MISO Type Mixed-Mode Biquad Filter Using Basic Active Elements

Chen-Nong Lee
Department of Computer and Communication Engineering, Taipei City University of Science and Technology, Taipei, Taiwan, R. O. C.

Abstract—This paper presents a new multiple-voltage/current-input single-voltage/current-output type (MISO type) mixed-mode (including voltage, current, transadmittance, and transimpedance modes) biquad filter using only two basic active elements (i.e. second-generation current conveyors (CCIs)), two grounded capacitors and two resistors, which are the least number of basic active components and the minimum number of passive components necessary for realizing current-mode all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass), in addition to voltage-mode bandpass, lowpass, transadmittance-mode highpass, bandpass, and transimpedance-mode bandpass, lowpass filtering responses without changing the filter topology. This represents the attractive feature from chip area and power consumption point of view. Moreover, the proposed biquad filter still achieves many advantages like having no need of components matching conditions, in addition to the employment of two grounded capacitors (attractive for integration), no need of inverting-type input signals or double-type input signals for the use of special input signals, high output impedance for current output and low sensitivity performance. H-SPICE simulation results confirm the theory.

Keywords—Active filters, basic active components, second-generation current conveyors, mixed-mode, biquad filter.

I. INTRODUCTION

Over the last decade, many voltage or current-mode universal biquad filters using different active elements have been reported. In some applications, however, we might intend to connect the voltage-mode circuits with the current-mode circuits. Thus, the transadmittance (i.e. input as voltage and output as current) and transimpedance (i.e. input as current and output as voltage) modes may play a very important role in the special filtering applications where we need to connect a voltage mode circuit with a current mode circuit and vice versa.

Therefore, the mixed-mode (input and output signals can be voltage or current) circuits are worthy of researches and presented for the use of any filtering requirement which is compatible with modern microelectronic systems applications, such as controls and voice and data communications, where consideration of size and weight make the use of inductors prohibitive.

In the past several decades, many mixed-mode filters using different active elements have been proposed [1-31]. The applications and advantages in the designing mixed-filters using basic active elements, such as second-generation current conveyors (CCIs), have received considerable attentions [1, 2, 7, 10, 18, 20, 21, 26, 30, 31]. The CCI has simpler implementation configuration than the other current conveyors, such as, differential voltage current conveyor (DVCC), differential difference current conveyor (DDCC), fully differential current conveyor (FDCCII), differential difference current conveyor transconductance amplifier (DDCCTA), differential voltage current conveyor transconductance amplifier (DVCCTA), current controlled current conveyor transconductance amplifiers (CCCTA), etc. For example, the use of a DCCII can be divided into two separate DDCCs. Similarly, a DCCCTA also can be produced by cascading a DDCC with an operational transconductance amplifier (OTA). Therefore, they can be regarded as two or more basic active elements. If active filters use only basic active elements, the filters have simple implementation configurations and this represents the attractive feature from chip area and power consumption point of view. Moreover, the CCI can also be built using commercially available IC, like AD844. It is well known that an AD844 can realize a CCI with additional buffered Z output. Several mixed-mode biquad filters using CCIs have been proposed [1, 2, 7, 10, 18, 20, 21, 26, 30, 31]. In [1], a current-conveyor-based mixed-mode universal biquad filter is proposed.
The biquad can realize all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) from the voltage and current output terminals. However, it needs to use seven CCIIIs, eight resistors, and two grounded capacitors. In [2], a mixed-mode universal biquad filter using CCIIIs is proposed. However, it needs to use five CCIIIs, seven resistors, and two grounded capacitors. Few mixed-mode (including voltage, current, transadmittance, and transimpedance modes) universal biquad filters which use only three CCIIIs have been presented [7, 10]. For example, in [7], the mixed-mode biquad filter uses three CCIIIs but it needs to use two switches and two/three grounded capacitors in addition to four resistors. In [10], the mixed-mode biquad filter also employs three CCIIIs, four resistors, and two capacitors but it needs to use floating capacitors which are not attractive for monolithic IC implementation. In 2009, Lee and Chang proposed a single FDCCII-based mixed-mode biquad filter [13]. The biquad filter [13] is based on one active element, namely fully differential current conveyor (FDCCII), and five floating/grounded passive elements. However, the FDCCII is not a basic active element. It can be divided into two separate DDCCs whereas the internal structure of the DDCC is also complex. Therefore, a FDCCII has more complex implementation configuration than two CCIIIs. In 2011, the reported mixed-mode universal biquad [24] use only three DDCCs, four resistors, and two grounded capacitors. However, the DDCCs are more complex active elements than the CCIIIs. In 2013, the recent publication [27] reported that mixed-mode biquad uses only four multiple-output current controlled second-generation current conveyors (MOCCCIIs) and two grounded capacitors. However, the biquad, reported in [27], needs to use four MOCCCIIs. In 2013, a new current-mode and transresistance-mode (i.e. transimpedance-mode) universal biquad filter was proposed by Lee [26]. Although the biquad filter [26] uses only two multiple-output CCIIIs (MOCCCIIs) in addition to two grounded capacitors and three grounded capacitors, it can not be operated in voltage-mode and transadmittance-mode. Moreover, the biquad filter [26] needs to use three resistors. In 2013, the recently reported mixed-mode [28] biquad using only two voltage differencing transconducatance amplifiers (VDTAs) and two grounded capacitors can realize all five universal filtering functions, but the biquad in [28] has not included current-mode and transimpedance-mode.

In 2014, the very recently reported mixed-mode [29] biquads using three OTAs and two grounded capacitors can realize all five universal filtering functions, but the biquad filter in [29] needs to use three basic active elements. Moreover, the biquad filter [29] only can be operated in transadmittance-mode.

Therefore, this leads to prospective research work: investigating and developing a mixed-mode (including voltage, current, transadmittance, and transimpedance modes) biquad filter structure using the least number of basic active components and the minimum number of passive components. In this paper, the proposed multiple-voltage/current-input single-voltage/current-output type (MISO type) circuit using only two CCIIIs (i.e. the least number of basic active components), two grounded capacitors and two resistors (i.e. the minimum number of passive components), which can be operated in all four possible modes (i.e. voltage, current, transadmittance, and transimpedance modes) and can realize current-mode all five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass) in addition to voltage-mode bandpass, lowpass, transadmittance-mode highpass, bandpass, and transimpedance-mode bandpass, lowpass filtering responses without changing the filter topology. Moreover, the proposed circuit still achieves many important advantages which are (i) using commercially available active components, (ii) using only two grounded capacitors at the Z terminals of the CCIIIs (attractive for monolithic IC implementation and absorbing shunt parasitic capacitance), (iii) high output impedance for current output, (iv) no need to impose component choice, (v) no need of inverting-type input signals or double-type input signals for the use of special input signals, and (vi) low active and passive sensitivities.

II. PROPOSED CIRCUIT

Figure 1 shows the proposed MISO type mixed-mode biquad filter structure using only two CCIIIs, two grounded capacitors and two resistors where $I_{in1}$, $I_{in2}$, and $I_{in3}$ are the filter input currents and $V_{in1}$ and $V_{in2}$ are the filter input voltages whose setting determine the filter functions as shown later, $I_{out}$ and $V_{out}$ are the filter current output and voltage output, respectively.
Using standard notation, the port relations of a CCII can be characterized by \( I_Y = 0, V_X = V_Y \) and \( I_{Za} = \pm I_X \). The multiple current outputs of CCII (1) can be simply reconstructed using current mirrors. Moreover, the current output has very high output impedance. We notice that two grounded capacitors at the Z terminals of two CCIIIs are attractive for integration and absorbing shunt parasitic capacitance. Routine circuit analysis for Figure 1 yields the following transfer functions:

\[
I_{out} = \frac{N_1(s) + G_1 N_2(s)}{D(s)}
\]

and

\[
V_{out} = \frac{N_3(s) + N_4(s)}{D(s)}
\]

in which

\[
N_1(s) = -s^2 C_1 C_2 I_{in1} + s C_3 G_1 I_{in2} - G_1 G_2 I_{in3}
\]

\[
N_2(s) = -s^2 C_1 C_2 V_{in1} + s C_1 G_2 V_{in2}
\]

\[
N_3(s) = -s C_2 I_{in1} + G_1 I_{in2} + (s C_2 + G_1) I_{in3}
\]

\[
N_4(s) = -s C_2 G_1 V_{in1} + G_1 G_2 V_{in2}
\]

\[
D(s) = s^2 C_1 C_2 + s C_1 G_1 + G_1 G_2
\]

From equation (1)-(7), the mixed-mode biquad filter transfer functions are obtained according to input voltage or current conditions as follows.

**Part I:** If \( V_{in1} = V_{in2} = 0 \), the following current-mode all five universal filtering responses can be obtained from \( I_{out} \) as below.

(i) Highpass: \( I_{in1} = I_{in}, \) and all the other input currents are zero.

(ii) Lowpass: \( I_{in3} = I_{in}, \) and all the other input currents are zero.

(iii) Bandpass: \( I_{in2} = I_{in}, \) and all the other input currents are zero.

(iv) Notch: \( I_{in1} = I_{in3} = I_{in}, \) and the other input current is zero.

(v) All-pass: \( I_{in1} = I_{in2} = I_{in3} = I_{in}. \)

**Part II:** If \( V_{in1} = V_{in2} = 0 \), the following transimpedance-mode bandpass and lowpass filtering responses can be obtained from \( V_{out} \) as below.

(i) Bandpass: \( V_{in1} = V_{in}, \) and all the other input currents are zero.

(ii) Lowpass: \( V_{in2} = V_{in}, \) and the other input voltage is zero.

**Part III:** If \( I_{in1} = I_{in2} = I_{in3} = 0 \), the following voltage-mode bandpass and lowpass filtering responses can be obtained from \( I_{out} \) as below.

(i) Bandpass: \( V_{in1} = V_{in}, \) and the other input voltage is zero.

(ii) Lowpass: \( V_{in2} = V_{in}, \) and the other input voltage is zero.

**Part IV:** If \( I_{in1} = I_{in2} = I_{in3} = 0 \), the following transadmittance-mode highpass and bandpass filtering responses can be obtained from \( I_{out} \) as below.

(i) Highpass: \( V_{in1} = V_{in}, \) and the other input voltage is zero.

(ii) Bandpass: \( V_{in2} = V_{in}, \) and the other input voltage is zero.

Note that there are no critical component-matching conditions or cancellation constraints in the design. Moreover, the structure does not need inverting-type input current signals or double-type amplifier and also does not need to change the network topology.

Inspection of Eq. (7) shows that, in all cases the parameters \( \omega_b, \omega_d/Q, \) and \( Q \) are given by

\[
\omega_b = \frac{G_1 G_2}{\sqrt{G_1 G_2}}
\]

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From Eqs. (8) and (9), the parameters \( \omega_0 \) and \( \omega_b/Q \) are orthogonally adjustable through the resistor \( R_1 \) and then the resistor \( R_2 \) in that order. From Eqs. (8) and (10), the parameters \( \omega_0 \) and \( Q \) are interactive. However, non-interactive filter parameter control can be obtained as follows: for the fix-valued capacitors, \( \omega_0 \) can be tuned arbitrarily without disturbing \( Q \) by simultaneously changing \( G_1 \) and \( G_2 \) and keeping the ratio \( G_2/G_1 \) constant. The parameter \( Q \) also can be adjusted without disturbing \( \omega_0 \) by simultaneously changing \( G_2 \) and \( G_1 \) and keeping the product \( G_2G_1 \) constant.

III. NONIDEAL ANALYSIS

Taking the tracking errors of the CCII into account, the relationship of the terminal voltages and currents can be written as: 
\[ I_Y = 0, \quad V_X = \beta(s)V_Y, \quad I_{Z^+} = \pm \alpha(s)I_X, \]
where \( \alpha(s) \) and \( \beta(s) \) represent the frequency transfer functions of the internal current and voltage followers of the CCII. They can be approximated by the first order lowpass functions [32, 33]. For frequencies much less than the corner frequencies of the CCII, all \( \alpha(s) \) and \( \beta(s) \) are real quantities of magnitudes slightly less than one [32, 33]. Assuming the circuit works at frequencies much less than the corner frequencies of \( \alpha(s) \) and \( \beta(s) \), namely, \( \alpha(s) = \alpha = 1 - \epsilon_i \) and \( \epsilon_i \) (\( \epsilon_i << 1 \)) denotes the current tracking error of the CCII and \( \beta(s) = \beta = 1 - \epsilon_v \) and \( \epsilon_v \) (\( \epsilon_v << 1 \)) denotes the voltage tracking error of the CCII. Taking into account the nonidealities of the CCII(1) and CCII(2), we obtain the nonidealities as below:

\[ I_Y = 0, V_X = \beta_1V_Y, I_{Z^+} = \alpha_{10}I_X, \quad \text{for CCII(1)} \]  
\[ I_{Z^+} = \alpha_{11}I_X, I_{Z^-} = -\alpha_{12}I_X, \quad \text{for CCII(2)} \]  
\[ I_Y = 0, V_X = \beta_2V_Y, I_{Z^-} = -\alpha_{20}I_X \quad \text{for CCII(2)} \]

The non-ideal denominator of the mixed-mode transfer functions becomes:

\[ D(s) = s^2C_1C_2 + sC_2G_1\alpha_{12}\beta_1 + G_1G_2\alpha_{20}\alpha_{10}\beta_1\beta_2 \]  

(13)

The \( \omega_0 \) and \( Q \) of the non-ideal mixed-mode biquad are:

\[ \omega_b = \sqrt{\frac{\alpha_{20}\alpha_{10}\beta_1\beta_2 G_1 G_2}{C_1 C_2}} \]  

(14)

\[ Q = \frac{1}{\alpha_{12}} \sqrt{\frac{\alpha_{10}\alpha_{20}\beta_1 G_2 C_2}{\beta_1 G_1 C_1}} \]  

(15)

The active and passive sensitivities of \( \omega_0 \) and \( Q \) are:

\[ -S_{\omega_b}^0 = S_{\omega_b}^0 = S_{\omega_b}^0 = \frac{\alpha_{10}\alpha_{20}\beta_1 G_2 C_2}{\beta_1 G_1 C_1} \quad \frac{1}{2} \]

\[ S_{\alpha_{12}}^Q = -S_{\alpha_{12}}^Q = S_{\alpha_{12}}^Q = \frac{1}{2} \]

(16)

From (16), the proposed MISO mixed-mode biquad filter has low active and passive sensitivities (not larger than unity in absolute value).

IV. H-SPICE SIMULATIONS

Two possible CMOS implementations of the CCII± are shown in Fig. 1 of Ref. [34] (without the cascode configuration) [35] and Fig. 2 (with the cascode configuration) [36]. Note that if the cascode configuration is not used in CCII, DVCC, DDCC, FDCCI, DDCTA, DVCCTA, and CCCCTA, the CCII has simplest implementation configuration in all of them. Similarly, if the cascode configuration is used in CCII, DVCC, DDCC, FDCCI, DDCTA, DVCCTA, and CCCCTA, the CCII also has simplest implementation configuration in all of them. Note that the multiple current outputs CCII applying the realization of current replicas are very simple. To verify the theoretical analysis of the proposed biquad filter, the H-SPICE simulations with the N MOS transistor aspect ratios \((W/L=5\mu m/1\mu m)\) and PMOS transistor aspect ratios \((W/L=10\mu m/1\mu m)\) of Fig. 2, using the TSMC 0.25\mu m process with the parameters of level 49 for the proposed MISO mixed-mode circuit of Fig. 1, were performed with the component values: \( C_1 = C_2 = 8pF \) and \( G_1 = G_2 = 100.532824\mu S \), for lowpass, bandpass, highpass, notch, and allpass filters, leading to a center frequency of \( f_0 = 2MHz \) and quality factor of \( Q = 1 \). Their supply voltages are \( V_{DD} = -V_{SS} = 1.25V \), \( V_{b1} = -0.3V \), and \( V_{b2} = -0.6V \). Fig. 3 presents the simulated current-mode bandpass and notch amplitude-frequency responses of the proposed biquad filter. Fig. 4 presents the simulated current-mode bandpass and highpass amplitude-frequency responses of the proposed biquad filter. Fig. 5 present the simulated current-mode allpass phase and amplitude-frequency responses of the proposed biquad filter.
Fig. 6 presents the simulated transadmittance-mode bandpass and highpass amplitude-frequency responses of the proposed biquad filter with the normalized transadmittance magnitude $= 20 \log \left| \frac{I_{\text{out}}}{(0.000100532824V_{\text{in}})} \right|$ dB due to $G_4 = 100.532824 \mu S$. Although not included in this paper, it can be shown that the other modes simulated results are very similar to the above simulated results. As can be seen, there is a close agreement between theory and simulation.

Figure 2. CMOS implementation of the CCII± (with the cascode configuration).

Figure 3. Current-mode bandpass and notch amplitude-frequency responses of the proposed biquad filter (*, simulated bandpass; □, simulated notch; and ____, theoretical curve ).

Figure 4. Current-mode highpass and lowpass amplitude-frequency responses of the proposed biquad filter (○, simulated highpass; □, simulated lowpass; and ____ , theoretical curve ).

Figure 5. Current-mode allpass phase and amplitude frequency responses of the proposed biquad filter (□, simulated phase; *, simulated amplitude; and ____, theoretical curve ).
V. Conclusions

None of the previously reported mixed-mode (including voltage, current, transadmittance, and transimpedance modes) biquad filters can offer the following attractive advantage: using only two second-generation current conveyors (i.e. the least number of basic active components), two grounded capacitors, and two resistors (i.e. the minimum number of passive components). In this paper, the proposed MISO type mixed-mode (including voltage, current, transadmittance, and transimpedance modes) biquad filter can achieve the above attractive advantage. Moreover, the proposed MISO mixed-mode circuit still enjoys many main advantages: using commercially available active components, no component-value constraints, no inverting or non-inverting amplifiers for special input signals, using grounded capacitors attractive for integration and for absorbing shunt parasitic capacitance, high output impedance for current output, and low active and passive sensitivities. H-Spice simulations with TSMC 0.25µm process confirm the theoretical predictions.

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