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Canonical Structures of ARC Biquad Based on Single Transimpedance Operational Amplifiers

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Abstract: - The paper deals with simplest canonical structures of the second order ARC filters employing only single transimpedance operational amplifiers (also titled current feedback amplifiers) and passive components R and C. A systematic design procedure of this circuits based on the suitable autonomous networks is described. Several appropriate general autonomous circuits are presented and studied.

Key-Words: - Active RC filters, single amplifier biquads, transimpedance operational amplifiers, current feedback.

1. Introduction

Circuits which employ a single active commercially available functional block (SAB) and RC passive elements are really right choice to realize a second-order transfer function. They usually offer a low cost, low DC power, low noise, low sensitivity and furthermore simple design.

Classical ARC filters based on standard operational amplifier are used only in low frequency applications, lower some hundred kHz. This limitation can be overcome replacing the conventional voltage amplifier by a transimpedance operational amplifier (TIOA) [1]. Owing to their current-mode operation, slew rate and bandwidth are higher. Note that usually the TIOA is also technically classified as a current feedback operational amplifier (CFA). Specially, a commercial type with external compensation pin Z (e.g. AD 844, [5]) gives much more suitable versatile structures, as is shown down. Note that in first approach the CFA is supposed as ideal, namely the parameters are:

$$Z_T \to \infty, Z_X \to 0, Z_Y \to \infty, Z_Z \to \infty, Z_O \to 0. \quad (1)$$

Then the real CFA and parasitic effects will be studied in detail, taking exact value of all impedances in (1).

Over the last decades, since the CFA was introduced, a several ARC filter structures based on this element have been developed, with different design approach in mind, see [1] - [4] and more others. Nevertheless a synthesis of this filter is still an active topic. In this paper the simplest structures of the second order filter (biquad) with only one single CFA, several resistors *R* and maximally two capacitors *C*, what is qualification of the canonical structure, are discussed. The here used systematic design procedure, given firstly for the circuits with current conveyors, is based on general autonomous network with suitable characteristic equation.

2. General autonomous circuits

To design biquadratic ARC filters and or oscillators we firstly choose an appropriate general autonomous circuit with the characteristic equation (CE) in the second-order general form (2) or in the following standard one (3)

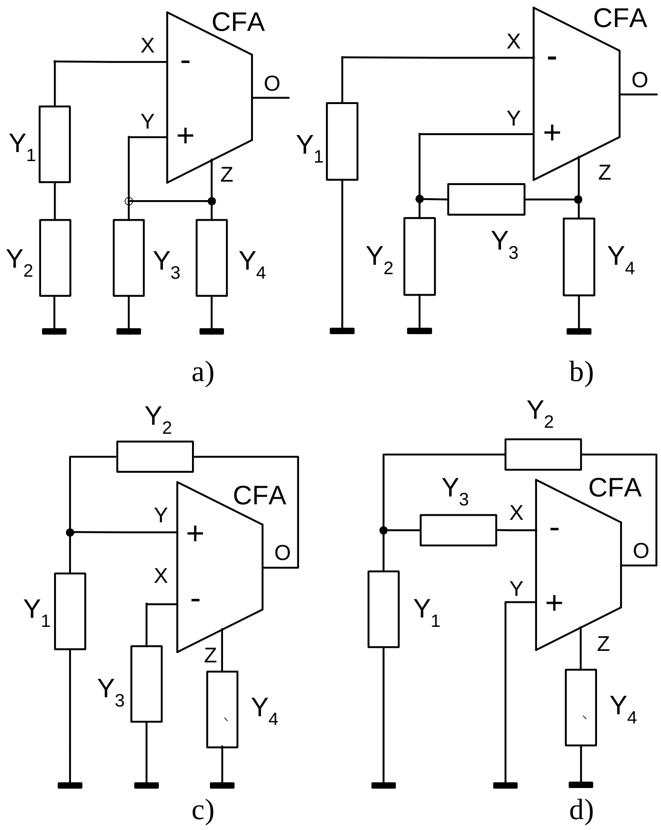

Fig. 1. General autonomous models of the biquads with one CFA and four single admittances.
a) Structure CFA1Y4A, b) Structure CFA1Y4B,
c) Structure CFA1Y4C, d) Structure CFA1Y4D.

$$a_2 s^2 + a_1 s + a_0 = 0 \ , \quad (2) \qquad s^2 + \frac{\omega_0}{Q} s + \omega_0^2 = 0 \ . \quad (3)$$

There ω_0 is the natural (undamped) frequency and Q is the quality factor.

The general autonomous circuit (Fig. 1) contains only one active CFA and certain number of admittances Y_i in feedback loop. An optimum is four passive admittances Y_i .(Fig. 1), which are single R or C only.

The simplest structure CFA1Y4A is in Fig. 1a. There two admittances are in series (Y_1, Y_2) and parallel (Y_3, Y_4) combination. By routine symbolical nodal analysis (det Y = 0) the following CE is obtained

$$Y_1 Y_3 + Y_2 Y_3 + Y_1 Y_4 + Y_2 Y_4 - Y_1 Y_2 = 0 \ . \qquad (4)$$

The structure CFA1Y4B on Fig. 1b has the CE

$$Y_2 Y_3 + Y_2 Y_4 + Y_3 Y_4 - Y_1 Y_3 = 0 \ . \qquad (5)$$

The CFA1Y4C (Fig. 1c) has

$$Y_1 Y_4 + Y_2 Y_4 - Y_2 Y_3 = 0 \ . \qquad (6)$$

The CFA1Y4D on Fig. 1d is corresponding to the CE

$$Y_1 Y_4 + Y_2 Y_3 + Y_3 Y_4 + Y_2 Y_4 = 0 \cdot \qquad (7)$$

A suitable modification with five passive elements can be obtained decomposing some admittance Y_i in the CFA1Y4 on two parallel connected. Then more filter architectures can be obtained. It is the reason for the modification of the structure OTA1Y4D (Fig. 1d) to the model with five admittances OTA1Y5, where Y_1 is $Y_1 = Y_{11} + Y_{12}$. Then the CE (7) tends to this form

$$Y_{11} Y_4 + Y_{12} Y_4 + Y_2 Y_3 + Y_3 Y_4 + Y_2 Y_4 = 0 \cdot \qquad (8)$$

3. Simplest structure

From the general characteristic equation (4) we can readily derive real filter of the simplest structure CFA1Y4A, choosing there the particular admittances Y_i, to obtain desired form (2) or (3) and postulating two capacitors for the 2nd order canonical circuit. For the choosing: $Y_1 = G_1, Y_2 = sC_1, Y_3 = G_2, Y_4 = sC_2$ (Fig.2) the CE (4) has the following concrete form

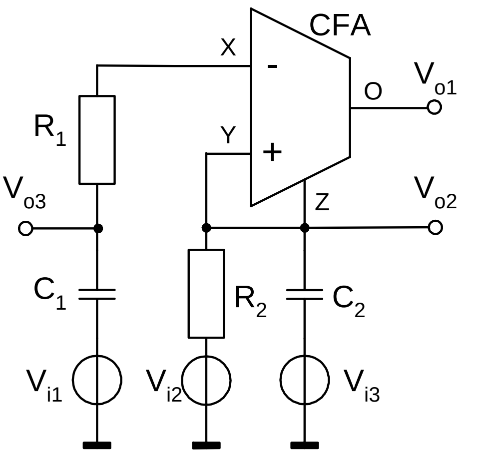

Fig. 2. ARC biquad with the structure CFA1Y4A

$$s^2 C_1 C_2 + s[C_1(G_2 - G_1) + C_2 G_1] + G_1 G_2 = 0 \ . \quad (9)$$

Comparing the formulas (9) and (3) the following design equations are done

$$\omega_0 = \sqrt{\frac{G_1 G_2}{C_1 C_2}} \ , \quad (10) \qquad Q = \frac{\sqrt{C_1 C_2 G_1 G_2}}{C_1(G_2 - G_1) + C_2 G_1} \ . \quad (11)$$

From the autonomous circuits given in Fig 1a, we can build a frequency filter so that we disconnect some grounded branch (Y_2, Y_3 and or Y_4) and we put there an independent input voltage source, as shown in Fig. 2. It is based on the known idea, that the CE remains the same if an ideal voltage source is connected into an arbitrary branch. Then we try to find a suitable output port examining all node voltages of this circuit. The Fig. 2 indicates all possibilities of driving (inputs) and loading (outputs) of this filter structure.

The first suitable variant CFA1Y4A11 has the input V_{i1} ($V_{i2} = V_{i3} = 0$, these sources are shorted). There the output $V_{o1} = V_{o2}$ and the following transfer function with band pass (BP) character was derived

$$\frac{V_{o1}}{V_{i1}} = \frac{V_{o2}}{V_{i1}} = \frac{-sG_1 C_1}{D(s)} \ , \qquad (12)$$

where the denominator is

$$D(s) = s^2 C_1 C_2 + s[C_1(G_2 - G_1) + C_2 G_1] + G_1 G_2 \ . \quad (13)$$

Similarly for the output V_{o3}

$$\frac{V_{o3}}{V_{i2}} = \frac{sC_1 G_2}{D(s)} \ , \quad (14) \qquad \frac{V_{o3}}{V_{i3}} = \frac{s^2 C_1 C_2}{D(s)} \ . \quad (15)$$

Note that from the independent loading point of view, the best is the output V_{o1}, with zero internal impedance.

4. Structures with four admittances

The previous structure CFA1Y4A (Fig. 1a) can be interpreted as a simplest one with two resulting admittances only. We will discuss now the structures with four separated admittances. In this case the structure CFA1Y4D is taken (Fig. 1d) with the CE (7). For the first variant (CFA1Y4D-a) the admittances are chosen to obtain the biquad in Fig. 3. This circuit has suitable transfer functions

$$\frac{V_{o3}}{V_{i1}} = \frac{V_{o2}}{V_{i1}} = \frac{-sC_1 G_3}{D(s)} \ , \qquad (16)$$

$$\frac{V_{o1}}{V_{i1}} = \frac{-s^2 C_1 C_2}{D(s)} \ , \quad (17) \qquad \frac{V_{o1}}{V_{i2}} = \frac{sC_2 G_2}{D(s)} \qquad (18)$$

with the form of the BP (16), (18) and or HP one (17) respectively. There the denominator is

$$D(s) = s^2 C_1 C_2 + sC_2(G_2 + G_3) + G_2 G_3 \ . \qquad (19)$$

The other variant (CFA1Y4D-b) can be obtained interchanging the elements R ↔ C in Fig. 3. Then also the low pass character has the transfer function V_{o1}/V_{i1}.

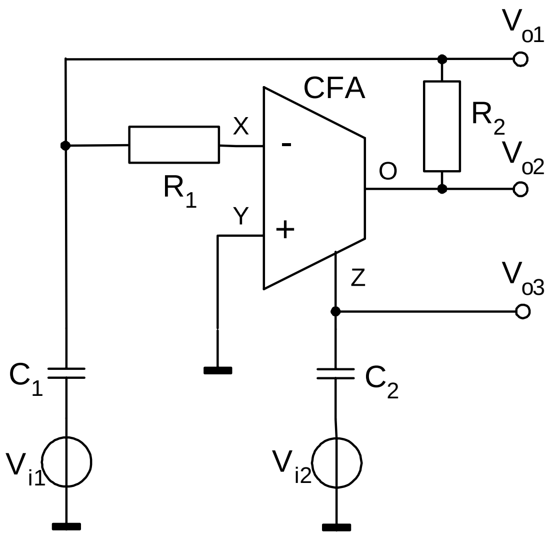

Fig. 3. ARC biquad with the structure CFA1Y4D-a

5. Structures with five admittances

A modification of the biquad CFA1Y4D-a given above (Fig. 3) into the version with five admittances (CFA1Y5D-a) is quite straightforward, namely the other resistor R_1 is parallel connected to the capacitor C_1, as shown in Fig. 4. All possible inputs and outputs are depicted there (Fig. 4) as a result of the routine symbolical nodal analysis using computer tool SNAP. The transfer functions are LP, BP and HP types as follows

$$\frac{V_{o2}}{V_{i2}} = \frac{V_{o3}}{V_{i2}} = \frac{-G_1G_3}{D(s)}, \quad (20) \qquad \frac{V_{o2}}{V_{i1}} = \frac{V_{o3}}{V_{i1}} = \frac{-sC_1G_3}{D(s)}, \quad (21)$$

$$\frac{V_{o1}}{V_{i2}} = \frac{sC_2G_1}{D(s)}, \ (22) \quad \frac{V_{o1}}{V_{i3}} = \frac{sC_2G_2}{D(s)}, \ (23) \quad \frac{V_{o1}}{V_{i1}} = \frac{s^2C_1C_2}{D(s)}. \ (24)$$

There the resulting denominator is

$$D(s) = s^2C_1C_2 + sC_2(G_1 + G_2 + G_3) + G_2G_3. \quad (25)$$

and the design equations are

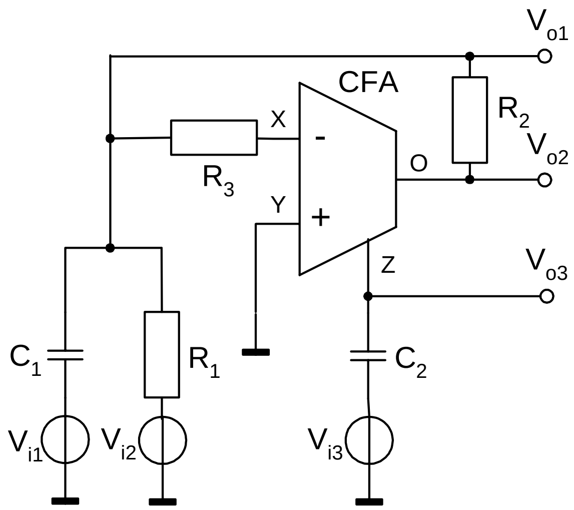

Fig. 4. ARC biquad with the structure CFA1Y5D-a

$$\omega_0 = \frac{1}{\sqrt{C_1C_2R_2R_3}}, \quad (26)$$

$$Q = \sqrt{\frac{C_1}{C_2}}\left[\frac{\sqrt{R_2R_3}}{R_1} + \sqrt{\frac{R_3}{R_2}} + \sqrt{\frac{R_2}{R_3}}\right]^{-1}. \quad (27)$$

A dual version (CFA1Y5D-b) is shown in Fig. 5. The routine symbolic analysis of this circuit yields the following transfer functions:

$$\frac{V_{o2}}{V_{i2}} = \frac{V_{o3}}{V_{i2}} = \frac{-s^2C_1C_3}{D(s)}, \ (28) \qquad \frac{V_{o1}}{V_{i1}} = \frac{sC_1G_2}{D(s)}, \quad (29)$$

$$\frac{V_{o2}}{V_{i2}} = \frac{V_{o3}}{V_{i2}} = \frac{-sC_3G_1}{D(s)}, \ (30) \qquad \frac{V_{o1}}{V_{i2}} = \frac{G_1G_2}{D(s)}, \quad (31)$$

whit the denominator

$$D(s) = s^2C_2C_3 + sG_2(C_1 + C_2 + C_3) + G_1G_2. \quad (32)$$

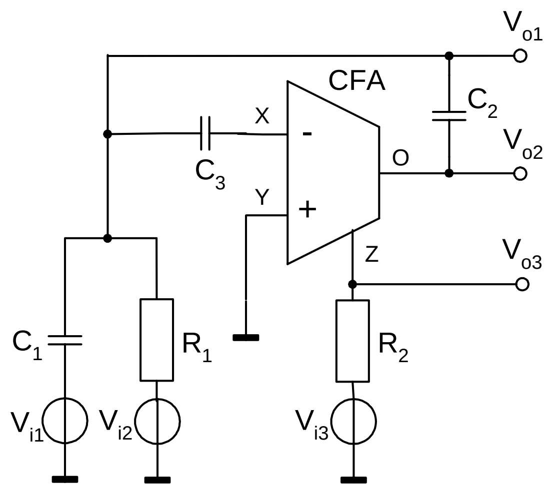

Fig. 5. ARC biquad with the structure CFA1Y5D-b

Then the natural frequency of this biquad is given by (26) and the quality factor is

$$Q = \sqrt{\frac{R_1}{R_2}}\left[\frac{C_1}{\sqrt{C_2C_3}} + \sqrt{\frac{C_3}{C_2}} + \sqrt{\frac{C_2}{C_3}}\right]^{-1}. \quad (33)$$

Another biquadratic structure, with five admittances, is CFA1Y5C (Fig. 6), associated with the general circuit diagram in Fig. 1c, decomposing the admittance Y_4 and choosing in the CE (7) admittances:

$$Y_1 = G_2, Y_2 = sC_2, Y_3 = G_3, Y_4 = sC_1 + G_1 \text{ (Fig. 6).}$$

For this circuit (Fig. 6) the resulting suitable transfer functions are as follows:

$$\frac{V_{o2}}{V_{i1}} = \frac{V_{o3}}{V_{i1}} = \frac{G_2G_3}{D(s)}, \quad (34) \qquad \frac{V_{o1}}{V_{i2}} = \frac{-sC_2G_3}{D(s)}, \quad (35)$$

$$\frac{V_{o1}}{V_{i3}} = \frac{sC_2G_1}{D(s)}, \quad (36) \qquad \frac{V_{o1}}{V_{i4}} = \frac{s^2C_1C_2}{D(s)}, \quad (37)$$

where the denominator is

$$D(s) = s^2C_1C_2 + s[C_1G_2 + C_2(G_1 - G_3)] + G_1G_3. \quad (38)$$

The quality factor in this case can be adjusted using the following equation

$$Q = \frac{R_2\sqrt{C_1C_2R_1R_3}}{C_1R_1R_3 + C_2R_2(R_3 - R_1)} . \qquad (39)$$

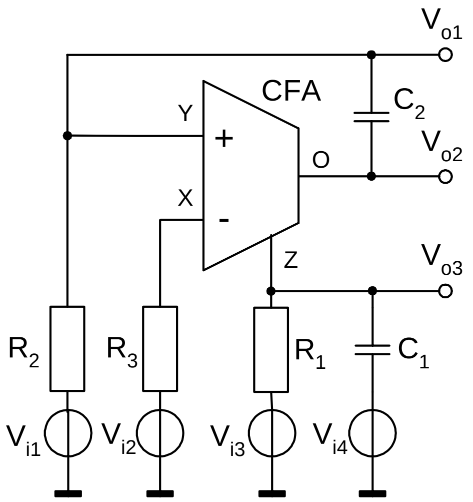

Fig. 6. ARC biquad with the structure CFA1Y5C

6. DC precise low pass filter

The structure CFA1Y5D-b (Fig. 5) can be ingeniously used as the low-drift DC precise second order low pass filter. This filter is suitable e.g. for D/A convertors and some measurement application. There the output node V_{o1} (internal node of the topology) and transfer function (31) is taken.

Nevertheless, for this application the circuit can be modified in the DC precise LP of the third order as shown in Fig. 7. Analysis yields the voltage transfer function in this polynominal form

$$\frac{V_{o1}}{V_{i2}} = \frac{1}{D(s)} , \qquad (40)$$

where the denominator is

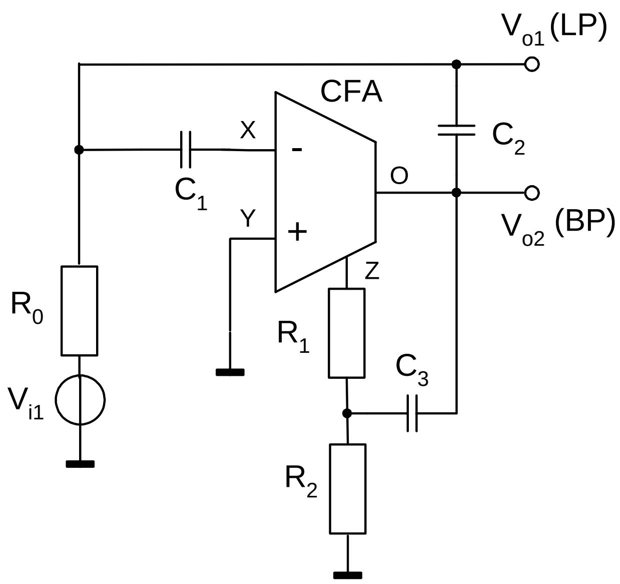

Fig. 7. Third-order DC precise low pass filter

$$D(s) = s^3C_1C_2C_3 + s^2C_1C_2(G_1 + G_2)G_0 + \\ + s(C_1 + C_2)G_1G_2 + G_0G_1G_2 \qquad (41)$$

Note that this circuit (Fig. 7) can be generalized in higher n-order DC precise LP filter, putting in the port Z more RC feedback cells.

7. Simulation

To verify the functionality of the proposed filter structures, the PSpice simulation has been carried out, using an adequate model of the ideal CFA. Results are confirming the theoretical assumptions and the given symbolical analysis. Additional studying of the parasitic influences and modelling of the real components and parasitic effects will be done.

8. Conclusions

The systematic uniform synthesis based on the general autonomous network with suitable characteristic equation is really good way how to obtain the ARC filters or oscillators with modern functional blocks, as has been shown here for the transimpedance operational amplifiers.

The given filters based on the single CFA can operate at higher frequency as active filters with standard (voltage) operational amplifiers. They can be also implemented in IC technologies. Only one CFA means smaller chip area, lower power consumption and lower noise.

Acknowledgments

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