Synthesis of New Biquad Filters Using Two CFOAs

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Abstract. *This paper deals with synthesis based on new autonomous circuit using two current feedback operational amplifiers. Four possible second-order structures are derived and several active RC filters are described. One new circuit of the band-pass filter is introduced in detail. Its parameters are studied symbolically, tested by simulations and confirmed by measurements.*

Keywords

Active RC filters, current feedback operational amplifiers.

1. Introduction

The current feedback operational amplifier (CFOA) [1] is a suitable active block for synthesis of filters for higher frequency domain. When the part with available compensation pin is mentioned, there are many options to create some new circuits. The design based on synthesis of general autonomous circuits [2] is a good way to obtain acceptable results. The use of two amplifiers has an advantage, because parameters of a final circuit can be usually set independently.

A general autonomous circuit is a structure without defined inputs and outputs. Its parameters are described by the determinant of the admittance matrix. When this term is given equal to zero, then the characteristic equation is derived. The particular coefficients can be appropriately set to match the typical form of the second-order circuit

$$s^2 + \frac{\omega_0}{Q}s + \omega_0^2 = 0 \cdot \qquad (1)$$

This equation composes the denominator $D(s)$ of the voltage transfer functions of all structures generated from the mentioned circuit. Practically two admittances are needed to be capacitive to obtain a biquad.

An example of the design specialized on filters is shown in this paper. Several inputs and outputs can be set to obtain a useful structure from the basic circuit. The transfer function was expressed for every input-output combination. The terms which exactly match the standards of typical filters were considered as correct. Standards, namely low-pass, high-pass, band-pass and band-rejection, are defined as follows

$$K_{LP} = \frac{K_0\omega_0^2}{D(s)}, \quad K_{HP} = \frac{K_0 s^2}{D(s)},$$
$$K_{BP} = \frac{K_0 \frac{\omega_0}{Q} s}{D(s)}, \quad K_{BR} = \frac{K_0\left(s^2 + \omega_0^2\right)}{D(s)}. \qquad (2)$$

The program SNAP [3] was used for symbolical analysis and numerical tests were carried out using program PSpice [4].

It is necessary to take into account a restriction in this field of circuit design. There are few types of mentioned CFOA with compensational pin, but just one of them is currently available for practical design. It is the amplifier AD844 [7] produced by Analog Devices with transimpedance 3 MΩ and with relatively narrow declared gain bandwidth 60 MHz. Other devices, e.g. AD846 and HFA1102, are marked as obsolete. Regarding this, the simulated and measured filters have the center frequency 100 kHz.

2. General Autonomous Circuit

The new circuit with two CFOAs and five admittances (Fig. 1) was intuitively compiled. Single admittances (Y_3 and Y_4) were connected to every compensational pin, which can reduce the influence of finite transimpedances. One feedback loop was created around the first CFOA and the second was created around the whole circuit. The part Y_4, when it would be set resistive, can reduce the non-zero input resistance of the second CFOA.

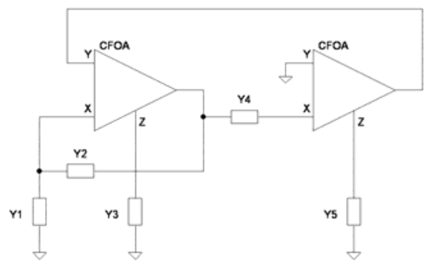

Fig. 1. General autonomous circuit.

The characteristic equation includes the determinant of the admittance matrix given equal to zero, concretely

$$Y_1Y_4 + Y_2Y_4 + Y_2Y_5 + Y_3Y_5 = 0\,. \qquad (3)$$

The formula (1) has three terms with different powers of symbolical operator *s*. It is needed to use such admittances, which establish all three terms. There are four possibilities to satisfy it by choosing two capacities:

$$\begin{aligned}&1.\,Y_1 = sC_1\,, Y_4 = sC_4\,; \quad 2.\,Y_2 = sC_2\,, Y_4 = sC_4\,;\\ &3.\,Y_2 = sC_2\,, Y_5 = sC_5\,; \quad 4.\,Y_3 = sC_3\,, Y_5 = sC_5\,.\end{aligned} \qquad (4)$$

All mentioned alternatives were studied and several simulations and measurements of particular designed filters were carried out. Mostly the parameters were similar to the chosen structure presented below. Nevertheless this circuit has an advantage, because its resistances R_3 and R_5 (see Fig. 2) are connected in parallel to transimpedances and this way the effect of their finite values can be reduced.

The shortcut of presented structure is simply derived from types and numbers of parts – “A2” means two amplifiers, “Y5” is equal to five used admittances and last shortcut indicates the order of the alternative.

3. Structure A2Y5–2

The individual admittances are defined as follows

$$Y_2 = sC_2\,, Y_4 = sC_4\,, Y_1 = G_1\,, Y_3 = G_3\,, Y_5 = G_5\,. \qquad (5)$$

Hence the standard characteristic equation becomes

$$\begin{aligned}&s^2 + s\frac{C_2G_5 + C_4G_2}{C_2C_4} + \frac{G_3G_5}{C_2C_4} =\\ &s^2 + s\frac{C_2R_1 + C_4R_5}{C_2C_4R_1R_5} + \frac{1}{C_2C_4R_3R_5} = 0.\end{aligned} \qquad (6)$$

It is practical to use some coefficients (*m*, *a*, *b*) which establish ratios between separate values. Capacitances and resistances are then simplified

$$C_2 = C, C_4 = mC, R_3 = R, R_5 = aR, R_1 = bR\,. \qquad (7)$$

The basic parameters of this structure, namely the characteristic frequency ω_0 and the quality factor *Q*, can be expressed after comparison with (1) as follows

$$\omega_0 = \frac{1}{\sqrt{C_2C_4R_3R_5}} = \frac{1}{CR\sqrt{ma}}\,, \qquad (8)$$

$$Q = \frac{R_1\sqrt{C_2C_4}}{C_2R_1 + C_4R_5}\sqrt{\frac{R_5}{R_3}} = \frac{b\sqrt{ma}}{b+ma}\,. \qquad (9)$$

The quality can be designed based on coefficient *b*. The maximum value is unfortunately restricted to

$$Q_{\max} = \sqrt{ma}\,, \qquad (10)$$

but it is possible to choose some proper coefficient to obtain a higher limit.

There are four potential inputs and two mutually independent outputs in this structure (see Fig. 2). The inputs are created step by step by inserting an ideal voltage source into each grounded branch. The outputs are in two independent junctions located on outputs of both amplifiers.

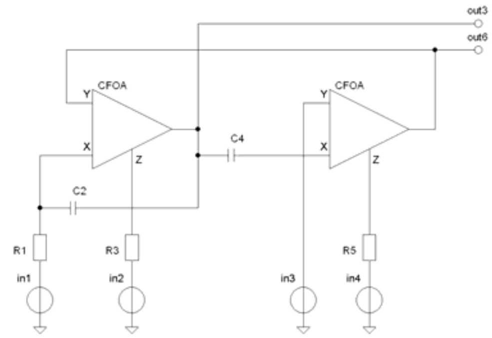

Fig. 2. Structure A2Y5–2 with defined inputs and outputs.

When all combinations of inputs and outputs are studied, four different standard second-order filters can be found: two low-passes and two band-passes. According to (2), the numerators of their voltage transfer functions *K*(*s*) are

$$\begin{aligned}&K_{i1o3} : N_{LP1} = -\frac{1}{C_2C_4R_1R_5}\,, K_{i1o6} : N_{BP1} = -\frac{s}{C_2R_1}\,,\\ &K_{i2o3} : N_{LP2} = \frac{1}{C_2C_4R_3R_5}\,, K_{i2o6} : N_{BP2} = -\frac{s}{C_2R_3}\,.\end{aligned} \qquad (11)$$

The first design with chosen parameters was done for analyses of functionality and of essential properties – concretely $f_0 = 1$ kHz, $Q = 1$, $m = 1$, $a = 10$ ($Q_{\max} = 3.1$), $C = 10$ nF and $b = 4.625$, $R = 3559\ \Omega$. The amplifiers AD844 [7] by Analog Devices, rather their models available in the standard library of PSpice, were used. Resulting simulated module and phase frequency characteristics are displayed in Fig. 3.

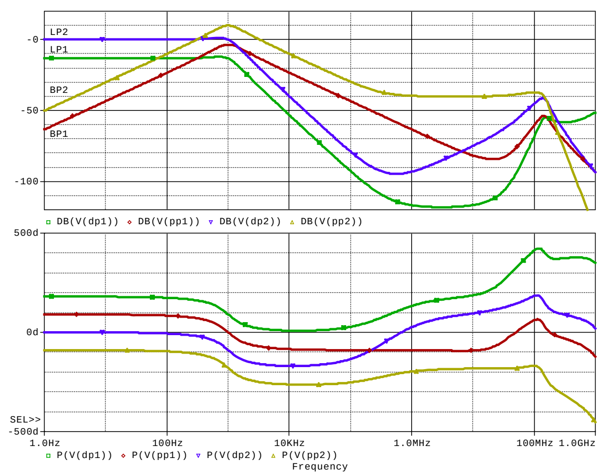

Fig. 3. Frequency characteristics of generated filters.

All curves are deformed on high frequencies, which is caused by parasitic zero points. The non-ideal parameters of CFOAs have demonstrably negative effect. The finite input resistances R_{X1} and R_{X2} of the current inputs and the nonzero output resistance of the second CFOA R_{OUT2} are the most critical.

The designed structure is stable with phase margin (shortly PM) about 50°, which is practical independent on setting the value of quality factor Q. But it is important to check the PM, when the higher characteristic frequency f_0 is chosen. In case of oscillations, it is possible to correct this state. A good way is to add some capacitor in parallel to resistor R_5.

4. Band-Pass Filter A2Y5–2–BP2

This new circuit (Fig. 4) was chosen because it can be used in higher frequency area and allows designing adequate quality factors. It uses input in_2 and output out_6 of the basic structure A2Y5–2 (see Fig. 2).

The complete voltage transfer function is

$$K_{BP2} = \frac{-s\dfrac{1}{C_2R_3}}{s^2 + s\dfrac{C_2R_1 + C_4R_5}{C_2C_4R_1R_5} + \dfrac{1}{C_2C_4R_3R_5}}. \tag{12}$$

A simplified form using above defined coefficients (7) is

$$K_{BP2} = \frac{-s\dfrac{1}{CR}}{s^2 + s\dfrac{b+ma}{mabCR} + \dfrac{1}{maC^2R^2}}. \tag{13}$$

Comparing with standards (1) and (2) gives the fundamental parameters

$$\omega_0 = \frac{1}{CR\sqrt{ma}},\ Q = \frac{b\sqrt{ma}}{b+ma},\ K_0 = \frac{mab}{b+ma}. \tag{14}$$

The quality factor Q can be changed by shifting of value b. The resistance $R_1 = bR$ may be electronically controlled. A method utilizing the voltage bootstrap [6] was tested. It is included in the scheme Fig. 4.

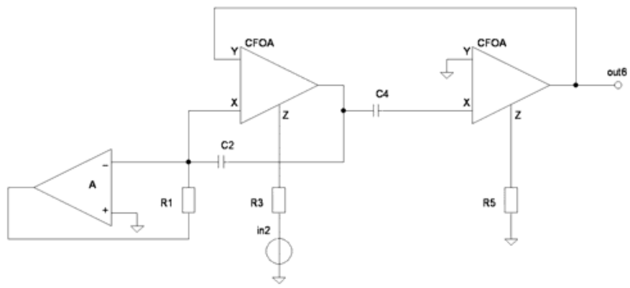

Fig. 4. Filter A2Y5–2–BP2 with controlled quality factor.

The parameters for design were chosen and calculated as follows: $f_0 = 100$ kHz, $Q = 5$, $m = 10$, $a = 10$, $b = 100$, $C = 100$ pF, $R = 1592\ \Omega$. The phase margin was determined using Nichols chart [5] and it is PM = 60°. The numerical analyses were done for three different values of f_0 adjusted by C. The resultant characteristics are in Fig. 5.

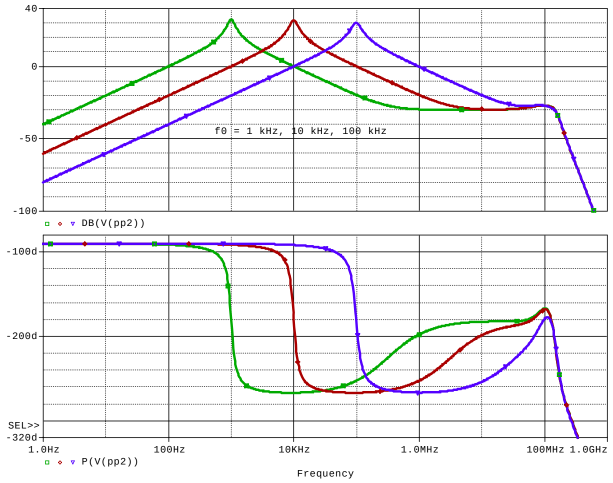

Fig. 5. Frequency characteristics of A2Y5–2–BP2.

There are some differences between the design and the simulation: $f'_0 = 1.00$ kHz; 9.95 kHz; 98.3 kHz and $Q' = 4.1$; 4.0; 3.3. The Q is evidently restricted. The attenuation is limited by a parasitic zero point, which can be symbolically expressed

$$z_1 = \frac{R_1 + R_{X1}}{C_2R_1R_{X1}}. \tag{14}$$

The mentioned zero stops the drop of the gain and makes the curve flat until the final sharp fall comes. This bad feature can be particularly eliminated, regarding to (14), by the design of right values C_2, R_1 and by using of the first CFOA with a small input resistance R_{X1}. It is very complicated to express the effect of basic non-ideal parameters of CFOA symbolically. Generally, the center frequency is mostly impressed with finite transimpedance of the second CFOA and the quality factor depends mainly on the gain bandwidth of both amplifiers.

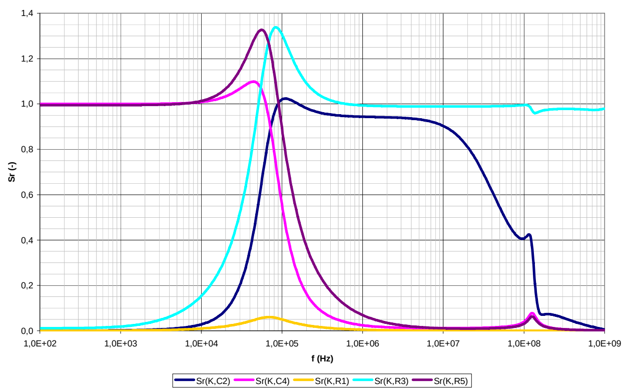

Fig. 6. Relative sensitivities of A2Y5–2–BP2.

Several simulations of the filter with $f_0 = 100$ kHz and $Q = 5$ were done in order to find the frequency dependent curves of relative sensitivities S_r [1] (Fig. 6). These terms are detailing the changes of module caused by tolerance of parts. The maximum values are in the center frequency area, namely about $S_r(K, R_3) = S_r(K, R_5) = 1.35$.

The filter was practically designed as a laboratory sample. The parameters were the same as in the previous paragraphs: $f_0 = 100$ kHz and $Q = 5$. Two AD844s were used and the passive parts were specific: $C_2 = C = 100$ pF, $C_4 = mC = 1$ nF, $R_1 = bR = 159.2$ kΩ → $R'_1 = 120$ kΩ + 39 kΩ = 159 kΩ; $R_3 = R = 1592$ Ω → R'_3 =1.2 kΩ + 390 Ω = 1590 Ω; $R_5 = aR = 15.92$ kΩ → $R'_5 = 12$ kΩ + 3.9 kΩ = 15.9 kΩ. The accurate resistances were put together from standardized values. The original configuration was unstable, but a capacitor $C_{stab} = 47$ pF added in parallel to R_5 solved this problem. The final measured curve was compared with the simulation of equal circuit. Results are in Fig. 7, the measurement in brown line and the simulation in blue line. Both center frequencies are the same $f'_{cm} = f'_{cs} = 96$ kHz. The used compensation capacitor causes a large reducing of the quality factor, both are also identical $Q'_{cm} = Q'_{cs} = 1.4$. Nevertheless there is a very good accordance between measured and simulated results in the range up to 10 MHz. The measured curve is deformed in high frequency area, which is probably caused by parasitic features of the constructed sample.

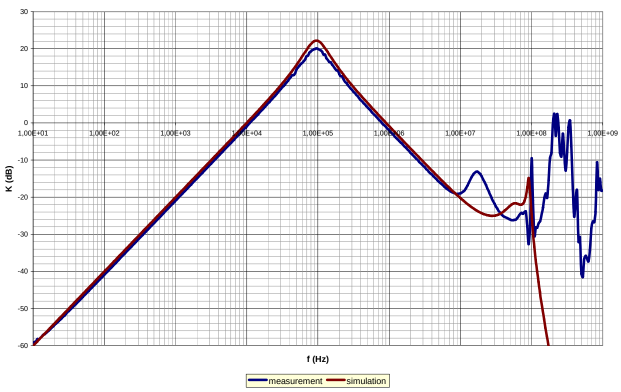

Fig. 7. Measured and simulated modules of A2Y5–2–BP2.

The presented circuit offers to change its quality factor electronically. This statement is evident from the definition term (14). A voltage bootstrap was applied on the resistor R_1. An additional inverting amplifier is placed between the lower junction and the ground as shown in Fig. 4. The final modified resistance and the set quality are as follows

$$R'_1 = \frac{bR}{1+A},\ Q' = \frac{b}{1+A}\frac{\sqrt{ma}}{1+\dfrac{ma(1+A)}{b}}. \tag{14}$$

The theory was successfully confirmed by simulations. The center frequency f_0 is not suitably defined for the electronic controlling.

5. Conclusion

The new autonomous circuit was introduced and some derived second-order structures were described. One final band-pass filter using two CFOAs was examined in detail. It is useful up to the center frequency about 100 kHz when amplifiers AD844 are placed. Main parameters were symbolically defined. Its frequency potential, sensitivities of voltage transfer function and electronic controlling of quality factor were tested by simulations. A laboratory application was designed and its module frequency characteristic was verified by measurement and simulation, too. The obtained results were mainly acceptable.

Unfortunately the constructed filter appears to be worse than the standard well-known structures e.g. Sallen-Key and Huelsman, especially in domains of the quality factor and sensitivities. The useful frequency range is significantly restricted due to only available type of the amplifier AD844 with insufficient 60 MHz gain-bandwidth.

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About Author...

Josef VOCHYÁN was born in 1980. He received his MSc. degree in 2003 from the University of Technology, Brno. He is currently finishing hid PhD. study at the same university. His research interest is in analysis and design of analog circuit using current feedback amplifiers.