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Cascadable current-mode first-order allpass filter using current controlled conveyors

***Abstract**. This paper presents a canonical current-mode first-order allpass filter using two current controlled conveyors (CCCIIs) and a single grounded capacitor. The proposed circuit simultaneously realizes both inverting and non-inverting types of first-order allpass functions without needing component matching constraints. Its pole frequency (ω_0) can be adjusted electronically by means of a bias current of the CCCII. The presented circuit also possesses both low-input and high-output impedances, which are suitable for current-mode cascading. Simulation results including frequency response and transient analysis are incorporated to confirm the theoretical analysis.*

Streszczenie.** W artykule przedstawiono kanoniczny, prądowy przesuwnik fazy pierwszego rzędu, wykorzystujący dwa, sterowane prądowo przekaźniki (CCCII) i kondensator do uziemienia. Proponowany obwód realizuje funkcję odwracającą i nieodwracającą bez ograniczeń w doborze elementów i zapewnia niską-wejściową i wysoką-wyjściową impedancję. Częstotliwość biegunowa może zostać dostrojona poprzez zmianę wartości średniej prądu wstępnego CCCII. Wyniki symulacyjne, odpowiedź częstotliwościowa i analiza czasowa potwierdzają analizę teoretyczną.* ***(Kaskadowy przesuwnik fazy prądu pierwszego rzędu z wykorzystanie przekaźników sterowanych prądowo)

Keywords: Allpass filter, Current Controlled Conveyor (CCCII), Current-mode Circuit.
Słowa kluczowe: przesuwnik fazy, przekaźnik sterowany prądowo, obwód prądowy

Introduction

The first-order allpass (AP) filter, namely phase shifter, is one of the most important and useful building block for realizing analog filtering and signal processing systems. This is because it provides a change in phase without modification the signal amplitude. Therefore, the AP filter is usually used to correct the undesired phase shifts produced during analog filtering operations, and audio and video signal processing. Considering the attractive advantages of current-mode circuits, such as simpler circuitry, wide bandwidth and wide dynamic range, several current-mode first-order AP filter realizations using different active building blocks have been reported in the literature [1]-[13]. A summary of the performance parameters of the recent AP filters reported in [1]-[13] is given in Table 1. As can be seen, none of the earlier reported filters is able to meet all the following desirable features simultaneously :

(i) Use of minimum number of active and passive components.

(ii) Low-input and high-output impedances, which are ideal for cascading in current-mode operation.

(iii) Achievement of both inverting and non-inverting types of first-order AP filtering functions simultaneously from the same topology.

(iv) No component matching constraints.

(v) Electronic tuning of the pole frequency.

(vi) Resistor-less realization.

(vii) Use of only grounded capacitor, which is desired issue in integrated circuit (IC) implementation.

(viii) Low component sensitivities.

The aim of this paper is, therefore, to present a novel current-mode first-order AP filter using only two identical current controlled conveyors (CCCIIs) and one grounded capacitor. Contrary to the previously reported AP filters [1]-[13] in Table 1, the proposed circuit is capable of achieving all the above-mentioned eight important specifications simultaneously. The non-ideal gains and the parasitic impedance effects of the conveyors on the filter performance are investigated in detail. PSPICE simulation results are also included to verify the theoretical analysis.

Description of the Proposed AP Filter

Fig.1 shows the circuit symbol for the CCCII with three output terminals. Using standard notation, the CCCII can be described by the following equations :

(1) $$i_y = 0\ ,\quad v_x = i_x R_x + v_y \quad \text{and} \quad i_{z\pm} = \pm i_x\ .$$

where the plus and minus signs of the i_z represent the positive and negative current conveyance from x to z+ and z- terminals, respectively. For the bipolar implementation of CCCII [14], the series parasitic resistance R_x in equation (1) is given by :

(2) $$R_x = \frac{V_T}{2I_O}$$

where I_O is an external DC bias current of conveyor and V_T is the thermal voltage (approximately 26 mV at room temperature). It is found that the resistance R_x is tunable over several decades by a supplied bias current I_O [14].

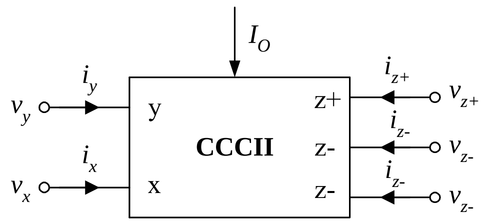


Fig.1. Circuit symbol of the CCCII.

Fig.2 shows an electronically tunable current-mode first-order AP filter using two CCCIIs and one grounded capacitor. In this configuration, the input impedance of the proposed filter is approximately equal to the x-terminal parasitic resistance of the CCCII1 ($R_{x1} = V_T/2I_{O1}$). Therefore, taking R_{x1} sufficiently low with high corresponding bias current I_{O1}, the the proposed filter with low-input impedance is consequently obtained as required. In addition, the use of only grounded capacitor is beneficial from the point of view of IC implementation. Routine circuit analysis of the circuit given in Fig.2 yields the following current transfer functions :

(3) $$\frac{I_{AP+}(s)}{I_{in}(s)} = -\frac{I_{AP-}(s)}{I_{in}(s)} = \frac{sR_{x2}C - 1}{sR_{x2}C + 1}$$

where R_{x2} (= $V_T/2I_{O2}$) is the R_x of the CCCII2.

Table 1. Comparison of performance parameters of previously published current-mode first-order AP filters.

AP Filters	No. of active elements	No. of passive elements	Low output impedance	High output impedance	Realisability of both AP types	Without matching conditions	Electronic tuning	Resistor-less circuit	Grounded capacitor	Low sensitivity
[1]	1	4	×	✓	×	×	×	×	×	✓
[2]	1	3	×	×	×	×	×	×	×	✓
[3]	1	2	×	✓	×	✓	×	×	×	✓
[4]	2/1	1	×	×	×	×/✓	×	✓	×	✓
[5]	1	2	×	×	×	✓	×	×	×/✓	✓
[6]	1	2	×	✓	✓	✓	×	×	×	✓
[7]	2	1	×	×	×	✓	✓	✓	×	✓
[8]	1	5	×	✓	✓	×	✓	×	×/✓	✓
[9]	2	4	×	✓	×	×	×	×	✓	✓
[10]	1	2	×	✓	×	✓	×	×	✓	✓
[11]	2	3	✓	✓	×	×	×	×	✓	✓
[12]	2	1	✓	✓	✓	✓	✓	✓	×	✓
[13]	2	1	×	✓	✓	✓	✓	✓	×	✓
Proposed	2	1	✓	✓	✓	✓	✓	✓	✓	✓

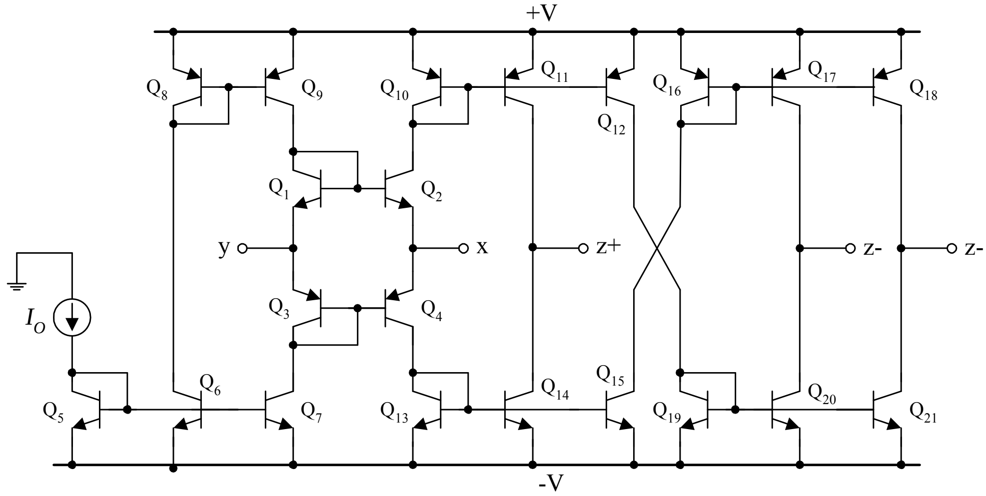


Fig.3. Bipolar technology implementation of the CCCII.

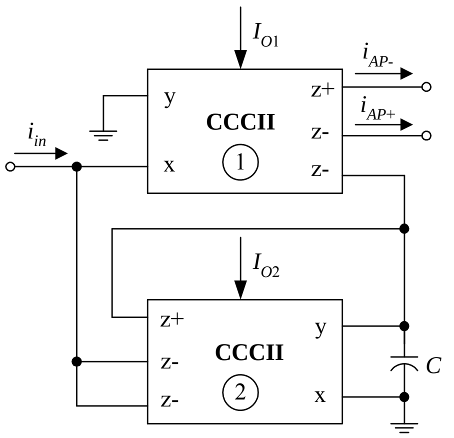


Fig.2. Proposed electronically tunable current-mode first-order allpass filter.

In equation (3), it is apparent that the circuit realizes both non-inverting and inverting type first-order AP filter functions without requiring any component matching conditions. As shown in Fig.2, the derived filters do not require any external passive resistor, and have high-output impedance terminals. It is also clear from equation (3) that the pole frequency of the circuit can be expressed as :

$$\omega_0 = \frac{1}{R_{x2}C} = \frac{2I_{O2}}{V_T C} \tag{4}$$

and the phase responses can be given by, respectively, :

$$\phi_{AP+} = 180^\circ - 2\tan^{-1}(\omega R_{x2}C) \tag{5}$$

and

$$\phi_{AP-} = -2\tan^{-1}(\omega R_{x2}C) \ . \tag{6}$$

As can be seen from above expressions, the proposed AP filter can provide phase shifting both between 180° to 0° and 0° to -180°. Also, the shifted phase value can be controlled electronically by adjusting the value of I_{O2}.

Effect of Active Element Non-Idealities

In this section, the effects of the active non-idealities of the conveyor on the introduced filter performance are studied in detail. Taking into consideration of the conveyor non-idealities, the terminal relations in equation (1) can be rewritten as :

$$i_y = 0,\ v_x = \beta v_y + i_x R_x,\ \ i_{z+} = \alpha i_x \ \text{ and } \ i_{z-} = -\gamma i_x \tag{7}$$

where β is the non-ideal voltage gain and α and γ are the non-ideal current gains of the conveyor, respectively. These non-ideal gains differ from unity by the voltage and current tracking errors of the conveyor. Reanalysis of the proposed filter circuit in Fig.2 by considering these effects yields the non-ideal current transfer functions to be as follows :

$$\frac{I_{AP+}(s)}{I_{in}(s)} = -\frac{I_{AP-}(s)}{I_{in}(s)} = \alpha_1\left[\frac{sR_{x2}C - \beta_2\alpha_2}{sR_{x2}C + (2\gamma_1\gamma_2 - \alpha_2)\beta_2}\right] \tag{8}$$

where β_i , α_i and γ_i are the parameters β , α and γ of the i-th CCCII (i = 1, 2), respectively. As easily seen from equation (8), the filter gain is influenced by the current tracking error of the first conveyor, as it now depends on

α_1. Also, the tracking errors do affect the pole frequency, as it now becomes :

(9) $$\omega_0 = \frac{(2\gamma_1\gamma_2 - \alpha_2)\beta_2}{R_{x2}C}$$.

The pole sensitivities of the proposed circuit are calculated as :

(10) $$S^{\omega_0}_{\gamma_1} = S^{\omega_0}_{\gamma_2} = \frac{2\gamma_1\gamma_2}{2\gamma_1\gamma_2 - \alpha_2} < 1$$

(11) $$S^{\omega_0}_{\alpha_2} = -\left(\frac{\alpha_2}{2\gamma_1\gamma_2 - \alpha_2}\right) < -1$$

(12) $$S^{\omega_0}_{\beta_2} = 1$$

(13) $$S^{\omega_0}_{R_{x2}} = S^{\omega_0}_{C} = -1$$.

The sensitivity analysis shows that the ω_0-sensitivity with respect to the non-idealities as well as active and passive components is no more than unity in magnitude.

The limited bandwidth of the voltage and current gains of the conveyor may also affect the high-frequency operation of the realized circuit. Practically, the non-ideal voltage and current gains are frequency dependent which can be defined by a single-pole model [15]. Their corresponding pole frequencies depend on the fabrication of the active device. Therefore, the high-frequency performance of the proposed circuit will be limited by the actual circuit parameters and the technology used.

Effect of Parasitic Elements

Another non-ideal effect to be considered is the parasitic elements of the conveyor. In reality, the practical conveyor possesses a parasitic resistance R_x in series to port x, and the shunt parasitic impedances at ports y and z (i.e. $R_y//C_y$ and $R_z//C_z$) [15]. Since an external grounded capacitor C is connected to port y of the CCCII2, there is a limitation at low frequencies due to the parasitic resistances in parallel at port y. Regarding this, the extra pole that determines the low-frequency operation of the filter will appear at

(14) $$\omega_1 = \frac{1}{R_1C_1}$$

where $R_1 = R_{y2}//R_{z1}//R_{z2}$ and $C_1 = C + C_{y2} + C_{z1} + C_{z2}$. In practice, the external capacitance C is very much greater than the parasitic capacitances, i.e. $C >> C_{y2}$, C_{z1}, C_{z2}. Thus, the frequency range at low frequencies can be approximated to :

(15) $$f_L >> \min\left\{\frac{1}{2\pi}\frac{1}{(R_{y2}//R_{z2}//R_{z1})C}\right\}$$

The other limitation on high-frequency performance of the filter in Fig.2 is attributed to the non-zero value of the input resistance at port x of the CCCII1 (R_{x1}). In this case, the frequency response of the filter at high frequencies is limited by the following dominant pole.

(16) $$\omega_2 = \frac{1}{R_2C_2}$$

where $R_2 = R_{x1}//(R_{z2}/2)$ and $C_2 = 2C_{z2}$. Usually, $R_{x1} << (R_{z2}/2)$, thus the restriction at high frequencies become as :

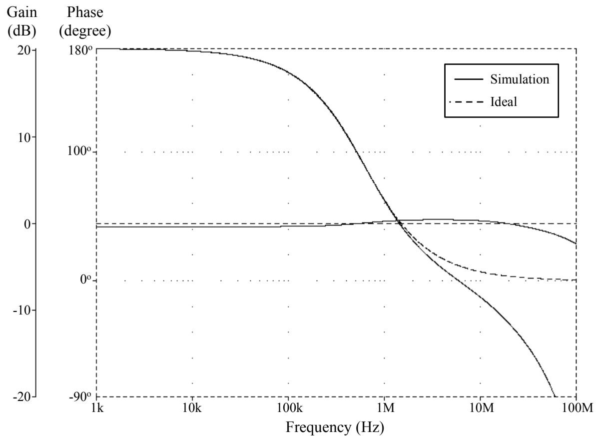
(17) $$f_H << \min\left\{\frac{1}{4\pi}\frac{1}{(R_{x1}C_{z2})}\right\}$$

As a result, combinations of equations (15) and (17), the useful frequency range of the proposed filter in Fig.2 can be defined as : $f_L << f << f_H$.

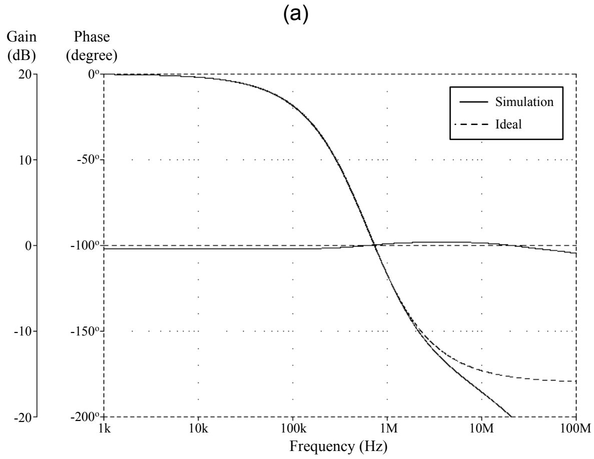
Simulation Results

The behavior of the designed AP filter in Fig.2 has been verified by PSPICE simulation program. In the simulations, the CCCII was realized by the schematic bipolar implementation given in Fig.3 with the transistor model parameters PR100N (PNP) and NP100N (NPN) of the bipolar arrays ALA400 from AT&T [16]. The supply voltages were selected as : ±V = ±3V.

As an example, the following settings for the proposed filter of Fig.2 are chosen as : C = 1 nF, I_{O1} = 500 μA (R_{x1} = 26 Ω) and I_{O2} = 50 μA (R_{x2} = 260 Ω), which results in the pole frequency of $f_0 = \omega_0/2\pi \cong$ 612 kHz, ϕ_{AP+} = 90° and ϕ_{AP-} = 270°. The simulated gain and phase frequency responses of the circuit are given in Fig.4, which is in conformity with ideal. The total power dissipation is found as 2.82 mW. Next, the electronic controllability of the proposed circuit is drawn in Fig.5, where the corresponding phase responses with respect to the bias current I_{O2} are given. The pole frequency f_0 is varied from 245 kHz, 613 kHz, 1.22 MHz to 1.83 MHz for a variation of I_{O2} from 20 μA, 50 μA, 100 μA to 150 μA.



(a)



(b)

Fig.4. Frequency responses of the proposed AP filters in Fig.2. (a) non-inverting-type AP (b) inverting type AP

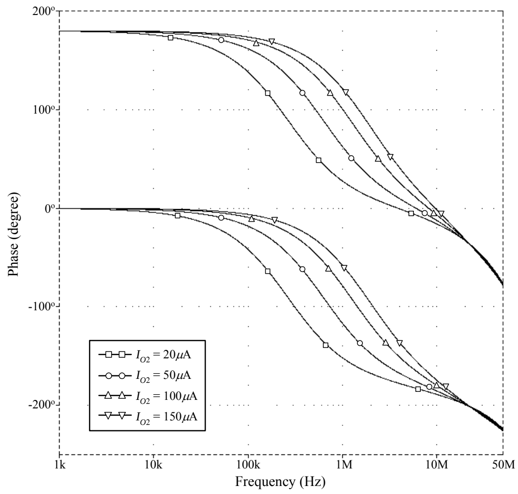


Fig.5. Electronically tunable phase response of the proposed AP filters.

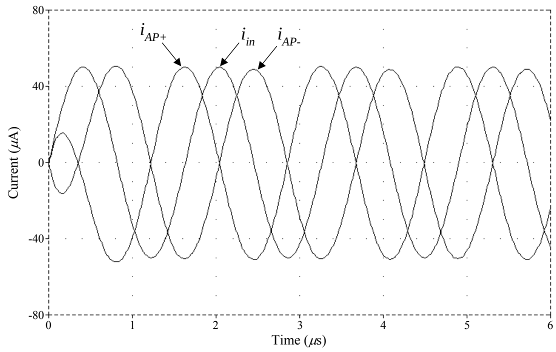


Fig.6 Time-domain responses of the proposed AP filter for input frequency 612 kHz.

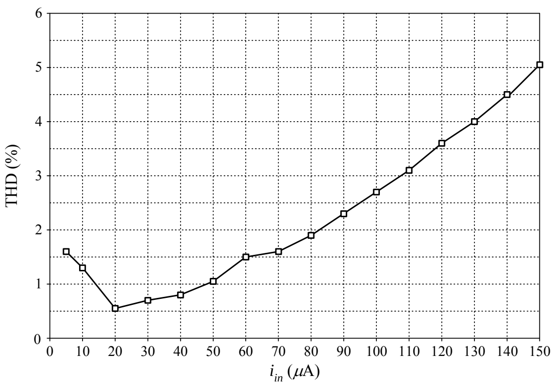


Fig.7 THD variations with respect to peak value of applied sinusoidal input current.

To demonstrate the time-domain performance, transient analysis is performed to evaluate the current swing capability of the proposed filter. A sinusoidal input with the frequency of 612 kHz and peak-to-peak value of 100 μA is applied to the filter constructed with above mentioned active and passive component values. Fig.6 shows the time-domain responses of the filter. This causes the time shifts of 423.37 nS and 1.23 μS at the filter outputs corresponding to the phase shifts of about 93.50° and 271.74°, respectively. The simulated results are in good agreement with the theoretical values.

To illustrate the large signal behavior, the circuit is tested by investigating the total harmonic distortion (THD) at the output for sinusoidal input signal of 612 kHz. Fig.7 shows the dependence of THD (%) on the input current signal level for the designed values as given above. The THD results also show that the input current of amplitude of 80 μA peak-to-peak results in THD values less than 2%.

Conclusions

In this paper, the first-order current-mode allpass filter is presented. The proposed circuit can be characterized by the following desirable features : (a) it consists of only two CCCIIs and one grounded capacitor, which is a resistor-less realization and very suitable for integration, (b) it can simultaneously realize two AP characteristics from the same topology, (c) it dose not any matching constraint for realizing filter functions, (d) its pole frequency can be tuned by electronic means through the bias current of the conveyor, (e) its has both low-input and high-output impedances, which are highly required for cascading in current-mode operation, (f) it has low component sensitivities. Simulation results have been used to verify the presented theory, and they are in close agreement.

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