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Composite CFOA based Non-inverting amplifier

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Abstract: To increase the bandwidth of a finite gain non-inverting voltage amplifier for use as a standalone amplifier, an active compensation method utilising two current feedback operational amplifiers (CFOAs) is proposed in this study. Additionally, it is demonstrated that using a feedforward capacitor with a composite CFOA-based amplifier will expand bandwidth while also improving phase response. The suggested circuits need an extra CFOA/capacitor. The analysis takes into account the effects of the current mirror pole of the CFOA, input resistance at the x terminal, and finite output impedance at the z terminal. Using both a behavioural macro-model of the CFOA and a real CFOA AD 844, the suggested circuits have been simulated in PSPICE.

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

I. INTRODUCTION

In analogue signal processing applications, current feedback operational amplifier (CFOA) based finite gain voltage amplifiers are chosen over voltage feedback operational amplifiers (VFOA) because they have a broader bandwidth [1]–[9]. Moreover, the realisation of integrators [10], biquads, and oscillators has made substantial use of CFOAs.

The theoretical analysis of CFOA based amplifiers using first-order macro models are widely addressedin the literature [3], [5]-[7]. These macro 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. 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 behavioural models of CFOA have been proposed in literature [12], [13] but they don't consider the current mirror pole and consider parasitic capacitances at the input x and y terminals.

The passive compensation scheme using capacitors for extending the bandwidth of CFOA-based inverting and non-inverting voltage amplifiers has been described [11], [14]. Boutin has proposed the use of a negative resistance at the virtual ground input for enhancing the bandwidth of opamp based finite gain amplifiers [15]. The frequency compensation of OTA based active RC filters using grounded negativeresistance has been reported [16]. Recently, the use of negative impedance converter (NIC) for compensationof CFOA based inverting amplifier has been reported [17].The compensation scheme using voltage buffer for extending the bandwidth of CFOA-based inverting and non-inverting voltage amplifiers has been proposed [18], [19].

The compensation of the non-ideal frequency response of one opamp using another opamp [20], [21] in amplifiers and integrators has also been extensively investigated. 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[TT]biquad. In the former case, the phase response is not a consideration. In some applications such as active networks and active RC filters, the amplitude response is not a consideration but the phase shift in the loop is important and phase error of the amplifier needs to be minimum [20]. This observation has led to several active/ passive compensation techniques for finite gain amplifiers using opamps e.g. [21].

The compensation of inverting amplifier using composite CFOA block has been described [22].In this paper, we explore active compensation technique based on composite CFOA structure for possible bandwidth enhancement of non-inverting amplifier. Also, a passive compensation scheme using feed-forward capacitor to reduce the phase error in addition to improvement in the amplitude response is proposed. In Section II the analysis of the uncompensated CFOA based non-inverting amplifier is considered. 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 andpractical (i.e., AD 844 CFOA [23]) macro-models of CFOA are presented in Section IV. A concluding section summarizes the results.

II. UNCOMPENSATED CFOA BASED NON-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:

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

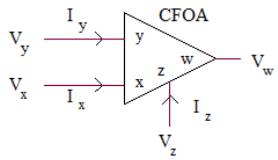
The two-pole behavioral macro-model of the CFOA taking into account the current mirror pole τ_{cm}, the series resistance R_x at the x input of the CFOA, the parasitics R_o and C_o at the z terminal of the CFOA is shown in Fig. 1 (b). Here, I_{xx} is modeled using a current mirror pole:

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

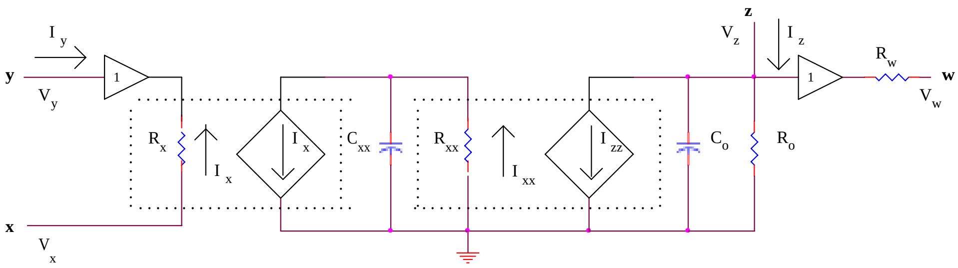
The voltage gain of the uncompensated CFOA based non-inverting amplifier circuit in Fig. 2, is shown to be a second-order low-pass type frequency response given as

$$\frac{V_o}{V_i} = \frac{G}{1 + K(1 + s\tau_{Cm1})(1 + s\tau_{o1})} \quad (3)$$

where $K = R_2'/R_o$; $R_2' = R_2 + GR_x$; $G = 1 + [R_2/R_1]$; $\tau_o = R_oC_o$, $\tau_{Cm} = R_{xx}C_{xx}$



(a)



(b)

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

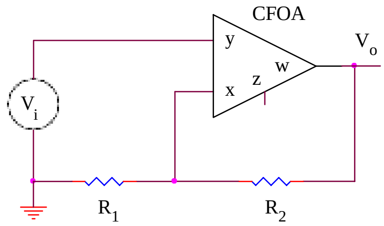


Figure 2: Uncompensated CFOA based non-inverting amplifier

Considering general expression for the denominator of 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

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

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

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

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

$$\omega_o = 1/\sqrt{\tau_{Cm}R'_2 C_o}\,, \; Q_o = \sqrt{\tau_{Cm}/(R'_2 C_o)} \quad (6a)$$

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

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

The pole frequency in this case will be

$$\omega_o = 1/(r_{cm}\sqrt{2}) \tag{6c}$$

For typical values of τ_{cm}= 2.2736 ns, R_o= 3 MΩ, C_o= 5.5 pF, (e.g. for CFOA AD 844 [22]) R'_2 = 826.76 Ω and the pole frequency is 49.498 MHz.

III. COMPOSITE CFOA BASED NON-INVERTING AMPLIFIER

A. Composite CFOA based Non-inverting Amplifier

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

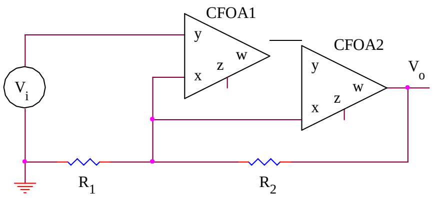


Figure 3: Compensated non-inverting amplifier using a composite CFOA

The transfer function of compensated non-inverting amplifier circuit in Fig. 3, is shown to be

$$\frac{V_o}{V_i} = G\,\frac{1 - \frac{(n-p)}{G}(s^2\tau_{Cm}\tau_o + s(\tau_{Cm} + \tau_o) + 1)}{\begin{array}{c}1 + n + m + s(\tau_{Cm} + \tau_o)(n + 2m) + s^2(\tau_{Cm}\tau_o(n + 2m) + (\tau_{Cm} + \tau_o)^2 m)\\ + s^3 2m\tau_{Cm}\tau_o(\tau_{Cm} + \tau_o) + s^4 m\tau_{Cm}{}^2\tau_o{}^2\end{array}} \tag{7a}$$

where

$$m = R_x(2R_2 + GR_x)/R_o{}^2 \text{and} n = (R_2 + R_x)/R_o \text{ and } p = R_x/R_o$$

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

$$\frac{V_o}{V_i} = G\,\frac{1 - \frac{(n-p)}{G}(s^2\tau_{Cm}\tau_o + s(\tau_{Cm} + \tau_o) + 1)}{1 + n + m + s(\tau_{Cm} + \tau_o)(n + 2m) + s^2(\tau_{Cm}\tau_o(n + 2m) + (\tau_{Cm} + \tau_o)^2 m)} \tag{7b}$$

From (7b), the pole frequency of compensated amplifier in Fig. 3 is shown to be

$$\omega_o = \frac{1}{\sqrt{\tau_{Cm}\tau_o(n + 2m) + \tau_o{}^2 m}} \tag{8}$$

From (8), we see that the pole frequency is larger than that of uncompensated amplifier. From (7b), it can be seen that exact condition for minimum phase error cannot be satisfied.

B. Composite CFOA based Non-inverting Amplifier with feed-forward capacitor

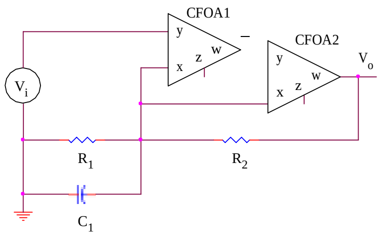


Figure 4: Compensated composite CFOA based non-inverting amplifier with feed-forward capacitor

Consider composite CFOA based non-inverting amplifier with feed-forward capacitorC_1 across R_1 in the circuit of Fig. 4, the transfer function can be obtained as

$$\frac{V_o}{V_i} = G\,\frac{1 - \frac{(n-p)}{G} + s\left(\frac{R_2C_1 - (n-p)(\tau_{Cm}+\tau_o)}{G}\right) - s^2\frac{\tau_{Cm}\tau_o(n-p)}{G}}{\begin{array}{c}1 + n + m + s((\tau_{Cm} + \tau_o)(n + 2m) + R_2C_1p^2)\\ + s^2(\tau_{Cm}\tau_o(n + 2m) + (\tau_{Cm} + \tau_o)^2 m + 2R_2C_1p^2(\tau_{Cm} + \tau_o))\\ + s^3(2m\tau_{Cm}\tau_o(\tau_{Cm} + \tau_o) + R_2C_1p^2(2\tau_{Cm}\tau_o + (\tau_{Cm} + \tau_o)^2))\\ + s^4(m\tau_{Cm}{}^2\tau_o{}^2 + 2R_2C_1p^2\tau_{Cm}\tau_o(\tau_{Cm} + \tau_o)) + s^5(R_2C_1p^2\tau_{Cm}{}^2\tau_o{}^2)\end{array}} \tag{9}$$

wherem = $R_x(2R_2 + GR_x)/R_o{}^2$ and $n = (R_2 + R_x)/R_o$ and $p = R_x/R_o$

Equating the coefficient of s-term in the numerator and denominator and $\tau_{Cm} \ll \tau_o$, the condition for phase compensation can be obtained as

$$R_2C_1 = \frac{(n(1+G) - p + 2mG)}{(1 - p^2G)}\tau_o \quad (10)$$

Noting that $p^2G \ll 1$ and $p \ll n(1+G)$, the condition given in (10) can be shown to be

$$C_1 = \left(1 + \frac{R_x}{R_2}\right)(1+G)C_o \approx (1+G)C_o \quad (11)$$

IV. SIMULATION RESULTS

The proposed composite CFOA based non-inverting amplifier circuit without and with feed-forward capacitor have been simulated in PSPICE using two-pole behavioral CFOA macro model (Fig. 1(b)) and AD 844 SPICE macro model [23]. The typical parameters of AD 844 considered in the behavioral 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.

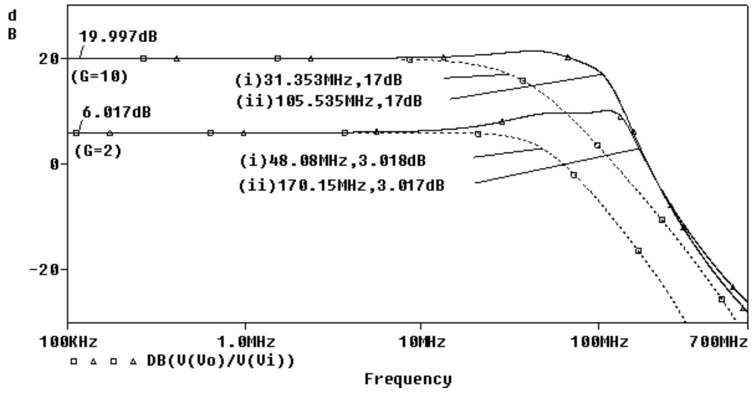
Table 1: Typical parameters of CFOA AD 844

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

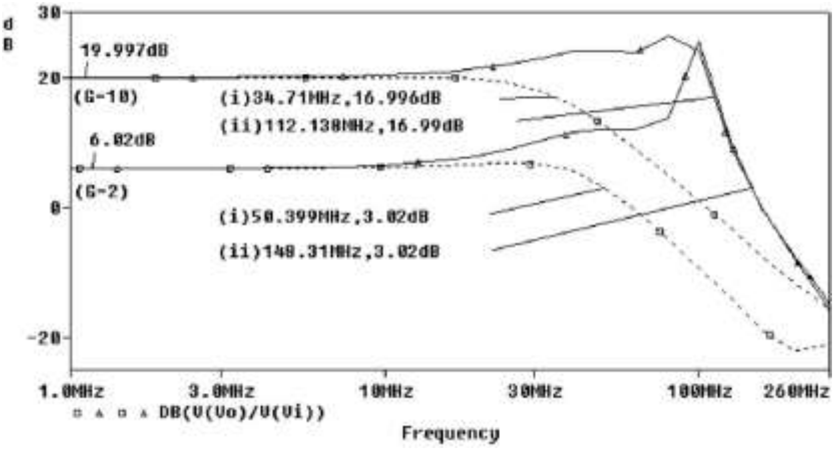
CFOA based non-inverting amplifier circuit	G	R_2 in Ω	R_1 in Ω	C_1 in pF
Uncompensated (single CFOA based) amplifier in Fig. 2 and Compensated(composite CFOA based)amplifier circuit in Fig. 3	2	726.76	726.76	-
	10	726.76	80.75	-
Compensated (composite CFOA based)amplifier circuit with C_1in Fig. 4	2	726.76	726.76	16.5
	10	726.76	80.75	60.5

The amplitude responses of the compensated amplifier of Fig. 3 using behavioral macro-model, are presented for gain G = 2 and G = 10(refer Table II for component values) in Fig. 5 together with those of the uncompensated amplifier, which shows that the bandwidth is increased. The amplitude response plot for the above case using AD 844 SPICE macro model [23] are presented in Fig. 6.



□ Uncompensated amplifier in Fig. 2 using proposed solution based on feedback resistor optimization
Δ Composite CFOA based compensated amplifier in Fig. 3

Figure 5: Amplitude response of the CFOA based non-inverting amplifier (of gain G = 2, 10) of Fig. 2 and Fig. 3using two-pole behavioral macro model

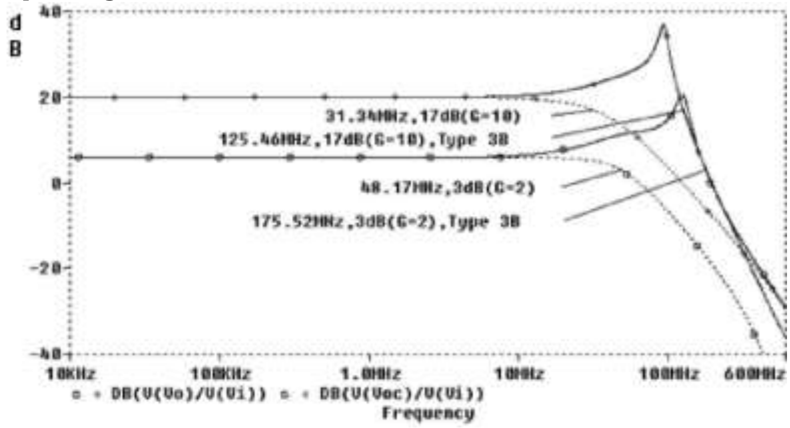


□ Uncompensated amplifier in Fig. 2 using proposed solution based on feedback resistor optimization

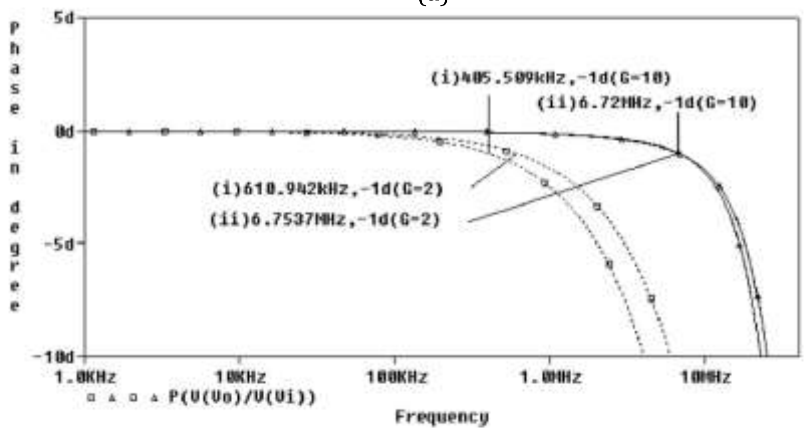
Δ Composite CFOA based compensated amplifier in Fig. 3

Figure 6: Amplitude response of the CFOA based non-inverting amplifier (of gain G = 2, 10) of Fig. 2 and Fig. 3usingAD 844 SPICE macro model

The amplitude and phase responses of the circuit of Fig. 4(refer Table II for component values) using behavioral macro-model are presented for gain G = 2 and G = 10 respectively in Fig. 7(a) and 7(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 [23] are presented in Fig. 8(a) and 8(b).From the plots in Fig. 7and Fig. 8, it is clear that the proposed compensated non-inverting amplifier using C_1 provides improved phase and amplitude responses. The improvement in the bandwidth is associated with slight peaking.



(a)

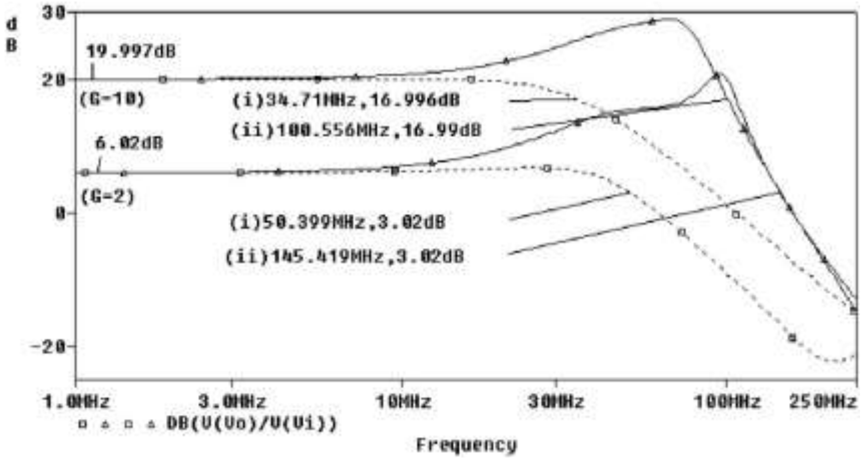


(b)

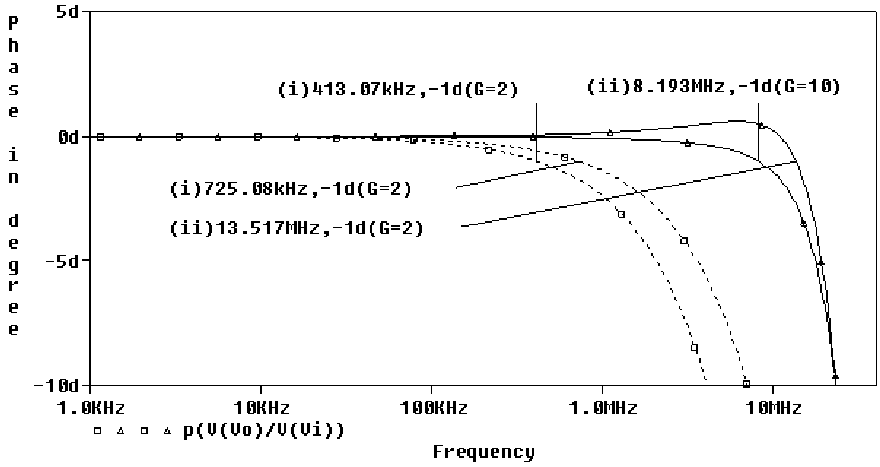
□ Uncompensated amplifier in Fig. 2 using proposed solution based on feedback resistor optimization

Δ Composite CFOA based compensated amplifier with C_1in Fig. 4

Figure 7: (a) Amplitude responses and (b) phase responses of the CFOA based non-inverting amplifier (of gain G = 2, 10) of Fig. 2 and Fig. 4 using two-pole behavioral macro model



(a)



(b)

□ Uncompensated amplifier in Fig. 2 using proposed solution based on feedback resistor optimization
Δ Composite CFOA based compensated amplifier with C_1in Fig. 4

Figure 8: (a) Amplitude responses and (b) phase responses of the CFOA based non-inverting amplifier (of gain G = 2, 10) of Fig. 2 and Fig. 4 using AD 844 SPICE macro model

V. CONCLUSION

In this study, we looked at active compensation strategies for CFOA-based non-inverting amplifiers to enhance their amplitude and phase response by utilising well-known techniques for active and passive compensation of opamp-based finite gain inverting amplifiers. After the two-opamp based finite gain amplifiers, the active compensation technique using two CFOAs in feed-forward mode has been studied. Moreover, the feed-forward capacitor passive compensation method has been researched for this arrangement to lessen phase error.

It has been demonstrated that the amplitude and phase response of the proposed compensated non-inverting amplifier circuits is superior to that of traditional CFOA-based amplifiers. Using a CFOA behavioural macro-model with a current mirror pole, finite series resistance at the x input terminal, finite output resistance, and capacitance at the current output terminal, the proposed circuits have been simulated. It has been demonstrated that the simulation results match those obtained using the AD 844 CFOA macromodel. Further research will focus on the implementation of the suggested compensating approaches to voltage buffers built using CFOA.

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