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Novel mixed-mode universal biquad configuration

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Abstract: Although a variety of CFOA-based biquads have been known in the literature, any CFOA-based circuit capable of realising universal biquad filters in all the four possible modes i.e. voltage-mode, current-mode, trans-admittance-mode and trans-impedance-mode, has not been reported in the literature so far. In this paper, a novel configuration has been presented, which realises all the five generic filter functions (namely, low-pass, band-pass, high-pass, notch and all-pass) from the same circuit in all the four possible modes, employing only four-Current feedback operational amplifiers (CFOA) along with two grounded-capacitors as desirable for Integrated Circuit implementation. The workability of the circuit has been confirmed by hardware implementation based on AD844 type CFOAs.

Keywords: current-feedback operational amplifiers, biquad filters, current-mode circuits, circuit theory and design, mixed-mode filters

Classification: Integrated circuits

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1 Introduction

A current feedback op-amp (CFOA)-based state variable (SV) biquad filter was recently presented in [1] 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 as desirable from Integrated Circuit implementation viewpoint (iv) independent control of various filter parameters (v) low sensitivities, and (vi) employment of a reasonable number (only four) of the CFOAs.

A limitation of the four-CFOA circuit of [1] was that it realised only three (LP, HP, BP) of the five generic filter functions (namely, LP, HP, BP, Notch and all-pass).

In this paper, we introduce a new four-CFOA-configuration which, by contrast to the circuit of [1], not only realises *all the five* generic filter functions in voltage mode but also realises *all the five* functions in current-mode, trans-admittance-mode and trans-impedance-mode (hence, the name 'mixed-mode') while providing all of the advantageous features mentioned above. To the best knowledge of the authors, any 'mixed-mode' universal biquad employing only *four CFOAs* has not been reported in the literature earlier.

The workability of the proposed circuit has been confirmed by hardware implementation based upon AD844 type CFOAs.

2 The proposed mixed-mode universal biquad structure

The proposed circuit which is devised using two inverting integrators and two specially devised summers, each realised by a single CFOA, is shown in Fig. 1. The universal biquad filters, in the four possible modes, are realisable from the configuration of Fig. 1 as follows:

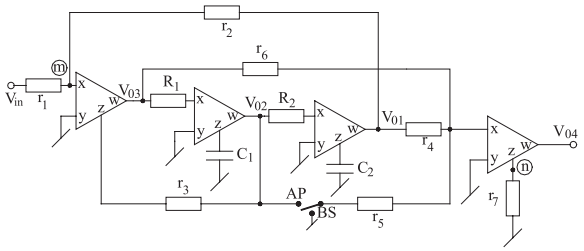

Fig. 1. The proposed CFOA-based mixed-mode universal biquad configuration

(i) Voltage-mode universal biquad filter: Assuming ideal CFOAs, characterized by $i_y = 0$, $i_z = i_x$, $v_x = v_y$, and $v_w = v_z$, the five voltage-mode transfer functions realized by this circuit are given by

$$\frac{V_{01}}{V_{in}} = \frac{H_0\omega_0^2}{D(s)} = \frac{-\left(\frac{r_2}{r_1}\right)\frac{r_3}{r_2R_1C_1R_2C_2}}{s^2 + \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}} \quad (1)$$

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$$\frac{V_{02}}{V_{in}} = \frac{H_0\left(\frac{\omega_0}{Q_0}\right)s}{D(s)} = \frac{\left(\frac{r_3}{r_1}\right)\frac{1}{R_1C_1}s}{s^2 + \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}} \tag{2}$$

$$\frac{V_{03}}{V_{in}} = \frac{H_0s^2}{D(s)} = \frac{-\left(\frac{r_3}{r_1}\right)s^2}{s^2 + \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}} \tag{3}$$

$$\frac{V_{04}}{V_{in}} = \frac{H_0\left(s^2+\omega_0^2\right)}{D(s)} = \frac{\left(\frac{r_3}{r_1}\right)\left(s^2 + \frac{r_3}{r_2R_1C_1R_2C_2}\right)}{s^2 + \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}} \tag{4}$$

with the switch at BS position and choosing $r_2 = r_3$; $r_4 = r_6 = r_7$

$$\text{and } \frac{V_{04}}{V_{in}} = \frac{H_0\left(s^2 - \left(\frac{\omega_0}{Q_0}\right)s + \omega_0^2\right)}{D(s)} = \frac{\left(\frac{r_3}{r_1}\right)\left(s^2 - \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}\right)}{s^2 + \frac{1}{R_1C_1}s + \frac{r_3}{r_2R_1C_1R_2C_2}} \tag{5}$$

with the switch at AP position and choosing $r_2 = r_3$; $r_4 = r_5 = r_6 = r_7$

Thus, the circuit realises a LP response at V_{01}, BP response at V_{02}, a HP response at V_{03}, and notch and all pass responses at V_{04} under appropriate conditions.

It is interesting to note that in all the five filters, all the three parameters of interest can be tuned through separate resistors as follows. After adjusting the bandwidth by R_1, the desired ω_0 can be adjusted by R_2 and finally, the gain H_0 of the filters (in all the five responses) is tunable by r_1.

We now show how the same circuit, with simple modifications, can also realise universal biquad filters in the remaining three modes.

(ii) Current-mode universal biquad filter: With r_1 and r_7 deleted, the circuit can be converted into an universal current-mode biquad with ideally zero input impedance and ideally infinite output impedance. With an input current I_{in} injected into input terminal 'm' and output current I_{out} taken out from the node 'n', the circuit can realise all the five filter functions in current mode. The general transfer function for this single-input-single-output universal current-mode filter is given by-

$$\frac{I_{out}}{I_{in}} = \frac{r_3\left\{\frac{s^2}{r_6} - \left(\frac{1}{C_1R_1r_5}\right)s + \frac{1}{C_1C_2R_1R_2r_4}\right\}}{\left[s^2 + s\frac{1}{C_1R_1} + \frac{r_3}{C_1C_2R_1R_2r_2}\right]} \tag{6}$$

The circuit realises a LPF with r_5 and r_6 open circuited; a bandpass with r_6 and r_4 open circuited; a high pass with r_5 and r_4 open circuited; a notch with r_5 open circuited (along with $r_2 = r_4 = r_6 = r_0$ (say) thereby yielding $H_0 = r_3/r_0$) and finally, an all pass with $r_2 = r_3 = r_4 = r_5 = r_6$ yielding $H_0 = 1$. The gains for LP, BP and HP responses are r_3/r_4, r_3/r_5 and r_3/r_6 respectively.

In the CM biquad, LP and HP filters have only H_0 controllable (through r_4 and r_6 respectively); in notch and AP, H_0 is not tunable, however, BW and ω_0 can be independently adjusted (through R_1 and R_2) respectively and finally, in BP realisation, BW, ω_0 and H_0, all are independently tunable (through R_1, R_2 and r_5 respectively).

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(iii) Trans-admittance universal biquad filter: In this case, we retain the input resistor r_1 but take the output I_{out} from z-terminal of the fourth CFOA. The various functions realised and their features are similar to those of case (ii).

(iv) Trans-impedance universal biquad filter: In this case, with r_1 deleted the input will be a current I_{in}, however, the output voltages will be V_{01}, V_{02}, V_{03} and V_{04}. The realisability conditions, parameters of filters and their features are similar to those of case (i).

Thus, the proposed circuit is an universal *mixed-mode* biquad.

3 Sensitivity

From the various expressions of the filter parameters featuring in the expressions (1)-(6) of the previous section, it can be easily deduced that all the sensitivity coefficients of ω_0, Q_0, BW and H_0 are given by

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

where F represents any of ω_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 in all the four modes of operation.

4 Consideration of CFOA parasitics

To keep the influence of C_z and x-port resistance r_x small, the external resistors need to be chosen such that all the resistors are smaller than $(1/\omega C_z)$ and larger than r_x [1, 2, 3, 4]. On the other hand, since the circuit employs both grounded capacitors (GC), it facilitates easy incorporation of z-pin parasitic capacitances of the CFOAs and is also desirable from the integrated circuit (IC) implementation view point. Thus, z-pin parasitic capacitance (C_z) of the CFOAs configured as integrators can be easily absorbed in capacitors C_1 and C_2.

5 Hardware implementation results

The proposed circuit was implemented in hardware using IC AD844 type CFOAs. In Fig. 2 (a)-(c) we present experimentally observed responses of LP, BP, HP, notch and AP filers realised from the proposed VM biquad with CFOAs biased with ±12 V DC. The circuit was designed for $Q_0 = 0.707$, $f_0 = 112.5$ kHz and $H_0 = 1$; the components values were taken as $R_1 = 1\,k\Omega$, $R_2 = 2\,k\Omega$, $r_i = 1\,k\Omega$, i = 1-7, $C_1 = 1$ nF and $C_2 = 1$ nF. The practically obtained responses of LP/HP filters are shown in Fig. 2 (a); those for BP/notch are shown in Fig. 2 (b) and the magnitude response of AP filter is shown in Fig. 2 (c). For obtaining correct AP response, the resistors r_4, r_5 and r_6 were required to be adjusted to the following values: $r_4 = 0.993\,k\Omega$, $r_5 = 0.689\,k\Omega$ and $r_6 = 0.797\,k\Omega$.

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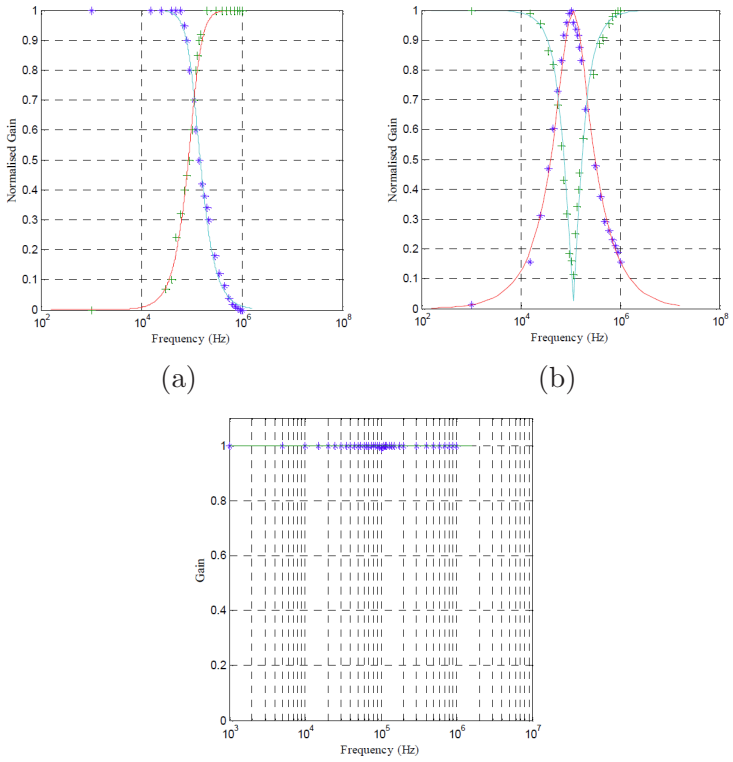

Fig. 2. Experimentally determined frequency responses for the CM LP/BP/HP/ Notch and AP filters realised from the biquad of Fig. 1

In all the cases, the practically observed behavior of the circuit was found to be in conformation to the theoretical results. The experimental results thus, establish the workability of the proposed configuration.

6 Comparison with previously known mixed-mode biquads

A comparison with previously known mixed mode biquads [2, 3, 4] is now in order. In this context, we note that whereas the circuits of [2, 3, 4] employ seven to ten CFOAs or Current Conveyors, the new circuit employs a much reduced number (only four!) of CFOAs. Furthermore, whereas the earlier circuits [2, 3, 4] realise only VM and CM biquads, the present one realises, in addition, trans-impedance and trans-admittance mode biquads also and hence, is a true mixed-mode universal biquad.

7 Concluding remarks

A novel configuration has been presented which realises all the five generic filter functions (namely, low-pass, band-pass, high-pass, notch and all-pass) from the same circuit in all the four possible modes namely, voltage-mode, current-mode, trans-admittance-mode and trans-impedance-mode and hence, is a true mixed-mode biquad, employing only four-Current feedback operational amplifiers (CFOA) along with two grounded-capacitors as desirable for Integrated Circuit implementation. The circuit allows tunabilityof the three

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filter parameters, namely, BW, ω_0 and H_0 through separate resistors in all the five responses and enjoys low sensitivity properties. The workability of the proposed circuit has been confirmed by hardware implementation results based on AD844 type CFOAs. To the best knowledge of the authors, the proposed circuit is the only one which is capable of realising universal biquads in all the four modes using only *four CFOAs* and any other CFOA-based circuit having these properties with only four CFOAs has never been reported in the literature earlier.

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