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Active Compensation of CFOA based Non-Inverting Amplifier

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Abstract: In this paper, we consider active compensation techniques using a voltage buffer to enhance the bandwidth of current feedback operational amplifier (CFOA) based finite gain non-inverting voltage amplifier. The use of feed forward capacitor in addition to voltage buffer is shown to achieve minimum phase error in the resulting frequency response. 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 are studied. The circuits considered have been simulated in PSPICE using a behavioral macro-model of the CFOA as well as that of a practical CFOA AD 844.

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

I. INTRODUCTION

The current feedback operational amplifier (CFOA) based voltage-mode amplifiers are preferred over those based on conventional voltage opamps (VOAs)in analog signal processing applications due to their advantages like wider bandwidth and higher slew rates [1]-[7]. CFOAs have also been increasingly used in circuit applications such as integrators, differentiators, analog filters and oscillators.
Initially, the simplified first-order models using output impedance at z terminal were used in the analysis of CFOA based amplifiers [3], [4]. The effect of current mirror pole and the output resistances of the buffers at x and w terminals of the CFOA in addition to the dominant-pole due to parasitic output capacitance and resistance at z node on the performance of CFOA based inverting finite gain amplifiers were considered by Mahattanakul and Toumazou [8]. Bayard [9]has used a two-pole model considering the current mirror pole and the pole due to the output capacitance and resistance of the CFOA at z output. The pathological element-based CFOA macro-models [10], [11] reported in the literature consider the parasitic R_y and C_y in addition to R_x, $R_o$and C_o. But, these models omit the current mirror pole.

The passive and active compensation of CFOA based inverting amplifier for bandwidth enhancement has been discussed [9], [12]-[14]. In this paper we will focus on the compensation methods to improve the amplitude and phase response of CFOA based non-inverting amplifier. The analysis of uncompensated CFOA based non-inverting amplifier using the two-pole behavioral macro-model is considered in section II. The proposed active compensation techniques for extending the bandwidth of CFOA based non-inverting voltage amplifiers have been described in section III. The analysis is performed on the proposed compensation circuits using voltage buffer without and with feed forward capacitor. The SPICE simulation results to verify the workability of the proposed circuits are presented in section IV. Finally, the concluding remarks and scope for further work are given in section V.

II.UNCOMPENSATED CFOA BASED NON-INVERTING AMPLIFIER

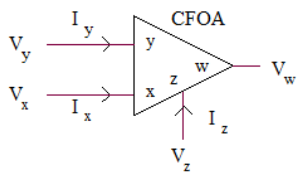
The circuit symbol of CFOA is shown in Fig. 1(a). Note that the x and y terminals of CFOA are current and voltage input terminals respectively. The CFOA is a four terminal device, ideally characterized by the equations:

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

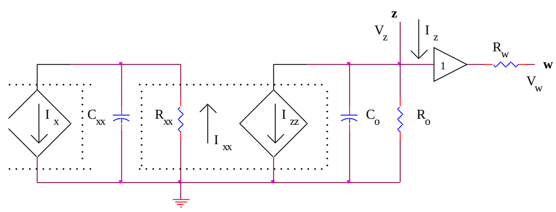
where V_x, V_y, V_z and V_w, I_x, I_y and I_z are the voltages and the currents of x, y, z and w terminals respectively.

A non-ideal two-pole behavioral macro-model of the CFOA is shown in Fig.1 (b). The dominant pole $\tau_o(=R_oC_o)$is due to the parasitic R_o and C_o at the z terminal of the CFOA. The second pole $\tau_{cm}(=R_{xx}C_{xx})$ is due to the CFOA first-stage current mirror.

$$\frac{V_w}{I_x}(s) = \frac{R_o}{(1+s\tau_{cm})(1+s\tau_o)} \quad (2)$$



(a)



(b)

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

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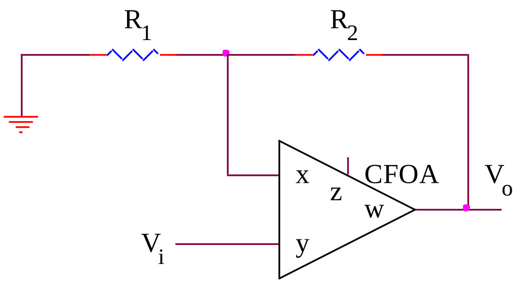

Fig. 2 Uncompensated CFOA based non-inverting amplifier

The R_x and R_w are the output resistances of unity-gain voltage buffers at x and w terminals of the CFOA. The open-loop transimpedance gain of CFOA is shown to be

Using open-loop transimpedance gain expression (2) of CFOA, the closed-loop voltage gain of the uncompensated CFOA based non-inverting amplifier circuit in Fig. 2, is shown to be a second-order low-pass type frequency response given as

$$\frac{V_o}{V_i} = -\frac{G}{1 + K\{1 + s(\tau_{cm} + \tau_o) + s^2\tau_{cm}\tau_o\}} \quad (3a)$$

Where

$$K = R_2'/R_o\,;\ R_2' = R_2 + GR_x;\ G = 1 + R_2/R_1 \quad (3b)$$

From (3a) it can be seen that the denominator of the second-order transfer function (3a) is of the general form $1 + K(1 + s\tau_{cm})(1 + s\tau_o)$ and the pole-frequency and pole-Q are given by

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

And

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

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

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

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

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

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

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

The pole frequency in this case is shown to be $\omega_o = 1/(\tau_{cm}\sqrt{2})$. However, Bayard [9] has given the approximate expression for R_2 neglecting R_x.Considering typical parameters of CFOA AD 844 [15] given in Table 1, R_2'= 826.76 Ω and the pole frequency is 49.498 MHz The actual R_2 to be used can be seen from (6b) to be R_2'-GR_x.

III.COMPENSATION TECHNIQUES FOR CFOA BASED NON-INVERTING AMPLIFIER USING A VOLTAGE BUFFER

It has been shown that the finite series resistance atx input of CFOA affects the frequency response of the inverting amplifier [16].Here we consider the compensation techniques where in, R_x of CFOA is isolated from the gain determining resistors and compensating capacitor using a unity gain voltage buffer. It is also interesting to consider passive compensation scheme in addition to voltage buffer to achieve the best possible performance.

A. Compensation method using a voltage buffer

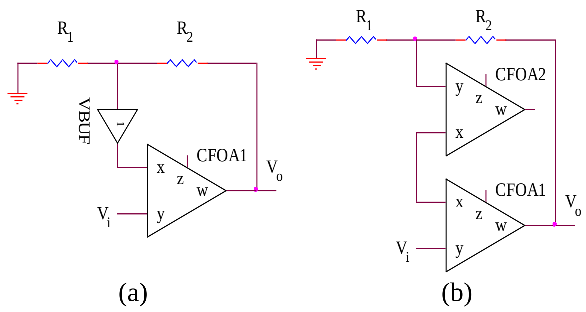

Fig. 3 Active compensation of CFOA based non-inverting amplifier using (a) unity gain voltage buffer (b) input voltage buffer of CFOA2

The CFOA based non-inverting amplifier using unity gain voltage buffer is shown in Fig. 3. The frequency dependent gain of this amplifier is shown to be

$$\frac{V_o}{V_i} = \frac{G}{1 + \frac{R_xG}{R_o}(1 + s\tau_{cm})(1 + s\tau_o)} (7a)$$

Alternatively input voltage buffer of CFOA2 can be used for active compensation as shown in Fig. 4(a), the frequency dependent gain of which is shown to be

$$\frac{V_o}{V_i} = -\frac{G}{1 + \frac{2R_xG}{R_{o1}}(1 + s\tau_{cm1})(1 + s\tau_{o1})} (7b)$$

For compensated amplifier circuit in Fig. 4(a), K value $(K = 2R_xG/R_{o1})$ is decreased as compared to uncompensated amplifier of Fig. 2(a), the pole frequency and pole-Q are increased (see (4)) over those of the uncompensated amplifier. Since there is no other degree of freedom, the compensated amplifier of Fig. 3 (a) cannot realize a Butterworth type of response.

B. Compensation method using a voltage buffer and feed forward capacitor C_1

The compensated CFOA based non-inverting amplifier circuit using feed forward capacitor C_1 across R_1in addition to voltage buffer is shown in Fig. 4.

The transfer function of compensated amplifier in Fig. 4 is shown to below.

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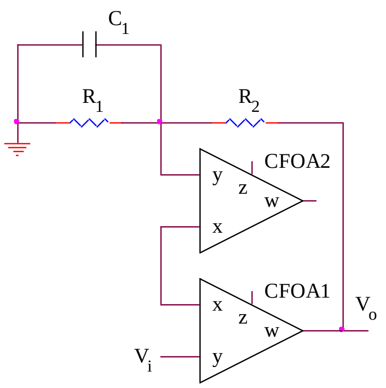


Fig. 4 Compensated CFOA based non-inverting amplifier using input voltage buffer of CFOA2 with $C_1$for realizing minimum phase error

$$\frac{V_o}{V_i}=\frac{G\left(1+s\frac{C_1R_2}{G}\right)}{1+\frac{2R_xG}{R_o}+sG\frac{2R_x}{R_o}(\tau_{cm}+\tau_o)+s\frac{2R_x}{R_o}C_1R_2+s^2G2R_x\tau_{cm}C_o+s^2\frac{2R_x}{R_o}C_1R_2(\tau_{cm}+\tau_o)+s^3 2R_xC_1R_2\tau_{cm}C_o} \qquad (8a)$$

From (8a), neglecting the s^3 term and noting that $R_x << R_o$, $R_2 << R_o$, $\tau_{cm} \ll \tau_o$,we have

$$\frac{V_o}{V_i}=\frac{G\left(1+s\frac{C_1R_2}{G}\right)}{1+s2R_x\left(GC_o+\frac{R_2C_1}{R_o}\right)+s^2 2R_xC_o(G\tau_{cm}+R_2C_1)} \qquad (8b)$$

Equating the coefficient of s-term in the numerator and denominator in (8b), the condition for minimum phase error in the resulting frequency response is shown to be

$$R_2C_1\left(\frac{1}{G}-\frac{2R_x}{R_o}\right)=2GR_xC_o$$
$$R_2C_1 \approx 2G^2R_xC_o \qquad (8c)$$

IV. SIMULATION RESULTS

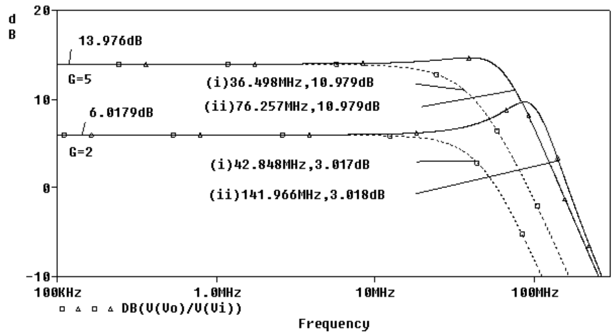
The proposed active compensation methods have been verified by simulating the circuits in PSPICE using two-pole behavioral CFOA macro model (Fig. 1(b)) and AD 844 SPICE macro model [15]. The typical parameter values for CFOA AD 844 given in Table 1 are considered for simulation. In this section, the amplitude and phase response plots displaying power gain in dB $(\text{i.e.}, 20 * \log_{10}(V_o/V_i))$ and phase in degree as a function of frequency has been considered.

Table 1: Typical parameters of CFOA AD 844

Parameter	Typical value
R_o	3 MΩ
C_o	5.5 pF
R_x	50 Ω
R_w	15 Ω
τ_{cm}	2.2736 ns
τ_o	16.5 µs

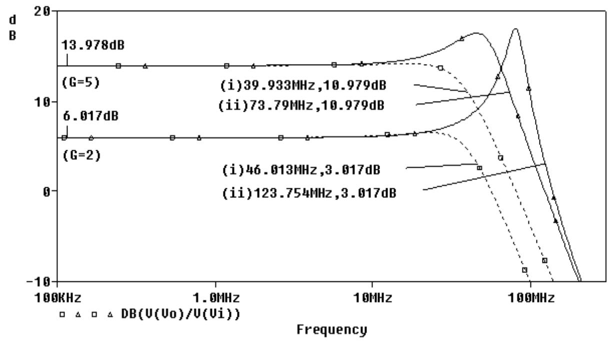
Table 2 Design values for CFOA based uncompensated and compensated non-inverting amplifier of Fig. 2, Fig. 3 and Fig. 4

CFOA based non-inverting amplifier circuit	G	R_2 in Ω	R_1 in Ω	C_1 in pF
Uncompensated and compensated amplifier (with voltage buffer) in Fig. 2 and Fig. 3(b)	2	826.76	826.76	-
	5	826.76	206.69	-
Compensated amplifier (using voltage buffer and C_1) in Fig. 4	2	826.76	826.76	2.661
	5	826.76	206.69	16.631



□ Uncompensated amplifier in Fig. 2 using Bayard's solution based on feedback resistor optimization (R_x = 0))
Δ Compensated amplifier using input voltage buffer of CFOA2 in Fig. 3(b)

Fig. 5Amplitude responses of the CFOA based non-inverting amplifier (of gain G = 2, 5) of Fig. 2 and Fig. 3(b) using two-pole behavioral macro model



□ Uncompensated amplifier in Fig. 2 using Bayard's solution based on feedback resistor optimization (R_x = 0))
Δ Compensated amplifier using input voltage buffer of CFOA2 in Fig. 3(b)

Fig. 6 Amplitude responses of the CFOA based non-inverting amplifier (of gain G = 2, 5) of Fig. 2 and Fig. 3(b) using AD 844 SPICE macro model

The amplitude response of compensated CFOA based non-inverting amplifier circuit of Fig. 3(b) for gains G = 2 and G = 5 using behavioral CFOA macro model are presented in Fig. 5 together with the plots for uncompensated amplifier of Fig. 2 showing that the bandwidth is increased. The amplitude response plots for the above case using AD 844 SPICE macro model [15] are presented in Fig. 6. The compensated amplifier using voltage buffer provides improved bandwidth with peaking.

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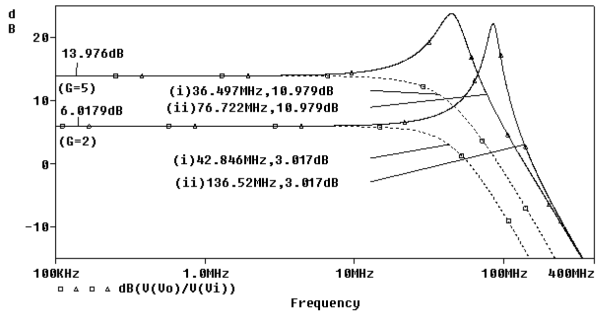
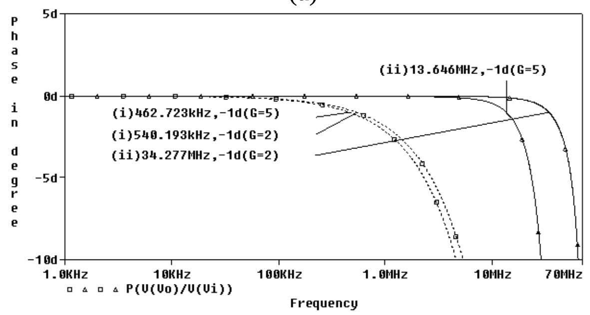


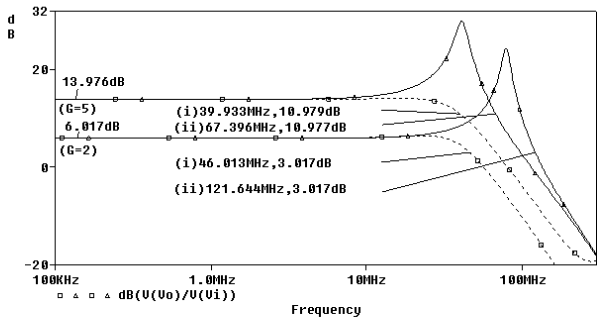
(a)



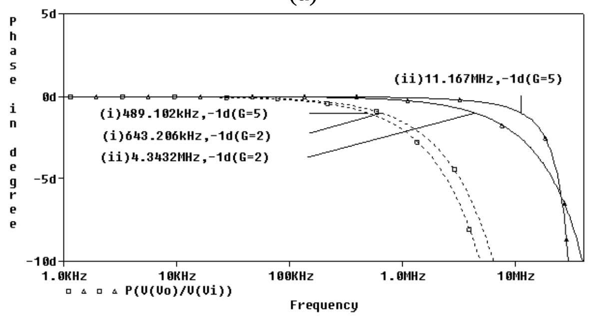
(b)

□ Uncompensated amplifier in Fig. 2 using Bayard's solution based on feedback resistor optimization ($R_x = 0$))
Δ Compensated amplifier (using voltage buffer and C_1) in Fig. 4

Fig. 7 (a) Amplitude responses and (b) phase responses of the CFOA based non-inverting amplifier (of gain G = 2, 5) of Fig. 2 and Fig. 4 using two-pole behavioral macro model



(a)



(b)

□ Uncompensated amplifier in Fig. 2 using Bayard's solution based on feedback resistor optimization ($R_x = 0$))
Δ Compensated amplifier (using voltage buffer and C_1) in Fig. 4

Fig. 8 (a) Amplitude responses and (b) phase responses of the CFOA based non-inverting amplifier (of gain G = 2, 5) of Fig. 2 and Fig. 4 using AD 844 SPICE macro model

The proposed compensated non-inverting amplifier using voltage buffer and C_1 in Fig. 4 (refer Table 2 for design values) was simulated for gains G = 2, 5 using two-pole behavioral macro model and the amplitude and phase responses of these are compared with uncompensated amplifier and are presented in Fig. 7 (a) and (b). Note that R_2 value is chosen for Butterworth response based on feedback resistor optimization [9]. The amplitude and phase responses for the above given two cases using AD844 macro-model is presented in Fig. 8 (a) and (b). For simulation of the compensated non-inverting amplifier (using voltage buffer and C_1) in Fig. 4 using AD 844 macro-model, the parasitic capacitor at y input i.e., C_y (≈2 pF) must be considered [17].

From the plots in Fig. 7(a)-(b) and Fig. 8(a)-(b), it is evident that the proposed compensated non-inverting amplifier using voltage buffer and C_1 provides improved phase and amplitude responses. The improvement in the bandwidth is associated with slight peaking.

V. CONCLUSION

In this paper, CFOA based non-inverting amplifiers have been investigated considering the effect of R_x, parasitic and C_o at z terminal and current mirror pole. The use of voltage buffer in a CFOA based non-inverting amplifier to isolate inverting input from the gain determining resistors has been proposed, which has been shown to improve the bandwidth. But this method will increase the pole-Q in addition to pole frequency and hence will not provide the Butterworth response. The use of C_1in addition to voltage buffer is shown to improve phase and amplitude responses. The proposed compensation techniques have been shown to extend the bandwidth over conventional CFOA based amplifiers. The proposed circuits have been simulated using CFOA behavioral as well as practical AD 844 CFOA macro-models. The scope for further work includes the applicability of the proposed compensation techniques to CFOA based voltage buffers.

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