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# CFOA-based state-variable biquad and its high-frequency compensation

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**Abstract:** A four-Current feedback operational amplifier (CFOA)-based state variable biquad is described which permits the accommodation of or compensation for the z-pin parasitic impedances of the CFOAsand offers a number of advantages over previously known CFOA-based biquad configurations. The workability of the circuit has been confirmed by SPICE simulation results based on commercially available AD844 type CFOAs.

**Keywords:** Current-feedback operational amplifiers, biquad filters, Circuit Theory and Design

**Classification:** Integrated circuits

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## 1 Introduction

Because of offering several advantages over conventional voltage-mode op-amps (VOA) such as, wide and nearly constant bandwidth with variable gains, very high slew rate and ease of realizing various functions with the least possible number of passive components without requiring any component-matching conditions, the current feedback op-amps (CFOA) are being regarded as attractive alternative building blocks for analog filter design and signal processing/generation; see [1]-[9] and the reference cited therein. While devising the circuits using CFOAs, use of only grounded capacitors makes the resulting circuits attractive for IC implementation. Furthermore, if CFOA structures could be involved using only grounded/virtual grounded resistors, it would become easier to incorporate electronic tunability of the parameters by replacing such resistors by VCRs.

Circuits simultaneously realizing lowpass, highpass and bandpass filters find applications in crossover networks used in three-way high-fedility loudspeakers, touch-tone telephone systems and phase locked loops FM stereo demodulators etc.

Among the previously known CFOA-based biquads those of [2]-[5] realize multiple-input-single output (MISO) type biquads which do not provide three outputs simultaneously. Only the circuits from [1], [6]-[9] realize fixed-topology single-input-multiple-output (SIMO)-type biquads with which this paper is concerned. A survey of the circuits from [1], [6]-[9] reveals that they suffer from one or more of the following drawbacks: (i) non-availability of infinite $Z_{in}$ (ii) non-availbility of tunability of all the parameters [6], [7], [9], and/or (iii) non-availability of all grounded/virtually grounded resistors [1] (three-CFOA-biquad therein), [6] and [9] and/or (iv) requirement of a relatively larger number (five to nine) of CFOAs [1] (five-CFOA-biquad therein), [8], [9].

A standard method of realizing multifunction filters is through the state variable (SV) formulation which is very widely known in the context of conventional op-amp-based biquad filters. However, comparatively, only a few SV structures have been proposed in the literature using CFOAs, for instance see [1]. This paper presents a specially-devised SV structure which employs only four CFOAs, two GCs and only grounded/virtual grounded resistors such that either it accommodates the z-pin parasitics or permits the application of a simple but effective high-frequency compensation scheme to compensate for the z-pin parasitics. The workability of the proposed circuit has been confirmed by hardware implementations and PSPICE simulations based upon AD844 type CFOAs.


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## 2 The proposed SV biquad structure

The proposed circuit is shown in Fig. 1 (a). The circuit contains two non-inverting integrators with a specially devised summer realized by a two-CFOA structure restricted to the employment of only grounded/virtual grounded resistors.

Before proceeding further, it is relevant to point out that using two integrators (both inverting, both non-inverting or one inverting and one non-inverting) and a single CFOA-based summer, a number of SV-structures could be evolved however, whereas the z-port parasitics (consisting of $R_p||C_p$) can be easily accommodated/accounted in the integrator, the same would become *parasitics* in case of CFOA-based summers. This, in turn, would degrade the high frequency performance of the summer and hence, also that of the resulting biquad[1]. By contrast, in the present circuit, it is the specific summer structure which permits the incorporation of a simple compensation scheme to reduce the effect of Z-pin parasitics.

Assuming ideal CFOAs, characterized by $i_y = 0$, $i_x = i_z$, $v_y = v_x$, and $v_z = v_w$, the three transfer functions realized by this circuit are given by

$$T_{LP}(s) = \left(\frac{V_{01}}{V_{in}}\right) = \frac{\left(\frac{R_2}{C_1C_2R_1R_3R_4}\right)}{D(s)} \tag{1}$$

$$T_{BP}(s) = \left(\frac{V_{02}}{V_{in}}\right) = \frac{s\left(\frac{R_2}{C_1R_3R_1}\right)}{D(s)} \tag{2}$$

$$T_{HP}(s) = \left(\frac{V_{03}}{V_{in}}\right) = \frac{s^2\left(\frac{R_2}{R_1}\right)}{D(s)} \tag{3}$$

$$\text{where} \quad D(s) = s^2 + s\left(\frac{R_2}{C_1R_3R_5}\right) + \frac{R_2}{C_1C_2R_3R_4R_6} \tag{4}$$

The expressions for the various parameters of the realised filters are found to be

$$\omega_0 = \sqrt{\left(\frac{R_2}{C_1C_2R_3R_4R_6}\right)} : \; Q_0 = R_5\sqrt{\left(\frac{C_1R_3}{C_2R_2R_4R_6}\right)}; \; BW = \left(\frac{R_2}{C_1R_3R_5}\right) \tag{5}$$

$$H_{LP} = \left(\frac{R_6}{R_1}\right); \; H_{BP} = \left(\frac{R_5}{R_1}\right) \text{ and } H_{HP} = \left(\frac{R_2}{R_1}\right) \tag{6}$$

## 3 Tunability of the Parameters

It is interesting to note that in LP and HP, having set $\omega_0$ and $Q_0$, the gain $H_0$ can be independently adjusted with $R_1$ and that in BP, $\omega_0$ is independently adjustable with $R_4$ and/or $R_6$ and after adjusting BW independently by $R_5$, $H_0$ can be independently adjusted by $R_1$. If the resistors $R_1$, $R_5$ and $R_4$, $R_6$ are replaced by CMOS VCRs driven by external voltage $V_{c1}$, $V_{c5}$ and $V_{c6}$ (common to both $R_4$ and $R_6$), these parameters can be electronically controlled independently.

[1]It is possibly this inherent difficulty which has discouraged researchers from coming out with SV- structures using CFOAs although a variety of other types of biquads have been proposed [1]-[9].


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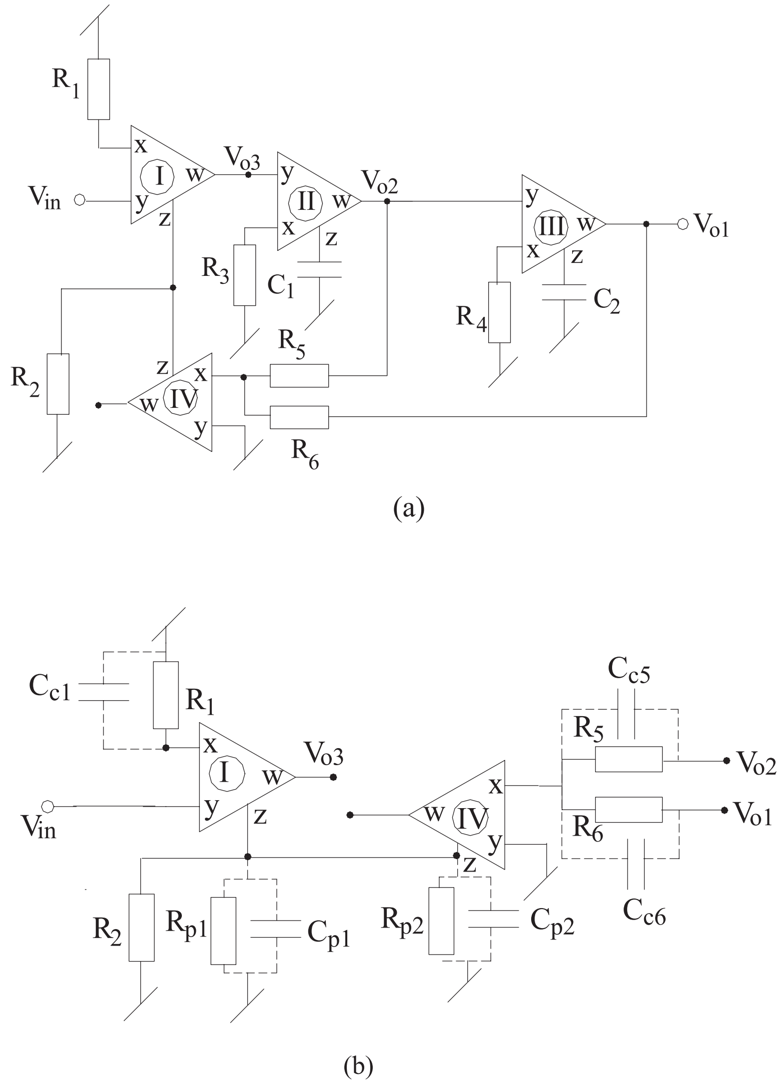


**Fig. 1.** (a) The proposed CFOA-based state-variable biquad (b) A simple passive-compensation of the summer

## 4 Sensitivity

From eqns (5) and (6), it can be easily deduced that all the sensitivity coefficients of $\omega_0$, $Q_0$, BW and $H_0$ are given by

$$0 \leq |S_x^F| \leq 1 \tag{7}$$

where F represents any of $\omega_0$, $Q_0$, BW and $H_0$ and x represents any of the resistors and capacitors with respect to which the sensitivities are to be evaluated. Thus, the circuit enjoys very low sensitivities

## 5 Effect of the various CFOA parasitics and a simple compensation scheme

We consider the effect of various parasitics namely (i) finite input impedance $r_x$ at port x and (ii) compensation pin parasitics $(R_p| |C_p)$ at port z. Since


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resistors $R_1$, $R_3$ and $R_4$ are connected at port x of CFOAs, '$r_x$' of the corresponding CFOA can be easily accommodated in these external resistors. The z-pin parasitic capacitances at CFOA-II and III can be easily accommodated in $C_1$ and $C_2$ respectively. A re-analysis of the integrator made from CFOA-II, for example, reveals that the non-ideal transfer function of the integrator becomes

$$\mathrm{T(s)} = \frac{1}{\left[\mathrm{s}\left(\mathrm{C_1} + \mathrm{C_{p2}}\right) + \frac{1}{\mathrm{R_{p2}}}\right]\left(\mathrm{R_3} + \mathrm{r_{x2}}\right)} \tag{8}$$

$$T(s) \cong \frac{1}{s\left(C_1 + C_{p2}\right)\left(R_3 + r_{x2}\right)} \tag{9}$$

provided

$$\omega(\mathrm{C_1} + \mathrm{C_{p2}}) \geq \frac{1}{\mathrm{R_{p2}}} \tag{10}$$

which can be approximated as provided (with $C_1 = 1\,\mathrm{nF}$, $C_{p3} = 4.5\,\mathrm{pF}$ and $R_{p3} = 3\,\mathrm{M\Omega}$, this constrains $f \gg 53\,\mathrm{Hz}$, which does not appear to be very restrictive).

We now show that the effect of z-pin parasitics of CFOA-I and CFOA-IV, constituting a summer, can be accomplished by shunting resistors $R_1$, $R_5$ and $R_6$ by small external capacitors $C_{C1}$, $C_{c5}$ and $C_{c6}$ as shown in Fig. 1 (b). An analysis of this circuit reveals that the output of CFOA-I is now given by

$$\mathrm{V_{03}} = \left\{\frac{\mathrm{V_{in}}\left(\mathrm{sC_{c1}R_1} + 1\right)}{\mathrm{R_1}} - \frac{\mathrm{V_{02}}\left(\mathrm{sC_{c5}R_5} + 1\right)}{\mathrm{R_5}} - \frac{\mathrm{V_{01}}\left(\mathrm{sC_{c6}R_6} + 1\right)}{\mathrm{R_6}}\right\} \cdot \left\{\frac{\mathrm{R_{p1}}|\,|\mathrm{R_{p2}}|\,|\mathrm{R_2}}{\mathrm{s}\left(\mathrm{C_{p1}} + \mathrm{C_{p2}}\right)\left(\mathrm{R_{p1}}|\,|\mathrm{R_{p2}}|\,|\mathrm{R_2}\right) + 1}\right\} \tag{11}$$

Thus, if we select $C_{C1}$, $C_{c5}$ and $C_{c6}$ such that

$$\mathrm{C_{c1}R_1} = \mathrm{C_{c5}R_5} = \mathrm{C_{c6}R_6} = (\mathrm{C_{p1}} + \mathrm{C_{p2}})(\mathrm{R_{p1}}|\,|\mathrm{R_{p2}}|\,|\mathrm{R_2}) \tag{12}$$

then equation (11) reduces to

$$\mathrm{V_{03}} = \frac{\mathrm{R_2}}{\mathrm{R_1}}\mathrm{V_{in}} - \frac{\mathrm{R_2}}{\mathrm{R_5}}\mathrm{V_{02}} - \frac{\mathrm{R_2}}{\mathrm{R_6}}\mathrm{V_{01}}\,;\ \text{assuming}\ \ (\mathrm{R_{p1}}\|\mathrm{R_{p2}}\|\mathrm{R_2}) \cong \mathrm{R_2} \tag{13}$$

which is the ideal value of $V_{03}$ and thus, perfect compensation for the z-pin parasitics of CFOA-I and CFOA-IV would be achieved subject to the satisfaction of condition (12).

Thus, by following the above strategy, the effect of various parasitics can be considerably reduced and as a consequence, the frequency range of operation of the circuit would, therefore, be extended. Experiments and simulations have confirmed this.

## 6 Hardware Implementation and SPICE simulation results

The proposed circuit was implemented in hardware using IC AD844 as well as simulated in PSPICE using the macro model of AD844 (Courtesy: Analog Devices). In both cases, the observed behavior of the circuit was in conformation to the theoretical results obtained. The PSPICE generated frequency


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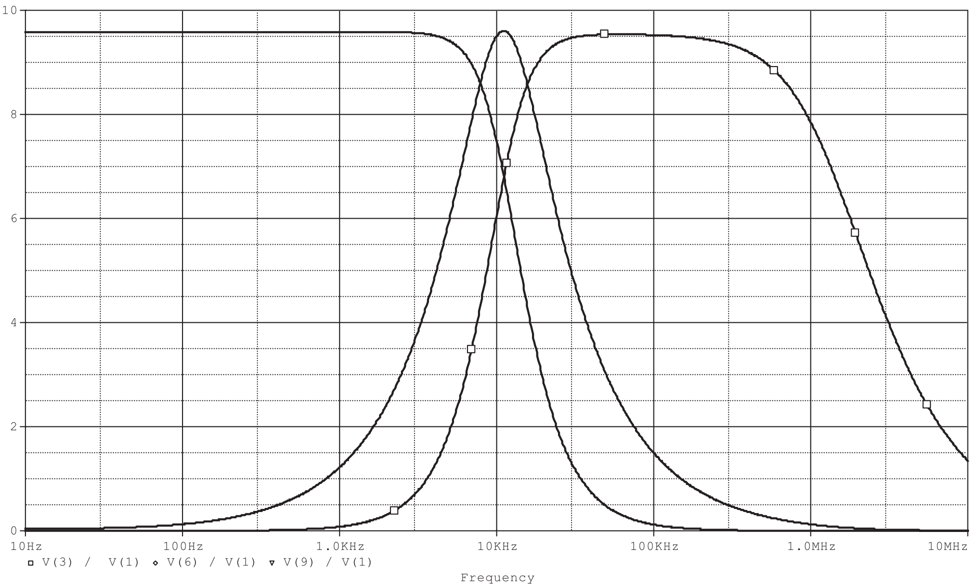
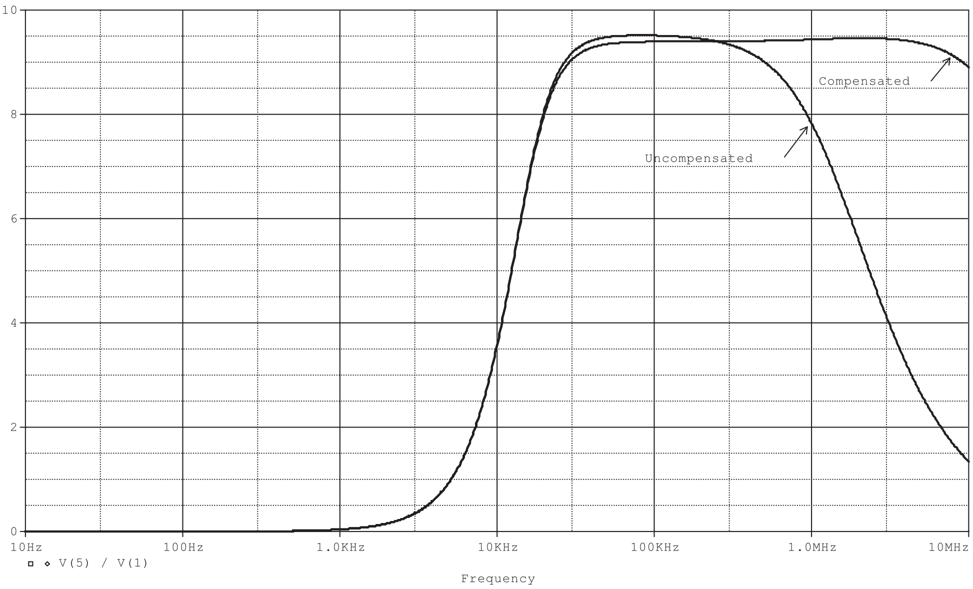



(a)




(b)

**Fig. 2.** SPICE simulation results
(a) Frequency responses for the LP/BP/HP filters realized from the biquad of Fig. 1 (a)
(b) Frequency response for the HP filter realized from the biquad of Fig. 1 (a) with and without the compensation

responses are shown in Fig. 2 (a) and Fig. 2 (b) for the circuits designed for $f_0 = 15.9$ kHz and $Q_0 = 0.7$ for low pass, high pass and band pass with gain of 10 by choosing $R_1 = 1\,k\Omega$, $R_2 = 10\,k\Omega$, $R_3 = 10\,k\Omega$, $R_4 = 10\,k\Omega$, $R_5 = 10\,k\Omega$, $R_6 = 10\,k\Omega$, with $C_1 = 1$ nF and $C_2 = 2$ nF. For acheving compensation, the external capacitance used were $C_{c1} = 108.9$ pF $C_{c5} = 15.557$ pF and $C_{c6} = 10.89$ pF (calculated using equation (12)). The frequency response shown in Fig. 2 (b) clearly demonstrates that the compensation method de-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scribed in the previous section extends the usable frequency range of the HP filter by almost one decade.

## 7 Concluding remarks

A four-CC-based state variable biquad capable of realizing LP, BP and HP filter was presented which possesses the following advantageous features: (i) simultaneous realisability of LP, HP and BP filters from the same circuit (ii) availability of low-output impedance outputs in all the cases (iii) use of both grounded capacitors (iv) independent control of various filter parameters (v) use of only grounded/virtually-grounded resistors (vi) low sensitivities (vii) easy accountability and compensation of the various CFOA z-pin parasitics and (viii) employment of a reasonable number (only four) of the CFOAs. To the best knowledge of the authors, all these properties have not been attained simultaneously by any of the CFOA-biquads known earlier [1]-[9].

The workability of the three modes of operation of the circuit as well as the efficacy of the applied high frequency compensation has been confirmed by implementation results based upon AD844 type CFOAs. Finally, it must be emphasized that although having once gone through the above presentation, the SV biquad presented here may appear rather simple, however, this specific structure alongwith its compensation as demonstrated here has not been reported explicitly in the published literature earlier.

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