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Voltage-mode OTA-based active-C universal filter and its transformation into CFA-based RC-filter

N A Shah & M F Rather
Department of Electronics & Instrumentation Technology, University of Kashmir, Srinagar 190 006
E-mail: farsgr@yahoo.co.in

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An absolute minimum component voltage-mode (VM) universal filter, employing two each of operational transconductance amplifiers (OTAs) and capacitors with three inputs and one output, is presented. The circuit can be transformed into CFA-based RC-filter involving two each of current feedback amplifiers (CFAs), capacitors and resistors. OTA-C circuit enjoys electronic tunability of filtering parameters while its CFA-based RC version offers low output impedance which suits cascadability. PSPICE simulation and the experimental results of both the circuits are included.

Keywords: Voltage-mode filters, Operational transconductance amplifiers, Current feedback amplifiers

IPC Code: H01S

1 Introduction

Operational transconductance amplifier (OTA) is a differential voltage-controlled current source (DVCCS) exhibiting several circuit design and contemporary IC design advantages of higher linear electronic tunability, wider tunable range of its transconductance gain, a powerful ability to generate various circuits through employment of transformation[3-7] besides rendering the circuit resistorless.[1] During the last several years OTA-C filters have received particular interest due to their well-known circuit performance features resulting in publication of such circuits which operate either in voltage-mode (VM) or in current-mode (CM). The salient features of the OTA-C structures from the viewpoint of synthesis are simplified architectural design and the employment of lesser number of components which contribute to reduction in volume, noise, parasitic effects and power dissipation[2]. The circuit[7], though have the feature of transformation into CFA-based RC-circuit, but has the drawback of using excessive number of active components. In this paper, we propose a VM circuit employing only two OTAs and two capacitors which is the absolute minimum requirement for second order filtering topology. The circuit with three inputs and one output enjoys the features of (i) saving of components *vis-à-vis* the reported circuit, (ii) implementing all the generic filtering functions, (iii) realizing all the filtering functions without changing the position of the passive elements used and without any additional active or passive element except for AP response, (iv) attractive particularly for realizing LP response as both the capacitors become grounded which are ideal for integration besides having input at high impedance which suits cascading, (v) orthogonal electronic adjustment of the natural frequency (ω_0) and the bandwidth (ω_0/Q) through the bias currents of OTAs, (vi) devoid of resistors, and (vii) low active and passive sensitivity figures.

However, the proposed OTA-C circuit has the drawback of not having low output impedance entailing use of additional devices to implement higher order transfer functions. This limitation can be circumvented through use of transformation into a CFA-based RC-circuit having the equivalent transfer function. A circuit configuration called CFA has been developed to improve the finite gain bandwidth product of the conventional voltage feedback amplifier (VFA)[11]. It not only provides a constant band-width independent of the closed-loop gain but enjoys high slew rate in addition to its low output impedance capability[12-13]. Due to these circuit enhancing features enjoyed by the device *per se*, there is a growing interest in the design and development of analog-signal processing circuits using CFAs. Many filter topologies[14-21] implementing different filtering functions have been developed around CFAs. Fabre[14-15] proposed two different VM circuits ─ one implementing HP and BP responses and the other BP

and HP/LP functions. Both these circuits have one input and two outputs and employ two and one CFA, respectively. Liu *et al.* [16-19] proposed four VM circuits ─ first circuit based on a single CFA realizes HP/BP/LP function but with different passive component combinations, second and third circuits with three inputs and one low impedance output constructed around two CFAs, two capacitors and four resistors realize all the generic filtering functions while the fourth circuit with high input impedance can be configured to realize one of the basic filtering functions. The VM circuit with one input and three low impedance outputs using three CFAs, three floating resistors and two grounded capacitors reported by Chang *et al.*[20] synthesize simultaneously Notch, LP and BP filtering signals. Abuelmaatti *et al.*[21] proposed a VM universal filter with three inputs and one low-impedance output, constructed around two CFAs, two capacitors and three resistors. It realizes all the generic filtering functions but implementation of AP signal needs matching condition. Shah *et al.*[22] proposed a VM filter having three inputs and two low impedance outputs, employing two CFAs, two capacitors and three resistors. It also realizes all the generic filtering functions with two functions simultaneously but AP implementation needs an inverter. The transformed CFA-based RC-circuit has the following salient features (i) uses two plus type CFAs, (ii) uses only four passive elements, (iii) realizes all the filtering functions without requiring change in the position of the passive elements or any additional active or passive element except for AP response, (iv) orthogonal tuning of ω_0 and ω_0/Q, (v) low output impedance lending cascading for higher order filters, (vi) ideal for realizing LP filter as both the capacitors are grounded which are desirable in IC implementation and high frequency operation besides having input at high impedance, and (vii) low active and passive sensitivities.

2 Circuit Description

Under ideal conditions OTA is characterized by the port relation

$I_o = gm\,(V^+ - V^-)$

where gm is the transconductance gain tunable through bias current, I_b is given by
$gm = I_b / 2V_T$; V_T is the thermal voltage (= 26 mV at 300K).

By routine analysis of the proposed circuit of Fig. 1, yields the following output voltage V_{01}:

$$V_{01} = \frac{s^2C_1C_2V_3 + sC_1g_{m2}V_2 + g_{m1}g_{m2}V_1}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}} \qquad \ldots (1)$$

2.1 CFA model

The symbol of the CFA and its non-ideal equivalent circuit are, respectively, shown in Fig. 1(a and b). Ideally CFA is a four terminal device and is equivalent to a second generation current conveyor (CCII) followed by a voltage follower.

It is characterized by the port relation

$I_z = I_x$, $I_y = 0$, $V_x = V_y$ and $V_o = V_z$

The non-inverting input (*y*) of a CFA connects to the input of a buffer; therefore it has a very high impedance. The inverting input (*x*) connects to the input buffer's output, so the inverting input impedance is very low. The output buffer provides low output impedance for the amplifier. The output impedance is modeled as a first-order RC parallel combination. This output impedance in parallel with output buffer's input impedance results in the parasitic high value impedance at the *I*-*V* conversion node, which is the compensating *z*-terminal. These characteristics help to operate filtering topologies in different-modes. When *y*-terminal of the CFA is used as input and the output achieved through the output buffer, the amplifier behaves ideally in voltage-mode.

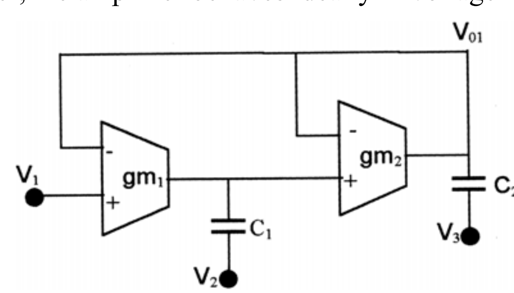

Fig. 1—Proposed voltage-mode OTA-C universal filter

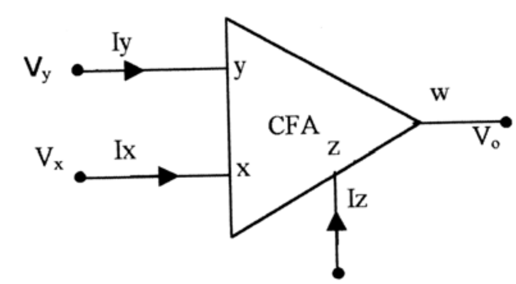

Fig. 2(a)—Symbol of non-inverting (plus-type) CFA

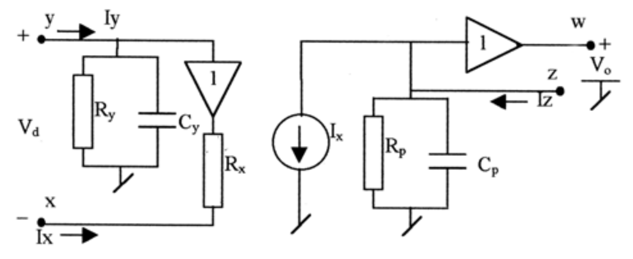

Fig. 2(b)—Non-ideal equivalent circuit of CFA (AD844 model with typical data sheet values of the various parasitics are: R_x = 50Ω, C_p = 5.5pF, R_p = 3MΩ, R_y = 2MΩ and C_y = 2pF)

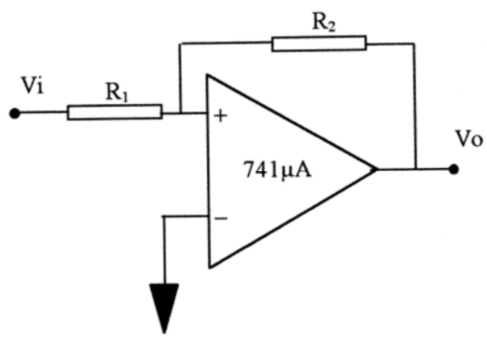

Fig. 2(c) —Implementation of inverter Fig. 3: Transformed CFA-based RC-filter of Fig. 1

After routine analysis, the output voltage V_{02} of the transformed circuit in Fig. 2 is expressed as

$$V_{02} = \frac{\left(s^2C_1C_2\right)V_3 + \left(\frac{sC_1}{R_2}\right)V_2 + \left(\frac{1}{R_1R_2}\right)V_1}{\left(s^2C_1C_2 + \frac{sC_1}{R_2} + \frac{1}{R_1R_2}\right)} \quad \ldots (2)$$

From Eqs (1) and (2), we can realize different filtering functions summarized in Table 1

The filtering parameters ω_0, ω_0/Q and the quality factor Q are given in Table 2. From Table 2, it is clear that ω_{01}/Q_1 can be electronically tuned by gm_2 and ω_{01} unaffected to ω_{01}/Q_1 by gm_1 in that order. Similarly ω_{02}/Q_2 by R_2 and ω_{02} by R_1 without disturbing ω_{02}/Q_2. However, Q and ω_0 are non-tunable.

Sensitivity—The active and passive sensitivities of the parameters ω_0, ω_0/Q_1 and Q_2 are:

$$S^{\omega_{01}}_{gm1,gm2} = -S^{\omega_{01}}_{C_1C_2} = -S^{\omega_{02}}_{C_1C_2R_1R_2} = \frac{1}{2}$$

$$S^{\omega_{01}/Q_1}_{gm2} = -S^{\omega_{01}/Q_1}_{C2} = -S^{\omega_{02}/Q_2}_{R2,C2} = 1$$

Table 1 – Different filtering function calculated from Eq (1) and (2)

Inputs			Outputs	
V_1	V_2	V_3	V_{01}	V_{02}
1	0	0	LP	LP
0	1	0	BP	BP
0	0	1	HP	HP
1	0	1	Notch	Notch
1	-1	1	AP	AP

Note: 1 and 0 denotes the terminal connected to the input voltage source and ground, respectively.

Table 2—The filtering parameters and quality factor

Filter Circuit	ω_0	ω_0/Q	Q
OTA-C	$\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}$	$\frac{gm_2}{C_2}$	$\sqrt{\frac{C_2gm_1}{C_1gm_2}}$
CFA-RC	$\frac{1}{\sqrt{C_1C_2R_1R_2}}$	$\frac{1}{R_2C_2}$	$\sqrt{\frac{C_2R_2}{C_1R_1}}$

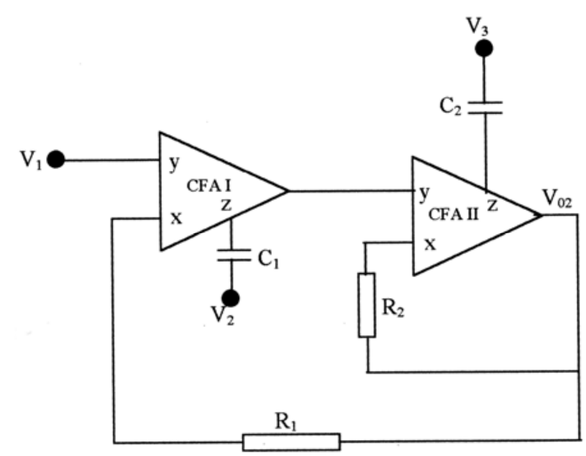

Fig. 3—Transformed CFA-based RC-filter of Fig. 1

$$S^{Q_1}_{gm1,C2} = -S^{Q_1}_{gm2,C1} = S^{Q_2}_{C2,R2} = -S^{Q_2}_{C1,R1} = \frac{1}{2}$$

which are no more than unity in magnitude.

3 Simulation and Experimental Results

PSPICE simulations were performed to verify the workability of the OTA-based circuit and its transformed CFA-based was verified experimentally. The macro model of CA3080 was used to implement OTA while commercially available AD844 supported by Analog Devices Inc. was used to implement the plus-type CFA. Inverter shown in Fig. 2(c) was implemented by using 741 μA with R_1=R_2=1kΩ so

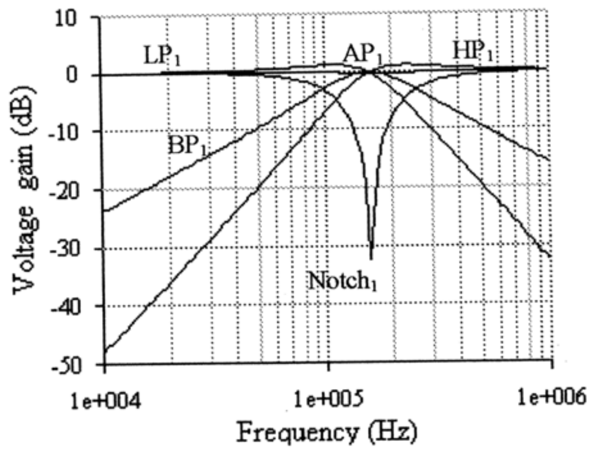

Fig. 4—Magnitude responses of Fig. 1 Fig. 5: Magnitude responses of Fig. 3

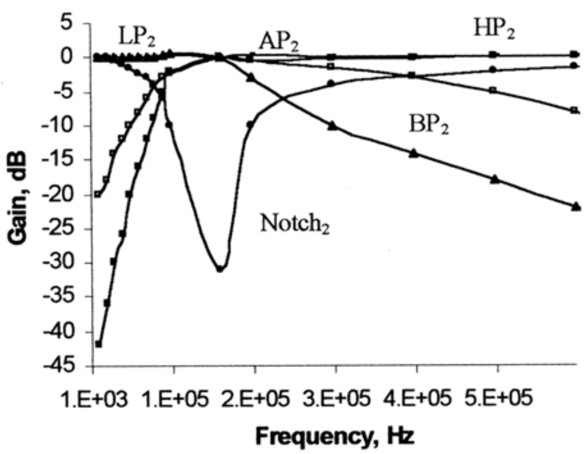

Fig. 5—Magnitude responses of Fig. 3

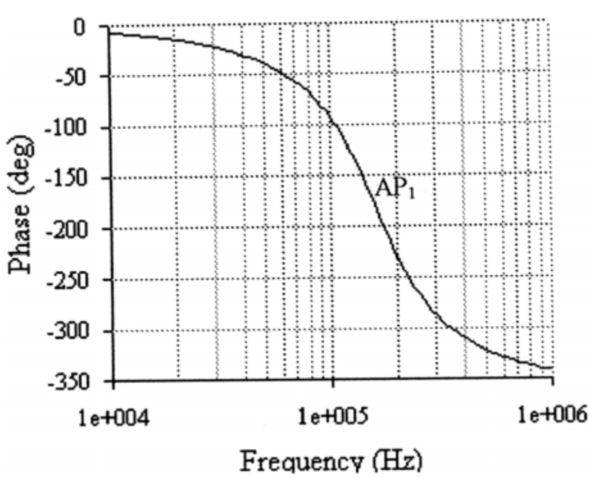

Fig. 6—Phase response for AP signal of Fig. 1

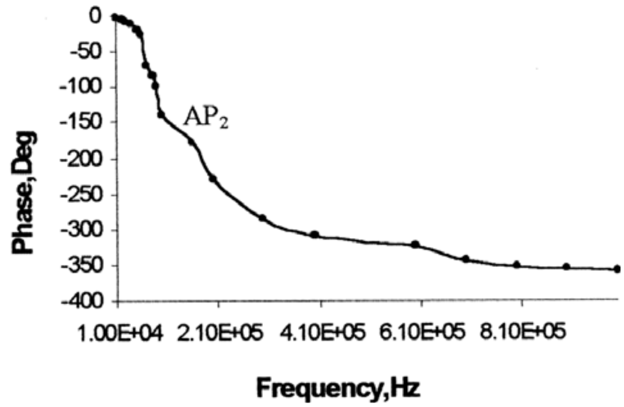

Fig. 7—Phase response for AP signal of Fig. 3

that V_o = $-V_i$. We selected the elemental values $gm_1=gm_2=1$mS, $R_1 = R_2 = 1\text{K}\Omega$ and $C_1 = C_2 = 1$nF to obtain LP, BP, HP, Notch and AP filtering functions. Figure 4 shows the simulated results of Fig. 1 while the experimental results of Fig. 3 are shown in Fig. 5, at cut-off frequency f_0 = 159.2 KHz and Q = 1. Simulated and experimental AP phase responses of Figs 1 & 3 are, respectively, shown in Figs 6 and 7. The simulated and experimental results are in good agreement with each other.

4 Conclusion

A bare minimum component voltage-mode universal filter employing two single output OTAs and two capacitors has been presented. The circuit is amenable for transformation into CFA-based RC-filter which employs two each of non-inverting CFAs, capacitors and resistors. Both the circuits with equivalent general transfer function enjoy the features of orthogonal control of the natural frequency and the bandwidth, low active and passive sensitivity figures and realize all the generic filtering functions without involving component matching or use of additional components. However, for the allpass realization an inverter is required. The transformed circuit offers low output impedance thereby promising construction of higher order filters.

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