Voltage-mode Lowpass, Bandpass, and Bandstop Programmable Filter using Four-terminal CFOAs

Ivailo M. Pandiev[1]

Abstract – **In this paper a voltage-mode programmable active-RC filter employing four Current-Feedback Operational Amplifiers (CFOAs), one dual CMOS digital potentiometer, seven virtually grounded resistors and two grounded capacitors is presented. The presented active-RC filter is the result of a systematic circuit synthesis and can comparatively easily be derived from the VFOA-based Fleischer-Laker (FL) Switched Capacitor (SC) biquad stage, providing lowpass, bandpass and bandstop responses. The proposed circuit offers the following advantages: (1) realization of lowpass, bandpass and bandstop (notch) responses from the same configuration, (2) orthogonal digital control of the natural frequency and the quality factor by grounded resistors, (3) the use of two grounded capacitors which is not the case in the FL circuit, (4) low active and passive sensitivities and (5) low output impedance. The workability of the new active-RC filter has been demonstrated by PSpice simulation results.**

Keywords – **Analogue circuits, Active-RC filters, Four-terminal CFOAs, CCII+s.**

I. Introduction

The applications and advantages in the realization of various active-RC filters, using four-terminal current-feedback operational amplifiers (CFOAs), have received a considerable amount of attention [1, 2]. The four-terminal CFOAs are special type of monolithic operational amplifiers (op amps) and can be represented as a cascade structure of positive second-generation current conveyor (CCII+) and an additional voltage buffer. These op amps provide wide bandwidth, which is relatively independent of the closed-loop gain, and a very high slew rate. Moreover, the CFOAs have a low-impedance output, which makes the circuit cascadable without the use of additional buffers. A number of active-RC filter circuits, built with CFOAs, have been presented in the literature [3−7]. Each of the CFOA-based filters uses two or three active elements and a small group of resistors and capacitors. The natural frequency (ω_o) and the quality factor (Q) can be orthogonally adjustable by grounded resistors or virtually grounded resistors. When a grounded resistor is replaced by a JFET transistor, a voltage-controlled filter can be obtained. However, the electronic control of the parameters is not demonstrated in the reported circuits.

On the other hand, the conveyed literature survey reveals that recently large numbers of tunable universal filters using CCIIs are available [8−12]. The benefits of these circuits are that the bandwidth and natural frequency can be tuned electronically via the input bias currents of the used op amps.

To the author's knowledge, the use of four-terminal CFOAs in designing programmable filters has not yet been reported in the literature. It is, therefore, the purpose of this paper to present a voltage-mode lowpass, bandpass and bandstop digitally programmable filter, employing CFOAs, one dual digital potentiometer and two grounded capacitors.

II. Four-terminal CFOAs

The four-terminal CFOA is equivalent to a CCII+ and an output voltage buffer. These op amps have a high impedance non-inverting input y, a low-impedance inverting input x, a current output z and a voltage output o. The port z is between the first stage (CCII+) and the second stage (voltage buffer), where the resistance is very high (magnitude of several mega ohms). This allows the usage of four-terminal CFOAs in selective amplifier circuits, sinusoidal oscillators and multivibrators. The port o is the output of the voltage buffer, where the resistance is very low (magnitude of several ohms). The schematic representation of a four-terminal CFOA is shown in Fig. 1a [1, 2]. The monolithic op amps AD844 (from Analog Dev.), OPA660, OPA860 (from Texas I.), MAX436 (from Maxim) and LM13700 (from National) can be used as four-terminal CFOAs. For some of the available op amps, such as OPA860, LM13700 and MAX436, the CCII+ is not connected to the output voltage buffer.

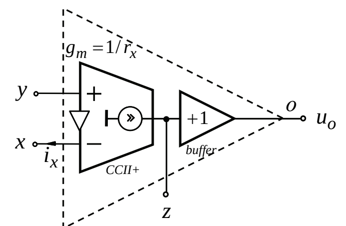

Fig. 1a. Symbol of a four-terminal CFOA.

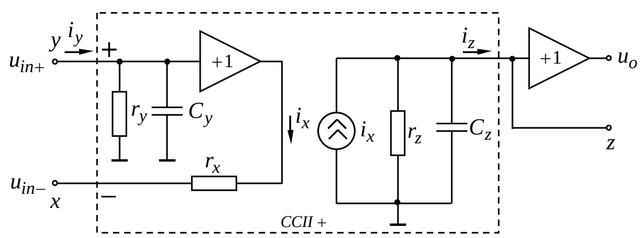

Fig. 1b. Linear macro-model of a four-terminal CFOA.

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The linear macro-model of the four-terminal CFOA, presented in Fig. 1b, reflects the small-signal behavior of the real device. The model includes the following elements: input and output buffers (voltage followers); i_x – controlled current source; r_y and C_y – input resistance and capacitance of the non-inverting input; r_x – resistance of the inverting input; r_z and C_z – output resistance and capacitance.

For this CFOA the general relation between input and output voltages and currents can be given by the following hybrid matrix

$$\begin{bmatrix} i_y \\ u_x \\ i_z \\ u_o \end{bmatrix} = \begin{bmatrix} 1/Z_y & 0 & 0 \\ 1 & r_e & 0 \\ 0 & 1 & 1/Z_z \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_y \\ i_x \\ u_z \end{bmatrix}, \qquad (1)$$

where $Z_y = r_y \parallel (1/sC_y)$ and $Z_z = r_z \parallel (1/sC_z)$.

The matrix representation given with (1) is valid only for ideal input and output voltage buffers.

The four-terminal CFOAs have several important applications. For example, these types of CFOAs are used in realization of analogue computing current-mode circuits, high-speed amplifiers, active filters, oscillators etc. The objective in this paper is to demonstrate the practicality of the four-terminal CFOAs in transforming well known Voltage-Feedback Op Amp (VFOA) based FL SC biquad stage, providing lowpass, bandpass and notch responses, to voltage-mode digitally programmable active-RC filter using CFOAs [13-14].

III. CIRCUIT DESCRIPTION

Fig. 2 represents Fleischer-Laker SC biquad stage providing notch, bandpass and lowpass responses. This circuit uses four voltage-feedback amplifiers and the natural frequency can be tuned via the clock frequency f_S. The aim here is to have an exact equivalent circuit with three outputs, notch, bandpass and lowpass, using four-terminal CFOAs. The approach is based on realizing the four basic building blocks, namely the two summers and two non-inverting integrators [1, 15], using four-terminal CFOAs plus a dual digital potentiometer, and then connecting these blocks correctly.

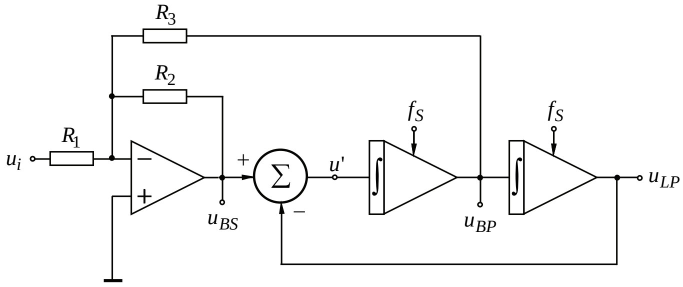

Fig. 2. VFOA based Fleischer-Laker SC biquad stage providing lowpass, bandpass and notch responses.

The first inverting summer of the circuit, shown in Fig. 2, is realized using equivalent closed-loop inverting summer circuit with a single four-terminal CFOA. For the second summer, an open-loop summing circuit with a second CFOA is used. In this circuit the output voltage from the first summer is applied directly to the y terminal of the CFOA and the output voltage from the second integrator is applied to the x terminal of the CFOA, through a resistor. The voltage summing node of the second summer is the z terminal of the op amp. Additionally, a resistor is connected between the z terminal and ground, equal to the one, connected to the x terminal of the CFOA [15]. The realization of the non-inverting active-RC integrator using a positive CCII, a grounded resistor and a grounded capacitor is well known [1]. Although summer output and the two integrators can be easily cascaded, the integrator outputs have to be buffered before being connected to the proper summer inputs. Here the two built in voltage buffers of the CFOAs are used.

The proposed voltage-mode lowpass (LP), bandpass (BP) and bandstop (BS) programmable filter with a single input and three outputs (LP, BP and BS), employing four CFOAs, is shown in Fig. 3. This circuit is a cascade structure of two non-inverting integrators, using monolithic CFOAs $U_3 - U_4$ (and the associated variable resistors $R_{AB1} = R_{AB2} = R_{AB}$ and capacitors $C_1 = C_2 = C$) and two summers, realized with CFOAs $U_1 - U_2$ and resistors $R_1 - R_5$. The capacitors and variable resistors of the two integrators are all connected to ground. This is particularly advantageous in facilitating the electronic control of the time constants. The pole frequency (or the time constant) of this filter are electronically controllable via the digital codes D (i.e. $D = D_1 = D_2$) of the dual grounded digital potentiometer − U_5. Moreover, the terminal W (wiper) of the dual potentiometer U_5 is connected to ground, which decreases the influence of the noise voltages. The programmable resistances $R_{WB1} = R_{WB2} = R_{WB}$ between W and B terminals are given by

$$R_{WB}(D) = \frac{D}{2^n} R_{AB} = qR_{AB}, \qquad (2)$$

where $q = D/2^n$, n is the resolution or “step size” of the potentiometer and R_{AB} is the nominal resistance between terminal A and terminal B.

Using the hybrid matrix given in equation (1), which characterizes the four-terminal CFOA, and using the condition $R_4 = R_5$ by routine analysis, the LP, BP and BS functions realized by this circuit are given by

$$A_{LP}(s) = \frac{u_{LP}}{u_i} = \frac{-\frac{R_2}{R_1}\frac{1}{\tau^2}}{D(s)}, \qquad (3)$$

$$A_{BP}(s) = \frac{u_{BP}}{u_i} = \frac{-\frac{R_2}{R_1}\frac{1}{\tau}s}{D(s)} \qquad (4)$$

and

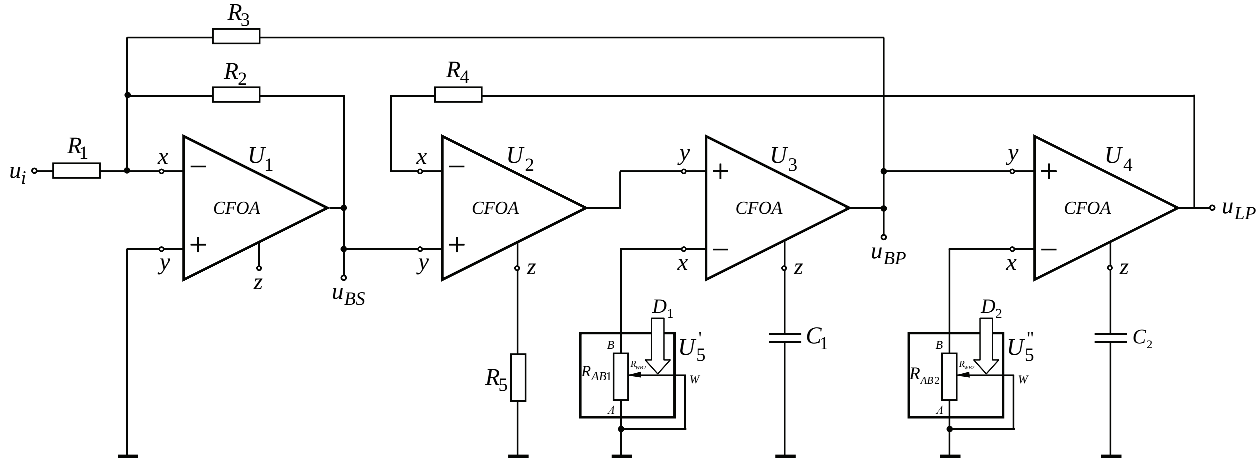

Fig. 3. Proposed digitally programmable lowpass, bandpass and bandstop filter configuration using monolithic four-terminal CFOAs.

$$A_{BS}(s) = \frac{u_{BS}}{u_i} = \frac{-\frac{R_2}{R_1}\left(s^2 + \frac{1}{\tau^2}\right)}{D(s)}, \tag{5}$$

where

$$D(s) = s^2 + \frac{R_2}{R_3}\frac{1}{\tau}s + \frac{1}{\tau^2}, \tag{6}$$

$$\omega_o = \frac{1}{\tau} = \frac{1}{\underbrace{(R_{WB} + r_x)C}_{\tau}} \overset{R_{WB} >> r_x}{\approx} \frac{2^n}{D}\frac{1}{R_{AB}C} \tag{7}$$

is the pole frequency of the filters,

$$Q = \frac{R_3}{R_2} \tag{8}$$

is the quality factor (Q-factor) and

$$H_{oLP} = -\frac{R_2}{R_1},\ \ H_{oBP} = -\frac{R_3}{R_1},\ \ H_{oBS} = -\frac{R_2}{R_1} \tag{9}$$

are the pass-band gains.

The above equations are identical of those of the circuit of Fig. 2. From (7) and (8), note that the pole frequency can be linearly adjusted directly by the digital code D of the dual digital potentiometer without disturbing the quality factor Q, while the quality factor can be adjusted independently from the pole frequency and the pass-band gains of the LP and BS functions by varying the resistor R_3. From (9), it can be remarked that the desired pass-band gain H_O can be independently adjusted by the resistor R_1. Other advantages of the proposed circuit are that they have no sample-data effect (increased clock feedthrough noise, reduced Power Supply Rejection Ratio – PSRR, aliasing errors) and they are better suitable for high frequency applications in comparison with the SC biquad stages [13, 14].

The above analytical formulas, as a result of the theoretical analysis, are the base of the design procedure of the proposed programmable filter with monolithic CFOAs. The basic design equations are given by

$$C_1 = C_2 = C \qquad R_4 = R_5 \qquad R_{WB1} = R_{WB2} = \frac{1}{\omega_o C} \tag{10}$$

$$R_3 = QR_2; \tag{11}$$

in case of LP: $R_2 = |H_{oLP}|R_1$,

in case of BP: $R_2 = |H_{oBP}|R_1/Q$ *or*

$$\textit{in case of BS}:\ R_2 = |H_{oBS}|R_1. \tag{12}$$

These design equations take into account that the two digital potentiometers $U_5^{'}$ and $U_5^{''}$ are implemented with one dual potentiometer with $R_{AB1} = R_{AB2}$ and moreover the positions of the wipers (W) are equally for a given digital code D, i.e. $R_{WB1} = R_{WB2}$. Other design equations are possible due to the available degrees of freedom, but are not discussed here.

IV. Simulation results

In order to confirm the validity of the proposed programmable active-RC filter (Fig. 3), the circuit has been simulated using PSpice simulation program. The four-terminal CFOA, given in Fig. 1a, was designed using an analog IC type OPA860 (from Texas I.), biased with $\pm 5V$. The digitally controlled variable resistors were constructed using the dual digital potentiometer AD8402 (from Analog Dev.), biased with $+5V$ single power supply. The IC AD8402 is with nominal resistances $R_{AB1} = R_{AB2} = 1k\Omega$ and has 256 positions of the wipers.

The active-RC filter example was designed for an initial pole frequency $f_o = \omega_o / 2\pi = 10kHz$ and a quality factor $Q = 0{,}707$ based on the Butterworth approximation method [1]. Capacitors $C_1 = C_2 = 16nF$ and resistors $R_4 = R_5 = 1k\Omega$

were chosen. Other parameters of the circuit are: $R_1 = R_2 = 1{,}4k\Omega$, $R_3 = 1k\Omega$ and $R_{WB1} = R_{WB2} = 1k\Omega$.

For the computer simulation the OPA860 and the AD8402 macromodels, given in the PSpice libraries, were used. The simulation results for the LP, BP and BS filter characteristics are shown in Fig. 4.

To demonstrate the digital tuning of ω_o, the digital codes D (i.e. $D = D_1 = D_2$) were simultaneously adjusted for the values 255, 128, 64 and 32 respectively, while keeping the rest of passive parameters for a constant $Q = 0{,}707$ and $|H_{oBP}| = 0{,}7$. The resulting responses of the BP filter for different digital codes D when $C_1 = C_2 = 16nF$ are given in Fig. 5.

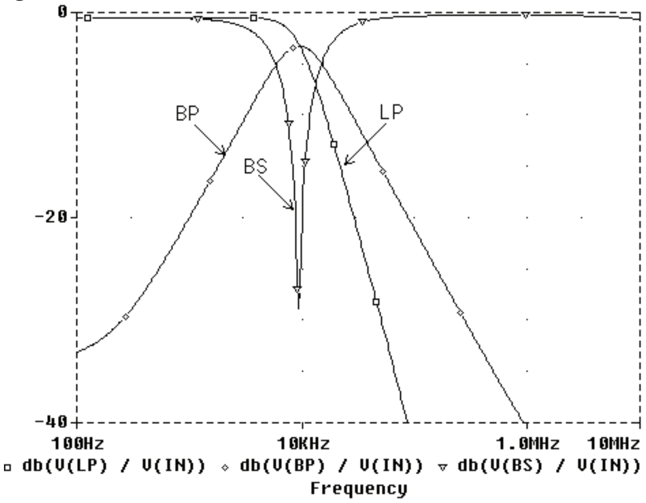

Fig. 4. Simulated frequency characteristics of LP, BP and BS of the proposed voltage-mode filter in Fig. 2.

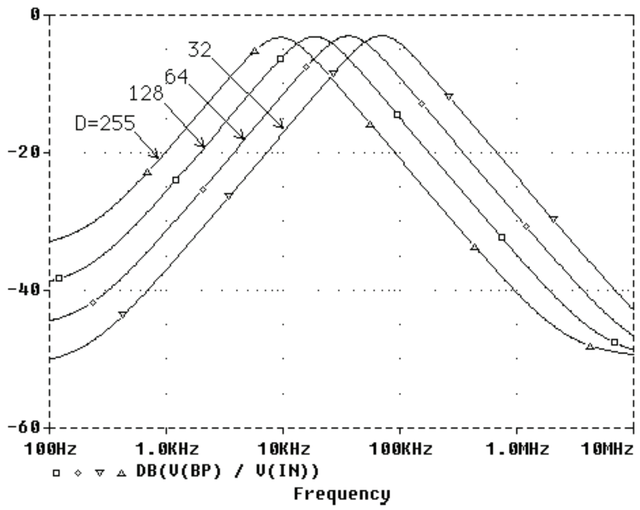

Fig. 5. Simulated frequency responses of the BP filter when the digital code D is varied.

V. CONCLUSION

It is seen that with the four-terminal CFOA one equivalent circuit to the Fleischer-Laker SC biquad stage providing notch, bandpass and lowpass responses is created, based on the equivalent building blocks. The proposed digitally programmable filter requires four CFOAs and one dual digital potentiometer. The circuit has two grounded capacitors, which is not the case in the Fleischer-Laker SC biquad stage. Moreover, the two variable resistors of the integrators are also connected to the ground. The created filter has been tested with monolithic op amp OPA860, used as CFOA, obtaining good behaviour for low and high frequencies.

In fact, the proposed circuit adds a new configuration to the existing group of electronically controllable active-RC filters with CFOAs and should be useful in offering some new features to the analog designers.

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