types of current conveyors [4–28]. The voltage-mode filters with high-input impedance are of great interest because they can be easily cascaded to synthesize higher-order filters [7, 10, 13, 17, 26, 28]. In the literature there are a number of voltage-mode universal biquadratic filters with single-input multiple-outputs (SIMO) [4–12, 18] that are available. However, these reported circuits suffer from one or more of the following drawbacks:

- (i) excessive use of passive components [4, 6, 7];
- (ii) low-input impedance [5, 6, 8, 9, 11, 18];

- (iii) lack of orthogonal control over the resonance angular frequency (ω_o) and quality factor (Q) [10, 12].

In this paper, a new voltage-mode universal biquadratic filter using three differential voltage current conveyors [29], two grounded capacitors, and three resistors is presented. The circuit realizes the entire standard filter functions, that is, high pass (HP), band pass (BP), low pass (LP), notch (NH), and all pass (AP) from the same circuit configuration. The circuit also possesses high-input impedance and provides orthogonal control of the ω_o and Q via grounded resistor.

2. Differential Voltage Current Conveyor (DVCC)

The DVCC is first introduced long back as a modified current conveyor by Pal [30] and developed by Elwan and Soliman in 1997 [29]. It is a versatile building block, especially designed to handle differential and floating input signals [30, 31]. Using standard notation, the terminal relations of a DVCC

FIGURE 1: (a) Symbol of DVCC. (b) CMOS implementation of DVCC.

FIGURE 2: Voltage-mode universal biquadratic filter.

are shown in Figure 1 and described by the following matrix equation:

$$\begin{bmatrix} I_{Y_1} \\ I_{Y_2} \\ V_X \\ I_{Z+} \\ I_{Z-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{Y_1} \\ V_{Y_2} \\ I_X \\ V_{Z+} \\ V_{Z-} \end{bmatrix}. \quad (1)$$

The difference of the \$Y_1\$ and \$Y_2\$ terminal voltages is conveyed to the \$X\$ terminal; the current input at the \$X\$ terminal is conveyed to the \$Z+\$, with the same polarity and \$Z-\$ terminal with inverse polarity. The DVCC is characterized by high-input impedance at the \$Y_1\$ and \$Y_2\$ terminals, high-output impedance at the \$Z+\$ and \$Z-\$ terminals, and low impedance at the \$X\$ terminal.

3. Proposed Circuit

The proposed voltage-mode universal biquadratic filter is shown in Figure 2, employing three DVCCs, three resistors, and two grounded capacitors. The routine analysis of the

proposed circuit in Figure 2 using (1) yields the filter transfer functions as

$$\begin{aligned} \frac{V_{OUT1}}{V_{IN}} &= \frac{1}{s^2 C_1 C_2 R_1 R_2 + s C_1 R_3 + 1} \\ \frac{V_{OUT2}}{V_{IN}} &= \frac{s^2 C_1 C_2 R_1 R_2}{s^2 C_1 C_2 R_1 R_2 + s C_1 R_3 + 1} \\ \frac{V_{OUT3}}{V_{IN}} &= \frac{s C_1 R_1}{s^2 C_1 C_2 R_1 R_2 + s C_1 R_3 + 1} \\ \frac{V_{OUT4}}{V_{IN}} &= \frac{s^2 C_1 C_2 R_1 R_2 + 1}{s^2 C_1 C_2 R_1 R_2 + s C_1 R_3 + 1} \\ \frac{V_{OUT5}}{V_{IN}} &= \frac{s^2 C_1 C_2 R_1 R_2 - s C_1 R_1 + 1}{s^2 C_1 C_2 R_1 R_2 + s C_1 R_3 + 1}. \end{aligned} \quad (2)$$

It can be seen from (2) that an LP response is obtained from \$V_{OUT1}\$; HP response is obtained from \$V_{OUT2}\$; BP response is obtained from \$V_{OUT3}\$; NH response is obtained from \$V_{OUT4}\$; if \$R_3 = R_1\$, AP response is obtained from \$V_{OUT5}\$. In all the cases, the parameters \$\omega_o\$ and \$Q\$ of the filter can be found as

$$\begin{aligned} \omega_o &= \left(\frac{1}{C_1 C_2 R_1 R_2} \right)^{1/2}, \\ Q &= \frac{1}{R_3} \sqrt{\frac{R_1 R_2 C_2}{C_1}}. \end{aligned} \quad (3)$$

TABLE 1: TSMC 0.35 μm CMOS process parameters.

NMOS
LEVEL = 3 TOX = $7.9E - 9$ NSUB = $1E17$ GAMMA = 0.5827871 PHI = 0.7 VTO = 0.5445549 DELTA = 0 UO = 436.256147 ETA = 0 THETA = 0.1749684
KP = $2.055786E - 4$ VMAX = $8.309444E4$ KAPPA = 0.2574081 RSH = 0.0559398 NFS = $1E12$ TPG = 1 XJ = $3E - 7$ LD = $3.162278E - 11$
WD = $7.04672E - 8$ CGDO = $2.82E - 10$ CGSO = $2.82E - 10$ CGBO = $1E - 10$ CJ = $1E - 3$ PB = 0.9758533 MJ = 0.3448504 CJSW = $3.777852E - 10$ MJSW = 0.3508721
PMOS
LEVEL = 3 TOX = $7.9E - 9$ NSUB = $1E17$ GAMMA = 0.4083894 PHI = 0.7 VTO = -0.7140674 DELTA = 0 UO = 212.2319801 ETA = $9.999762E - 4$
THETA = 0.2020774 KP = $6.733755E - 5$ VMAX = $1.181551E5$ KAPPA = 1.5 RSH = 30.0712458 NFS = $1E12$ TPG = -1 XJ = $2E - 7$ LD = $5.000001E - 13$
WD = $1.249872E - 7$ CGDO = $3.09E - 10$ CGSO = $3.09E - 10$ CGBO = $1E - 10$ CJ = $1.419508E - 3$ PB = 0.8152753 MJ = 0.5 CJSW = $4.813504E - 10$ MJSW = 0.5

From (3), the Q of the proposed filter can be controlled independently of ω_o by varying R_3 . Since the input voltage signal is connected directly to the Y_1 port of the DVCC (1) and the input current to the Y_1 port is zero ($I_{Y_1} = 0$), the circuit has the feature of high-input impedance. Thus the proposed circuit is capable to realize all five standard filter functions simultaneously and without changing the circuit topology, unlike the previously proposed circuit in [26]. The circuit reported in [26] uses two floating resistors but the proposed circuit employs only one floating resistor. The circuit needs no component-matching conditions except for the all-pass filter realization.

Note that the proposed circuit uses two grounded capacitors at the Z -terminal and three resistors at the X -terminal of the DVCCs. The design offers the feature of a direct incorporation of the shunt parasitic capacitances at the Z -terminals and the series parasitic resistances at the X -terminal, as a part of the main capacitors (C_1 and C_2) and resistors (R_1 , R_2 , and R_3).

4. Nonideal Analysis

Taking the nonidealities of the DVCC into account, the relationship of the terminal voltages and currents of the DVCC can be rewritten as

$$\begin{bmatrix} I_{Y_1} \\ I_{Y_2} \\ V_X \\ I_{Z+} \\ I_{Z-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \beta_{k1} & -\beta_{k2} & 0 & 0 & 0 \\ 0 & 0 & \alpha_{k1} & 0 & 0 \\ 0 & 0 & -\alpha_{k2} & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{Y_1} \\ V_{Y_2} \\ I_X \\ V_{Z+} \\ V_{Z-} \end{bmatrix}, \quad (4)$$

where $\beta_{k1}(s)$, $\beta_{k2}(s)$ represent the frequency transfers of the internal voltage followers and $\alpha_{k1}(s)$, $\alpha_{k2}(s)$ represent the frequency transfers of the internal current followers of the k th-DVCC, respectively. They can be approximated by first-order low-pass functions, which can be considered to have a unity value for frequencies [30]. If this circuit is working at frequencies much less than the corner frequencies of $\beta_{k1}(s)$, $\beta_{k2}(s)$, $\alpha_{k1}(s)$, and, $\alpha_{k2}(s)$, namely, then $\beta_{k1}(s) = \beta_{k1} = 1 - \varepsilon_{kv1}$

FIGURE 3: Gain plots of LP, HP, and BP filters for $Q = 1$ at 3.18 MHz. FIGURE 4: Gain and phase plots of NH filter for $Q = 1$ at 3.18 MHz.

and $\varepsilon_{kv1}(|\varepsilon_{kv1}| \ll 1)$ denotes the voltage tracking error from the Y_1 terminal to the X terminal of the k th-DVCC; $\beta_{k2}(s) = \beta_{k2} = 1 - \varepsilon_{kv2}$ and $\varepsilon_{kv2}(|\varepsilon_{kv2}| \ll 1)$ denotes the voltage tracking error from the Y_2 terminal to the X terminal of the

FIGURE 5: Gain and phase plots of AP filter for $Q = 1$ at 3.18 MHz. FIGURE 6: Q tuning ($Q = 1, 5$, and 10) of BP filter at 3.18 MHz.

k th-DVCC, $\alpha_{k1}(s) = \alpha_{k1} = 1 - \varepsilon_{ki1}$, and $\varepsilon_{ki1}(|\varepsilon_{ki1}| \ll 1)$ denotes the current tracking error from the X terminal to the $Z+$ terminal; $\alpha_{k2}(s) = \alpha_{k2} = 1 - \varepsilon_{ki2}$ and $\varepsilon_{ki2}(|\varepsilon_{ki2}| \ll 1)$ denotes the current tracking error from the X terminal to the $Z-$ terminal of the k th-DVCC.

Taking the tracking errors of the nonideal DVCC into account, the denominator of (2) becomes

$$D(s) = s_2 C_1 C_2 R_2 \alpha_{22} (R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21}) + s C_1 R_3 \beta_{22} \beta_{31} \alpha_{11} \alpha_{22} + \beta_{12} \beta_{22} \beta_{32}. \quad (5)$$

The parameters ω_o and Q from (5) can be rewritten as

$$\omega_o = \left(\frac{\beta_{12} \beta_{22} \beta_{32}}{C_1 C_2 R_2 \alpha_{22} (R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})} \right)^{1/2},$$

$$Q = \frac{1}{R_3 \beta_{31} \alpha_{11}} \left(\frac{C_2 R_2 \beta_{12} \beta_{32} (R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})}{C_1 \beta_{22} \alpha_{22}} \right)^{1/2}. \quad (6)$$

The active and passive sensitivities of the proposed SIMO voltage-mode filter are derived from (6). These are as follows:

$$S_{C_1, C_2, R_2}^{\omega_o} = -\frac{1}{2},$$

$$S_{R_1}^{\omega_o} = -\frac{1}{2} \frac{R_1 \beta_{12}}{(R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})},$$

$$S_{\beta_{22}, \beta_{32}}^{\omega_o} = -S_{\alpha_{22}}^{\omega_o} = \frac{1}{2},$$

$$S_{\beta_{12}}^{\omega_o} = \frac{1}{2} \frac{(R_3 \alpha_{11} - R_3 \alpha_{11} \beta_{21})}{(R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})},$$

$$S_{R_3, \alpha_{11}}^{\omega_o} = -\frac{1}{2} \frac{R_3 \alpha_{11} (1 - \beta_{21})}{(R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})},$$

$$S_{\beta_{21}}^{\omega_o} = \frac{1}{2} \frac{R_3 \alpha_{11} \beta_{21}}{(R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})}, \quad (7)$$

$$S_{C_2, R_2}^Q = -S_{C_1}^Q = \frac{1}{2}, \quad S_{\beta_{32}}^Q = -S_{\beta_{22}, \alpha_{22}}^Q = \frac{1}{2},$$

$$S_{R_1}^Q = \frac{1}{2} \frac{R_1 \beta_{12}}{(R_3 \alpha_{11} (1 - \beta_{21}) + R_1 \beta_{12})},$$

$$S_{R_3, \alpha_{11}}^Q = \frac{(-2R_1 \beta_{12} - R_3 \alpha_{11} (1 - \beta_{21}))}{2(R_3 \alpha_{11} (1 - \beta_{21}) + R_1 \beta_{12})},$$

$$S_{\beta_{31}}^Q = -1,$$

$$S_{\beta_{12}}^Q = \frac{1}{2} \frac{(R_3 \alpha_{11} + 2R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})}{(R_3 \alpha_{11} + R_1 \beta_{12} - R_3 \alpha_{11} \beta_{21})},$$

$$S_{\beta_{21}}^Q = -\frac{1}{2} \frac{R_3 \alpha_{11} \beta_{21}}{(R_3 \alpha_{11} (1 - \beta_{21}) + R_1 \beta_{12})}.$$

From the results it is evident that the sensitivities are low and within unity in absolute value. Thus the proposed circuit can be classified as insensitive as all the active and passive sensitivities are less than or equal to unity [28].

5. Simulation Results

The performance of the proposed voltage-mode universal biquadratic filter in Figure 2 is verified using the PSPICE simulation program. The MOS transistors are simulated using 0.35 μ m CMOS process parameters given in Table 1. The aspect ratios of the transistors used in the simulation are given in Table 2. The supply voltages and biasing voltage are given by $V_+ = 2$ V, $V_- = -1.9$ V, $V_{b1} = -1.23$ V, and $V_{b2} = -1.15$ V, respectively. The proposed circuit is designed for 3.18 MHz and $Q = 1$ by choosing $R_1 = R_2 = R_3 = 5$ k Ω and $C_1 = C_2 = 10$ pF. Figure 3 shows the simulated gain responses for the LP, HP, and BP filters and agrees well with the designed values. Figures 4 and 5 show the simulated gain and phase responses for the NH and AP filters. Next, Q tuning of BP filter at constant frequency of 3.18 MHz is shown in Figure 6. The circuit of Figure 2 is designed for Q values of 1, 5, and 10 with R_3 values as 5 k Ω , 1 k Ω , and 500 Ω , respectively, with $C_1 = C_2 = 10$ pF and $R_1 = R_2 = 5$ k Ω .

FIGURE 7: Input (a) and HP output (b) signal waveforms to demonstrate the ac dynamic range at V_{OUT2} . FIGURE 8: THD variation with V_{IN} for HP filter at V_{OUT2} .

TABLE 2: Aspect ratios of the MOS in Figure 1.

MOS transistors	W (μm)	L (μm)
M_1 – M_4	1.2	0.8
M_7 , M_8	6.6	0.8
M_9 – M_{11} , M_{17} – M_{18}	18.6	0.6
M_5 , M_6 , M_{12} – M_{16}	24	0.8

To test the input dynamic range of the proposed filter, the simulation of the HP filter as example has been repeated for a sinusoidal input signal at 3.18 MHz. Figure 7 shows the input dynamic range of the HP filter which extends upto amplitude 200 mV (peak to peak) without significant distortion. In Figure 8, the total harmonic distortion (THD) of the V_{OUT2} output voltage is given at 3.18 MHz operation frequency. Figure 9 shows the INOISE and ONOISE simulated amplitude-frequency responses of the proposed LP filter at V_{OUT1} .

6. Conclusion

The voltage-mode universal biquadratic filter realizes all the standard filter functions by employing three DVCCs and five passive components. It offers high-input impedance, which permit the use of circuits in cascade without requiring any impedance-matching device. Moreover, the proposed circuit enjoys the following features: orthogonal control of ω_o and Q , low active and passive sensitivity, and the direct incorporation of parasitic resistance and parasitic capacitance at

FIGURE 9: The input and output referred noise spectral densities of the proposed LP filter at V_{OUT1} .

the X-terminal and Z-terminal of the respective DVCCs, as a part of main resistor and capacitor. So, the new circuit will enhance the existing knowledge on the voltage-mode universal biquadratic filter. PSPICE simulations with TSMC 0.35 μm process confirm the theoretical prediction.

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