High-Order CCII-Based Mixed-Mode Universal Filter

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Abstract—This paper presents a new high-order mixed-mode (including voltage, current, transadmittance, and transimpedance modes) universal filter structure using \(n+1\) second-generation current conveyors (CCIs), \(n\) grounded capacitors and \(n+2\) resistors, which are the minimum number of active component counts for realizing an \(n\)th-order mixed-mode universal filtering responses (low-pass, high-pass, band-pass, band-reject, and all-pass) from the same topology. Many important advantages are simultaneously achieved which are (i) using only CCIs (with simpler implementation configuration than the differential difference current conveyors (DDCCs) and fully differential current conveyors (FDCCIs)), (ii) all grounded capacitors (attractive for integration), (iii) high output impedance for current output (good for cascadability), (iv) no need to impose component choice except the voltage and transadmittance all-pass response, (v) no need of inverting-type input signals or double-type input signals for the use of special input signals, and (vi) low sensitivity performance. H-Spice simulation results confirm the theory.

Keywords—Active filters, second-generation current conveyors, mixed-mode, high-order filter, universal filter.

I. INTRODUCTION

Over the last decade, many high-order voltage-mode or current-mode filters have been presented in the literature [1-17]. From historical progress point of view, we might intend to replace the traditional voltage-mode circuits with the more precise current-mode circuits. There might be a transferring period from voltage-mode to current-mode world. Then, the transadmittance (i.e. input as voltage and output as current) and transimpedance (i.e. input as current and output as voltage) modes will be involved in that between voltage and current modes, and therefore, 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. Hence, in analog signal processing applications, we may be desirable to have active filter with input currents or voltages and output currents and voltages, defined as mixed-mode filter.

Therefore, the mixed-mode (including voltage, current, transadmittance, and transimpedance modes) 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. Although many mixed-mode biquad filters have been proposed, few high-order mixed-mode filters have been presented in the literature [15, 18-20]. In 2009, an \(n\)th-order mixed-mode filter was proposed [19]. The filter structure [19] employs \(n+2\) operational transconductance amplifiers (OTAs) and \(n\) grounded capacitors, which can realize \(n\)th-order mixed-mode (including voltage, current, transadmittance, and transimpedance modes) universal filtering responses (low-pass, high-pass, band-pass, band-reject, and all-pass) from the same topology. However, the structure [19] offers three following disadvantages: (i) need of extra inverting amplifiers for realizing voltage and transadmittance modes allpass signals, (ii) need of the two same \(n\)th input current \(I_{in}\) for constructing current output and voltage output, and (iii) inconvenient input currents settings for realizing current and transimpedance modes highpass, bandreject, and allpass signals. Therefore, in 2012, a new \(n\)th-order mixed-mode filter was proposed [20]. The structure, reported in [20], can overcome the above three disadvantages but it need to use \(n+3\) active elements (i.e. OTAs) in addition to \(n\) grounded capacitors. Although the \(n\)th-order mixed-mode structure reported in [18] uses only \(n+1\) active elements (i.e. DDCCs) in addition to \(n\) grounded capacitors and \(n+2\) resistors, the DDCCs are more complex active elements than CCIs. In 2009, a good high-order current-mode and transimpedance-mode universal filter was proposed in [15]. The filter [15] employs only \(n+1\) active elements (i.e. multiple outputs CCIs (MOCCIs)) in addition to \(n\) grounded capacitors and \(n+1\) resistors but it can not be used in voltage and transadmittance modes.
Therefore, this leads to prospective research work: investigating and developing a high-order mixed-mode (including voltage, current, transadmittance, and transimpedance modes) universal filter structure using reduced number (no more than n+1) of active components which have the simpler structure than DDCC. In this paper, the proposed high-order mixed-mode universal filter uses only n+1 CCII$s$ (with the simpler structure than DDCC), in addition to n grounded capacitors and n+2 resistors, which can realize n-th order voltage, current, transadmittance, and transimpedance modes universal filtering responses (low-pass, high-pass, band-pass, band-reject, and all-pass) from the same topology. It should be noted that up until now, no previous papers have reported a high-order “CCII-based” mixed-mode universal filter. Moreover, the proposed high-order mixed-mode circuit does not need the two same n-th input current ($I_n$) for constructing current output and voltage output and also does not need extra inverting-type or double-type amplifiers for special input signals. Furthermore, the new proposed structure provides more convenient input current settings than [19] for realizing current and transimpedance modes highpass, bandreject, and allpass signals. For example, the new structure uses a single current input signal instead of n same current input signals [19] for realizing the n-th order high-pass filter response. Therefore, the proposed circuit also can overcome the above three disadvantages. With respect to the references [19, 20], the proposed structure uses less number of active components. With respect to the reference [18], the proposed circuit uses the active components with simpler structure. With respect to the reference [15], the proposed circuit not only realizes high-order current-mode and transimpedance-mode universal filtering responses but also achieves high-order voltage and transadmittance modes universal filtering responses.

II. HIGH-ORDER CCII-BASED MIXED-MODE FILTER

Figure 1 shows the proposed mixed-mode nth-order universal filter structure where $I_n$, $I_{n+1}$, $I_{n+2}$, ..., $I_2$, $I_1$, $I_0$ are the filter input currents and $V_n$, $V_{n+1}$, $V_{n+2}$, ..., $V_2$, $V_1$, $V_0$ 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. The choice of the subscript +/- of the output terminal $Z_{out}$ in the CCII(n) depends on an even/odd order n of the high-order filter, respectively. Using standard notation, the port relations of a CCII can be characterized by $I_Y = 0$, $V_X = V_Y$ and $I_Z = \pm I_X$. The multiple current outputs of CCII(n) can be simply reconstructed using current mirrors. Moreover, all current outputs have very high output impedance.

Routine circuit analysis for Figure 1 yields the following transfer functions:

\[
V_{out} = \frac{N_v(s) + N_i(s)}{G_{n+1}D(s)} \quad (1)
\]

and

\[
I_{out} = \frac{N_v(s) + N_i(s)}{D(s)} \quad (2)
\]

in which

\[
N_v(s) = \sum_{i=0}^{n} \left[ (-1)^i a_i G_i V_i s^i \right] \quad (3)
\]
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\[ N_i(s) = \sum_{i=0}^{n} \left( -1 \right)^i a_i I_i s^i \]  \hspace{1cm} (4)

\[ D(s) = \left( -1 \right)^n \sum_{i=0}^{n} a_i s^i \]  \hspace{1cm} (5)

where

\[ a_n = \prod_{i=1}^{n} C_i \]  \hspace{1cm} (6)

\[ a_k = \left( \prod_{i=1}^{k} C_i \right) \left( \prod_{j=k+1}^{n} G_j \right) \text{ for } k = 1, 2, 3, \ldots, n-1 \]  \hspace{1cm} (7)

\[ a_0 = \prod_{j=1}^{n} G_j \]  \hspace{1cm} (8)

From equation (1)-(8), the high-order mixed-mode universal filter transfer functions are obtained according to input voltage or current conditions as follows.

**Part I:** If \( I_0 = I_{n-1} = I_{n-2} = \ldots = I_2 = I_1 = I_0 = 0 \), the following nth-order voltage-mode and transadmittance-mode filter responses can be obtained as below.

(i) Highpass: \( V_n = V_{n-1} = V_{n-2} = \ldots = V_2 = V_1 = V_0 = 0 \), and all the other input voltages are zero (grounded).

(ii) Lowpass: \( V_0 = V_{n} \), and all the other input voltages are zero (grounded).

(iii) Bandpass: If \( n \) is even, then \( V_{(n/2)} = V_{n} \), whilst all the other input voltages are zero (grounded). If \( n \) is odd, then the input current \( I_{n} \) is applied to either \( I_{(n-1)/2} \) or \( I_{(n+1)/2} \), whilst all the other input currents are zero (grounded).

(iv) Band-reject: \( V_n = V_0 = V_{n} \), and all the other input voltages are zero (grounded).

(v) All-pass: \( V_n = V_{n-1} = V_{n-2} = \ldots = V_2 = V_1 = V_0 = 0 \) and \( G_n = G_{n-1} = \ldots = G_1 = G_0 \)

**Part II:** If \( V_n = V_{n-1} = V_{n-2} = \ldots = V_2 = V_1 = V_0 = 0 \), the following nth-order current-mode and transimpedance-mode filter responses can be obtained as below.

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

(ii) Lowpass: \( I_0 = I_{n} \), and all the other input currents are zero.

(iii) Bandpass: If \( n \) is even, then \( I_{(n/2)} = I_{n} \), whilst all the other input currents are zero. If \( n \) is odd, then the input current \( I_{n} \) is applied to either \( I_{(n-1)/2} \) or \( I_{(n+1)/2} \), whilst all the other input currents are zero.

(iv) Band-reject: \( I_n = I_0 = I_{n} \), and all the other input currents are zero.

(v) All-pass: \( I_n = I_{n-1} = I_{n-2} = \ldots = I_2 = I_1 = I_0 = I_{n} \).

Note that there are no critical component-matching conditions or cancellation constraints in the design except the transconductance/voltage allpass response. Moreover, the structure does not need inverting-type input current signals or double-type amplifier for realizing any filter transfer functions and also does not need to change the network topology. Observing all of the coefficients in \( D(s) \) (i.e., \( a_n \)), because \( a_n \) consists of the product of all \( n \) capacitances, \( \ldots, a_{n-i} \) consists of the product of \( n-i \) capacitances and \( i \) conductances \( \ldots, \) and \( a_0 \) consists of the product of all \( n \) conductances, all filtering parameters produced from the coefficient in the denominator are orthogonally controllable. In addition to this advantage, the coefficient sensitivity to each capacitance or each conductance is easily calculated and equal to 0 or 1, both of which are low. To illustrate the proposed mixed-mode high-order filter structure, Figure 2 shows a sixth-order transadmittance-mode and voltage-mode highpass filter. Figure 3 shows a sixth-order current-mode and transimpedance-mode bandpass filter. Figure 4 shows a sixth-order transadmittance-mode and voltage-mode lowpass filter.
Figure 2. Proposed sixth-order transadmittance-mode and voltage-mode high-pass filter structure.

Figure 3. Proposed sixth-order current-mode and transimpedance-mode band-pass filter structure.
III. H-SPICE SIMULATIONS

A CMOS implementation of the CCII± is shown in Figure 5 [21] with the NMOS transistor aspect ratios (W/L=5µm/1µm) and PMOS transistor aspect ratios (W/L=10µm/1µm). Note that the multiple current outputs of CCII applying the realization of current replicas are very simple. To verify the theoretical analysis of the high-order mixed-mode universal filters, the H-SPICE simulations, using the TSMC 0.25µm process for the proposed circuits of Figure 1, were performed with the component values: (i) $R_0 = R_1 = \ldots = R_6 = R_7 = 10k\Omega$, and $C_1 = C_2 = \ldots = C_5 = C_6 = 5pF$ for the sixth-order high-pass, low-pass, band-pass, and band-reject filters of the Figure 1, leading to a center frequency of $f_0 = 3.183MHz$, and (ii) $C_1 = C_2 = C_3 = 5pF$, $R_1 = 20k\Omega$, $R_2 = 10k\Omega$, and $R_3 = 5k\Omega$ for the third-order all-pass filter of the Figure 1, leading to a center frequency of $f_0 = 3.183MHz$. Their supply voltages are $V_{DD} = -V_{SS} = 1.25V$, $V_{b1} = -0.3V$, and $V_{b2} = -0.6V$. Figure 6 presents the simulated sixth-order lowpass, bandpass, highpass, and band-reject amplitude-frequency responses of the proposed voltage-mode (VM) and transadmittance-mode (TAM) filters with the normalized transadmittance magnitude = 20 log $|10000I_{out} / V_{in}|$ dB due to $R_7 =10k\Omega$. Figure 7 presents the simulated third-order all-pass phase and amplitude-frequency responses of the proposed current-mode (CM) and transimpedance-mode (TIM) filters with the normalized transimpedances magnitude = 20 log $|V_{out} / 10000 I_{in}|$ dB due to $R_7 =10k\Omega$. Although not included in this paper, it can be shown that the other simulated results are very similar to the above simulated results. As can be seen, there is a close agreement between theory and simulation.
IV. Conclusions

Using only \(n+1\) CCIs, \(n\) grounded capacitors, and \(n+2\) resistors, a mixed-mode universal high-order filter is presented which can realize \(n\)-th-order lowpass, highpass, bandpass, band-reject, and allpass responses. Moreover, the proposed high-order circuit offers the following advantages: the minimum active components, using grounded capacitors attractive for integration, high output impedance good for cascadability, no need to change the filter topology, no component-value constraints except the transadmittance/voltage allpass response, no need of inverting or double-type amplifiers for special input signals, and low active and passive sensitivities. As far as active components is concerned, the proposed \(n\)-th-order mixed-mode universal filter using \(n+1\) CCIs is the minimum active components. H-Spice simulations confirm the theoretical predictions.

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