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Bandwidth enhancement of inverting amplifier using composite CFOA block

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Abstract: In this paper, an active compensation method using two current feedback operational amplifiers (CFOAs) to enhance the bandwidth of finite gain inverting voltage amplifier for use as stand-alone amplifier is presented. It is also shown that the inexpensive passive compensation technique can be applied to composite CFOA based amplifier to improve the phase response in addition to bandwidth enhancement. The proposed circuits require one additional CFOA/ capacitor. The effect of finite output impedance at *z* terminal, input resistance at *x* terminal and current mirror pole of the CFOA is considered in the analysis. The proposed circuits have been simulated in PSPICE using a behavioral macro-model of the CFOA as well as that of a practical CFOA AD 844.

Keywords: Passive compensation; Current-feedback op-amp (CFOA); Active compensation

I. INTRODUCTION

The current feedback operational amplifier (CFOA) based finite gain voltage amplifiers have a wider bandwidth than that of voltage feedback operational amplifiers and are preferred in analog signal processing applications [1]-[9]. CFOAs have also been used extensively to realize integrators [10] and biquads and oscillators.

The theoretical analysis of CFOA based amplifiers using first-order models is widely addressed in the literature [3], [5]-[7]. These simplified models are not accurate. Mahattanakul and Toumazou [10] have considered the effect of current mirror pole and the output resistances of the voltage buffers at *x* and *w* terminals of the CFOA in addition to parasitic output resistance and capacitance at *z* node on the performance of inverting finite gain amplifiers using CFOA. Recently, Bayard [11] has proposed a passive compensation scheme using capacitors for extending the bandwidth of CFOA based inverting voltage amplifiers. Bayard [11] has used a two-pole model accounting the current mirror pole in addition to dominant pole due to output resistance and capacitance of the CFOA at *z* output to describe the transfer function at high frequencies. Note that other models have been proposed in literature [12], [13] but they omit the current mirror pole and consider parasitic capacitances at the input *x* and *y* terminals.

The compensation of the non-ideal frequency response of one opamp using another opamp [14], [15] in amplifiers and integrators has also been extensively investigated. In this paper, we explore active compensation technique based on composite CFOA structure for possible bandwidth enhancement of inverting amplifier.

The finite gain amplifiers can be used as stand-alone amplifiers or can be used within second-order active RC filters such as Tow-Thomas biquad. In the former case, the phase response is not a consideration. On the other hand, in active networks and active RC filters, the phase shift in the loop is important and phase error of the amplifier needs to be small [14]. In such applications, amplitude response is not a consideration. This observation has led to several active/ passive compensation techniques for finite gain amplifiers using opamps e.g. [14]. Hence, a passive compensation scheme using feed-forward capacitor to reduce the phase error in addition to bandwidth enhancement has been considered in this paper.

In Section II we analyze the uncompensated CFOA based inverting amplifier. The proposed compensation method using composite CFOA block without and with feed-forward capacitor has been discussed in Section III. SPICE simulation results using two-pole behavioral and practical (i.e., AD 844 CFOA [16]) macro-model of CFOA are presented in Section IV. A concluding section summarizes the results.

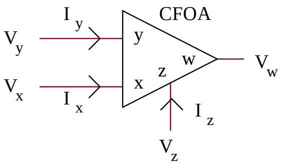
II. UNCOMPENSATED CFOA BASED INVERTING AMPLIFIER

The circuit symbol of CFOA is shown in Fig. 1(a). Note that *x* terminal is a current input terminal and *y* terminal is a voltage input terminal. The ideal properties of CFOA can be expressed in the equation form as:

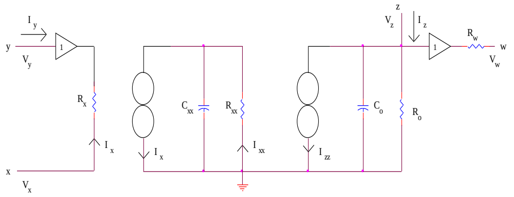
$$\begin{bmatrix} I_y \\ V_x \\ I_z \\ V_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_z \\ V_w \end{bmatrix} \tag{1}$$

The two-pole behavioral macro-model of the CFOA taking into account the current mirror pole τ_{cm}, the series resistance R_x at the *x* input of the CFOA, the parasitics R_o and C_o at the *z* terminal of the CFOA is shown in Fig. 1 (b). Here, $I_{xx}$is modeled using a current mirror pole:

$$I_{xx}(s) = I_x/(1 + s\tau_{cm}) \tag{2}$$



(a)



(b)

Fig. 1 (a) Circuit symbol of CFOA and (b) the non-ideal two-pole CFOA macro model

The voltage gain of the uncompensated CFOA based inverting amplifier circuit in Fig. 2, is shown to be a second-order low-pass type frequency response given as

$$\frac{V_o}{V_i} = -\frac{G}{1+K(1+s\tau_{cm1})(1+s\tau_{o1})} \qquad (3a)$$

where

$$K = R_2'/R_o\,;\ R_2' = R_2 + R_x(1+G);\ G = R_2/R_1\,;\ \tau_o = R_oC_o,\ \tau_{cm} = R_{xx}C_{xx} \qquad 3(b)$$

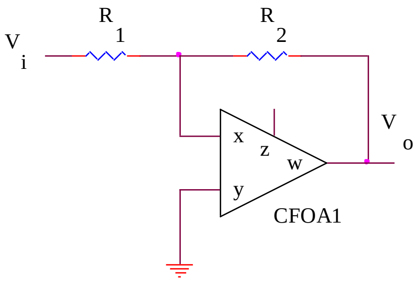


Fig. 2 Uncompensated CFOA-based inverting amplifier

Considering the general expression for the denominator of the second-order transfer function of the type $1 + K(1 + s\tau_{cm1})(1 + s\tau_{o1})$, it can be seen that the pole frequency and pole-Q are given by

$$\omega_o = \sqrt{(1+K^{-1})/\tau_{cm}\tau_o}$$

and

$$Q_o = \sqrt{(1+K^{-1})\tau_{cm}\tau_o}/(\tau_{cm}+\tau_o) \qquad (4)$$

For realizing a Butterworth type response, it can be seen from (4)that

$$1 + K^{-1} = \tau_o/2\tau_{cm} \qquad (5)$$

Noting $1 \ll (R_{o1}/R_2')$ and $\tau_{cm} \ll \tau_o$ in (4), the simplified expressions for pole frequency and pole-Q are shown to be

$$\omega_o = 1/\sqrt{\tau_{cm}R_2'C_o}\,,\ Q_o = \sqrt{\tau_{cm}/(R_2'C_o)} \qquad (6a)$$

The condition for realizing Butterworth type of response (i.e., $Q = 1/\sqrt{2}$) is shown to be

$$R_2' = 2\tau_{cm}/C_o \qquad (6b)$$

The pole frequency in this case will be $\omega_o = 1/(\tau_{cm}\sqrt{2})$.For typical values of τ_{cm} = 2.2736 ns, R_o = 3 MΩ, C_o = 5.5 pF, (e.g. for CFOA AD 844 [16]) R'_2 = 826.76 Ω and the pole frequency is 49.498 MHz.

III. COMPENSATION USING COMPOSITE CFOA

In the compensated composite CFOA based inverting amplifier circuit considered in Fig. 3, a composite CFOA consisting CFOA1 and CFOA2 is used in place of single CFOA.

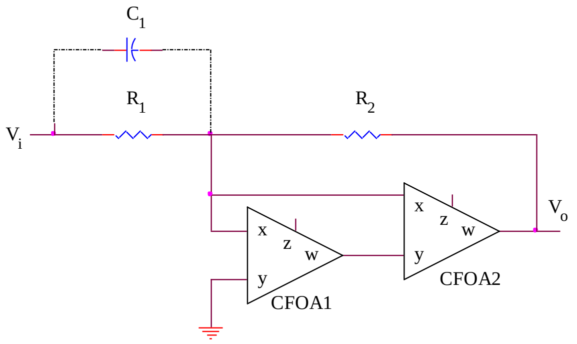


Fig. 3 Compensated inverting amplifier using a composite CFOA

The transfer function of this circuit without considering C_1, is given as

$$\frac{V_o}{V_i} = -\frac{G\{1+\{R_x(1+s(\tau_{cm}+\tau_o)+s^2\tau_{cm}\tau_o)/R_o\}\}}{\begin{Bmatrix}1+n+m+s(\tau_{cm}+\tau_o)(n+2m)\\ +s^2(\tau_{cm}\tau_o(n+2m)+(\tau_{cm}+\tau_o)^2m)\\ +s^3 2m\tau_{cm}\tau_o(\tau_{cm}+\tau_o)+s^4m\tau_{cm}{}^2\tau_o{}^2\end{Bmatrix}} \qquad (7)$$

where

$m = \{R_x(2R_2 + (G+1)R_x)\}/R_o{}^2andn = (R_2 + R_x)/R_o$and $p = R_x/R_o$

Note that m, n and p are quite small compared to unity. Neglecting third and fourth order terms in (7)

$$\frac{V_o}{V_i} = -\frac{G\left\{1+\frac{R_x}{R_o}(1+s(\tau_{cm}+\tau_o)+s^2\tau_{cm}\tau_o)\right\}}{\begin{Bmatrix}1+n+m+s(\tau_{cm}+\tau_o)(n+2m)\\ +s^2(\tau_{cm}\tau_o(n+2m)+(\tau_{cm}+\tau_o)^2m)\end{Bmatrix}} \qquad (8)$$

From (8), the pole frequency of compensated amplifier in Fig. 3 without C_1 is shown to be

$$\omega_o \simeq 1/\sqrt{\tau_{cm}\tau_o(n+2m)+\tau_o{}^2m} \qquad (9)$$

From (9), we see that the pole frequency is larger than that of uncompensated amplifier. From (8), it can be seen that exact condition for minimum phase error cannot be satisfied.

Considering the use of a feed-forward capacitor C_1 across R_1 in the circuit of Fig. 3, the transfer function can be obtained as

$$\frac{V_o}{V_i} = -\frac{G\left(1+\frac{R_x}{R_o}(1+s(\tau_{cm}+\tau_o)+s^2\tau_{cm}\tau_o)\right)(1+sC_1R_1)}{\begin{Bmatrix}1+n+m+s\big((\tau_{cm}+\tau_o)(n+2m)+C_1R_2p^2\big)\\ +s^2\begin{pmatrix}\tau_{cm}\tau_o(n+2m)+(\tau_{cm}+\tau_o)^2m\\ +2C_1R_2p^2(\tau_{cm}+\tau_o)\end{pmatrix}\\ +s^3\begin{pmatrix}2m\tau_{cm}\tau_o(\tau_{cm}+\tau_o)\\ +C_1R_2p^2(2\tau_{cm}\tau_o+(\tau_{cm}+\tau_o)^2)\end{pmatrix}\\ +s^4(m\tau_{cm}{}^2\tau_o{}^2+2C_1R_2p^2\tau_{cm}\tau_o(\tau_{cm}+\tau_o))\\ +s^5(C_1R_2p^2\tau_{cm}{}^2\tau_o{}^2)\end{Bmatrix}} \qquad (10)$$

The condition for phase compensation can be obtained as

$$C_1R_1 = \frac{(\tau_{cm}+\tau_o)(n-p+2m+mp)}{(1+p)\big((1+n+m)-Gp^2\big)} \qquad (11)$$

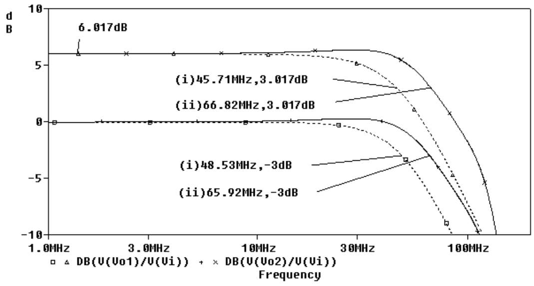
Noting that $(1+p)\big((1+n+m)-Gp^2\big) \cong 1, (2m+mp) \ll (n-p),\ \tau_{cm} \ll \tau_o$, the condition given in (11)can be shown to be

$$C_1R_1 = R_2C_o \qquad (12)$$

IV. SIMULATION RESULTS

The proposed composite CFOA based inverting amplifier circuit without and with feed-forward capacitor have been simulated in PSPICE using two-pole behavioural CFOA macro model (Fig. 1(b)) and AD 844 SPICE macro model [16]. The typical parameters of AD 844 considered in the behavioural macro model and simulation are τ_{cm} = 2.2736 nsec, R_o = 3 MΩ, C_o = 5.5 pF, R_x= 50 Ω, R_w= 15 Ω.

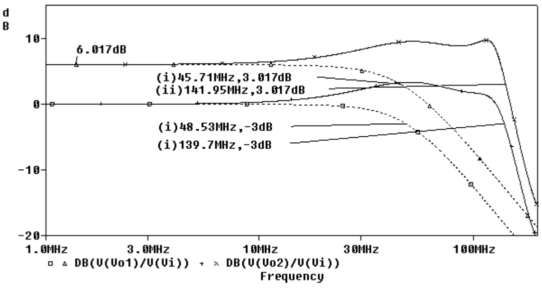
The amplitude responses of the compensated amplifier of Fig. 3 with C_1 = 0 using behavioural macro-model, are presented for gain G = 1 (R_2 =R_1 = 727 Ω) and G = 2 (R_2= 727 Ω, R_1= 363.5 Ω) in Fig. 4 together with those of the uncompensated amplifier, which shows that the bandwidth is increased.



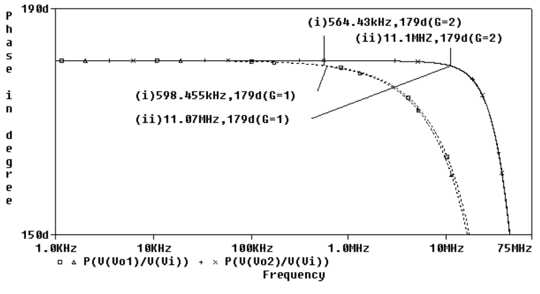
□, Δ Uncompensated CFOA based amplifier +, × Composite CFOA based amplifier without C_1

Fig. 4 Amplitude response of the composite CFOA based inverting amplifier of gain G = 1, 2 of Fig. 3without C_1 using two-pole behavioural macro-model

The amplitude and phase responses of the circuit of Fig. 3 using C_1 = 5.5 pF, 11 pF using behavioural macro-model are presented for gain G = 1 (R_2 =R_1 = 727 Ω) and G = 2 (R_2 = 727 Ω, R_1= 363.5 Ω) respectively in Fig. 5(a) and 5(b), which show that there is bandwidth enhancement as well as improvement in the phase response. The amplitude and phase response plots for the above case using AD 844 SPICE macro model [16] are presented in Fig. 6(a)-(b).



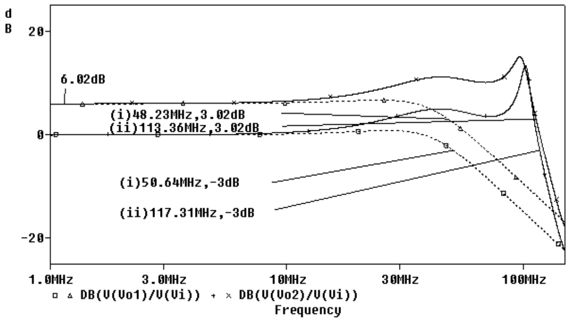
(a)



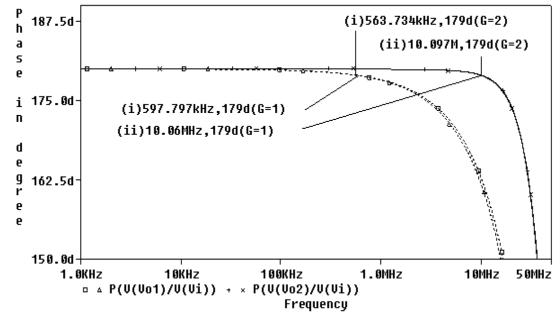
(b)

□, Δ Uncompensated CFOA based amplifier +, × Composite CFOA based amplifier with C_1

Fig. 5 (a) Amplitude responses and (b) phase responses of the composite CFOA based inverting amplifier of gain G = 1, 2 of Fig. 3with C_1using two-pole behavioural macro-model



(a)



(b)

□, Δ Uncompensated CFOA based amplifier +, × Composite CFOA based amplifier with C_1

Fig. 6 (a) Amplitude responses and (b) phase responses of the composite CFOA based inverting amplifier of gain G = 1, 2 of Fig. 3with C_1using AD844 macro-model

V. CONCLUSION

In this paper, we have investigated the compensation techniques for improving the amplitude and phase response of CFOA based amplifiers borrowing well-known techniques used in the active and passive compensation of opamp based finite gain inverting amplifiers. The active compensation technique using two CFOAs in feed-forward mode following the two-opamp based finite gain amplifiers has been studied. Further, the passive compensation technique using feed-forward capacitor for this configuration to reduce the phase error has also been investigated.

The proposed circuits have been shown to improve the amplitude and phase response over conventional CFOA based amplifiers. The proposed circuits have been simulated using CFOA behavioral macro-model containing current mirror pole, finite series resistance at x input terminal and finite output resistance and capacitance of the current output terminal of the CFOA. The simulation results have been shown to agree with those obtained using macro-model of AD 844 CFOA. Application of the proposed compensation techniques to non-inverting amplifiers and integrators and biquads will be the subject of future work.

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Dr. D. V. Kamath obtained PhD in the field of Analog VLSI Signal Processing from Manipal University, Manipal in the year 2013. Currently working as Professor in the Department of E&C, Manipal Institute of Technology, Manipal. The research and academic contribution includes one US patent, 4 full regular papers published in indexed international journals of good repute, 2 indexed international IEEE conference publications. His areas of Areas of Research Interest include Analog and Mixed Signal VLSI design and Analog VLSI Signal Processing