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Multifunctional adjustable biquadratic active RC filters: design approach by modification of corresponding signal flow graphs

***Abstract**. An useful modification of well known signal flow graph technique for the circuit synthesis is described in this paper in order to obtain the filters working in the current mode, with maximally variable parameters, namely characteristic frequency, quality factor, bandwidth and basic gain. Procedure is based on reciprocal conversion of the branch variables (V→I and I→V) with the adjustable conversion constants. The obtained structures are discussed in detail and then is described an example of current-mode multifunctional RC active biquadratic filter, what is today very popular analogue application. Theoretic assumptions are supported by experimental results using modern functional blocks CC II(-).*

***Streszczenie.** Opisano metodę analizy grafów przepływowych do projektowania filtrów pracujących w trybie prądowym z uwzględnieniem charakterystyki częstotliwościowej, współczynnika jakości, pasma I wzmocnienia. Procedura bazuje na odwrotnej konwersji zmiennych. Otrzymaną strukturę filtru przedyskutowano na przykładzie wielofunkcyjnego filtru RC w trybie prądowym. Analiza teoretyczna poparta jest wynikami eksperymentu. (**Wielofunkcyjny nastawny aktywny filtr RC – projektowanie z wykorzystaniem grafów przepływowych**)*

Keywords: Signal flown graphs, current-mode circuits, ARC filters, electronic adjusting, current conveyors.
Słowa kluczowe: filtry aktywne, grafy przepływowe, tryb prądowy.

Introduction

Today there are available many functional blocks for the analogue signal processing that are better in some views than the classical operational amplifiers. We can mention for example larger bandwidth, better dynamics and linearity, lower power consumption and first of all possibilities of electronic adjusting, via typical parameter controlled in most cases by external DC voltage or current. For example there are transconductors (OTA) [1, 2], where transconductance (g_m) is driven by DC bias current, many types of current conveyors (CC) [1, 3], where is driven input resistance of current input (R_x) by DC bias current and some types of novel modified active elements like current differencing transconductance amplifier (CDTA) [1, 4], current conveyor transconductance amplifier CCTA [1, 5], current follower transconductance amplifier (CFTA) [1, 6], etc. These and similarly elements described in [1] have possibilities for application in electronic adjustable devices and functional blocks.

To design and synthesis novel linear circuits, first of all frequency filters, several methods can be used. Note for example the method based on autonomous circuits [7], using adjoint transformation [8, 12, 13], method based on passive prototypes [9], synthetic elements [10], etc. Each of these methods has some advantages and disadvantages. For example implementation of the method based on autonomous circuit is practically very easy, but manual selection of suitable variants based on supposed characteristic equation is in some complex cases almost impossible. Computer support is sometimes very complicated and time-consuming, especially for more than two active elements, it means more than 10 admittances in full admittance network. We have to take into account that input/output properties (impedances) of proposed circuit are not matched to the signal source or load and mostly are frequency dependent. There is necessary to very careful analyze the sensitivities and parasitic influences. And first of all there is not directly evident how the given circuit works. Nevertheless it can be reduced using the signal flow graph technique given down. This method is based on the flow of the signal in circuit and therefore it is better for imagination how the circuit works and mainly for state-variable structures and high order structures [11-22].

Signal flow graphs

The graph methods [11, 12] are based on graphical representation of mathematical description of the given circuit and special way to obtain the desired network variables (V, I) or to obtain directly network functions (voltage/current transfer functions or input/output port impedances). There several improved graph technique are known [21, 22]. A widespread using the MC graphs [16-22] have found. They are the Coates graphs (with self-loops), evaluated by Mason formulas and directly corresponding with classical nodal analysis (with admittance matrices). However, for our applications in active filters, for complicated systems and block approach is better to use simpler M graphs (without self-loops), especially the signal flow graphs (SFG), where the flow of the signal is presented. In [12] were shown that SFG are very suitable as a design model for high order state variable filters too.

To introduce the SFG technique the simple example of the passive filter is given in Fig. 1. The RC ladder circuit (Fig. 1a) can be described by the following set of equations affecting the cause and effect of the flow of the signal

(1)
$$V_{inp} = V_1,\quad I_1 = \frac{1}{R_1}(V_1 - V_2),\quad V_2 = \frac{1}{sC_2}(I_1 - I_3),$$
$$I_3 = \frac{1}{R_3}(V_2 - V_4),\quad V_4 = R_4 I_3,\quad V_{out} = V_4.$$

The SFG corresponding with eq's (1) is shown in Fig. 1b. Arrows in branches, representing a branch transfer of the voltage (open arrow) and the current (closed arrow) or a conversion $V \leftrightarrow I$, are consistent with Table 1, where will be clarified more.

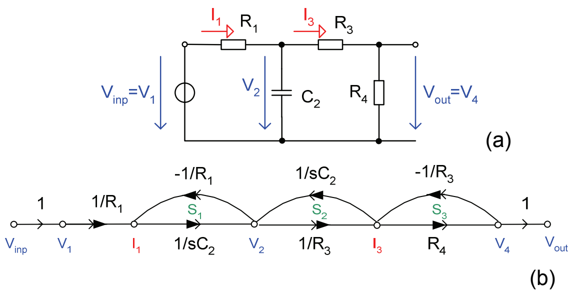


Fig.1. Elementary example of signal flow graph analysis.

The voltage transfer function can be easy evaluated by Mason formula [11, 13, 16] in general form

$$K_V=\frac{V_{out}}{V_{inp}}=\frac{\sum_i P_i\Delta_i}{\Delta\left(V_{inp}\right)}\ , \tag{2}$$

where P_i is the transfer of the i-th direct path from the input to the output node, Δ is the determinant of the graph, Δ_i is the determinant of the subgraph non-touching i-th direct path and $\Delta(V_{inp})$ is the determinant of the subgraph non-touching input node. The determinant is generally given by the known formula

$$\Delta=1-\sum_k S_k+\sum_l S_a^{(l)}S_b^{(l)}-\sum_m S_a^{(m)}S_b^{(m)}S_c^{(m)}+\ldots, \tag{3}$$

where S_k is the transfer of the k-th oriented loop, $S_a^{(l)}S_b^{(l)}$ is the product of the transfer of the two non-touching oriented loops, $S_a^{(m)}S_b^{(m)}S_c^{(m)}$ is the product of the transfer of the three non-touching oriented loops, etc.

Evaluating the graph in Fig. 1b, the voltage transfer (2) is given by this set of equations

$$K_V=\frac{V_{out}}{V_{inp}}=\frac{P\left(V_{inp}\to V_{out}\right)\Delta\left(V_{inp}\to V_{out}\right)}{\Delta\left(V_{inp}\right)},$$

$$P\left(V_{inp}\to V_{out}\right)=\frac{1}{R_1}\frac{1}{sC_2}\frac{1}{R_3}R_4,\quad \Delta\left(V_{inp}\to V_{out}\right)=1, \tag{4}$$

$$\Delta\left(V_{inp}\right)=1-S_1-S_2-S_3+S_1S_3,$$

$$S_1=\frac{1}{sC_2}\left(-\frac{1}{R_1}\right),\quad S_2=\frac{1}{R_3}\left(-\frac{1}{sC_2}\right),\quad S_3=R_4\left(-\frac{1}{R_3}\right).$$

Multi-loop feedback structures

The given SFG technique can be used to obtain an ingenious model of the circuits, especially the filters, with multi-loop feedback structure in current mode (CM) [14], as was firstly shown in [12]. These filters have advantageous over the cascade and ladder structures, namely in universality of function (low-pass, high-pass, band-pass, band-reject and all-pass currently together), simplicity in direct design and independently adjustable parameters. Note that any transfer function can be directly implemented by one of the state-variable multi-loop feedback structures, as follow-the-leader feedback one etc. All these structures can be represented by the sufficient SFG's [12]. A circuit realization of this SFG requires some building blocks, namely an adjustable integrator (realizing branch k/s), an adjustable differentiator (realizing branch ks), a summer (adder), a distributor (splitter or mirror), an inverter and a proportional amplifier with adjustable gain (A or B). Note that in the CM is very easy to realize the summation, by a node only, but the current distribution is a little complicated.

There, in the circuit synthesis, usually we known the desired transfer function. In first step we must construct a SFG, which can provide this transfer. In other case we known the basic SFG of similar circuit and than we seemly modify this graph. In second step we are trying to find corresponding appropriate circuit. There we have many possibilities, but it is always necessary to used only the components mentioned in Tab. 1. The summation and distribution can be realized together in the same point (node). This can be used specially for mixed systems (current-voltage or voltage-current). It will be shown here that the adjustable properties of the summation or distribution point have some important features and advantages for the adjustable applications.

Now we take your attention to the two-loop feedback structure realizing the multifunctional (LP, BP, HP) second order active RC filter. The basic SFG of the general two-loop feedback structure is shown in Fig. 2. In voltage mode (VM) is well known the filter of KHN type [15], also titled as the two-loop state-variable structure. This structure is very used in many applications, for example [1, 4, 12]. Controlling the important parameters of this filter there is necessary to change some constants and gains in specific paths. Then it is easy to modify this graph (Fig. 2) by help of an adjoint transformation, given in [14], to obtain the SFG in Fig. 3. This transformation converts the graph in the VM to the CM equivalent, whereas the directions of the signal paths are reversed and the inputs are changed to the outputs. Therefore the CM structure contains three inputs and one output only (Fig. 3).

Table 1. Basic components of the block SFG approach

block component	voltage-mode	current-mode
Buffer (special direct path)	V_1 1 V_2	I_1 1 I_2
amplifier (proportional path)	V_1 A V_2	I_1 B I_2
Integrator (lossless)	V_1 $k\frac{1}{s}$ V_2	I_1 $k\frac{1}{s}$ I_2
differentiator (lossless)	V_1 ks V_2	I_1 ks I_2
summer (adder)	V_1, V_2, V_n, ±1, ±1, ±1, 1, $V_o=\sum_{i=1}^{n}\pm1\cdot V_i$	I_1, I_2, I_n, ±1, ±1, ±1, 1, $I_o=\sum_{i=1}^{n}\pm1\cdot I_i$
Distributor (mirror)	V_1 1, ±1 ±V_1, ±1 ±V_1, ±1 ±V_1	I_1 1, ±1 ±I_1, ±1 ±I_1, ±1 ±I_1
voltage to current converter g,	V_1 ±g $I_2=\pm g.V_1$	
current to voltage converter r	I_1 ±r $V_2=\pm r.I_1$	
Summer with conversion and gain control g, r	V_1, V_2, V_n, ±g_1, ±g_2, ±g_n, ±r, $V_\Sigma=\pm r\sum_{i=1}^{n}\pm g_iV_i$, I_Σ	I_1, I_2, I_n, ±r_1, ±r_2, ±r_n, ±g, $I_\Sigma=\pm g\sum_{i=1}^{n}\pm r_iI_i$, V_Σ
Distributor with conversion and gain control g, r	V_1, ±g, ±r_1, ±r_2, ±r_n, $V_{o1}=\pm g(\pm r_1)V_1$, $V_{o2}=\pm g(\pm r_2)V_1$, $V_{on}=\pm g(\pm r_n)V_1$	I_1, ±r, ±g_1, ±g_2, ±g_n, $I_{o1}=\pm r(\pm g_1)I_1$, $I_{o2}=\pm r(\pm g_2)I_1$, $I_{on}=\pm r(\pm g_n)I_1$
Combined point with gain control g, r	V_1, V_2, V_n, ±g_1, ±g_2, ±g_n, ±r_1, ±r_2, ±r_k, $V_{o1}=\pm r_1\sum_{i=1}^{n}\pm g_iV_i$, $V_{o2}=\pm r_2\sum_{i=1}^{n}\pm g_iV_i$, $V_{ok}=\pm r_k\sum_{i=1}^{n}\pm g_iV_i$	I_1, I_2, I_n, ±r_1, ±r_2, ±r_n, ±g_1, ±g_2, ±g_k, $I_{o1}=\pm g_1\sum_{i=1}^{n}\pm r_iI_i$, $I_{o2}=\pm g_2\sum_{i=1}^{n}\pm r_iI_i$, $I_{ok}=\pm g_k\sum_{i=1}^{n}\pm r_iI_i$
g, r - conversion constants and it can be used also for amplification or attenuation (proportional path)		

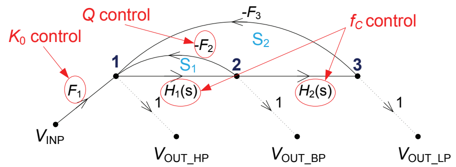


Fig.2. Signal flow graph of the two-loop general feedback structure in voltage mode

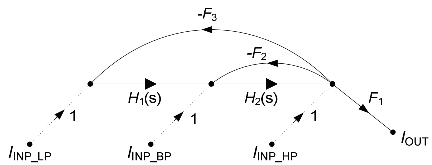


Fig.3. The graph of the transformed current-mode structure

Building blocks implemented by current conveyors

The basic blocks, realizing the subgraphs from Table 1 and building the circuit corresponding with the given SFG, can be implemented by current conveyors (CC), as shown in Table 2, and also with other elements introduced in [1].

One from most suitable of these is the second generation three-port negative type CCII-, with a possibility of electronic adjusting of the current gain, in contrast to many other elements from [1]. The CCII- is defined by the following hybrid matrix description

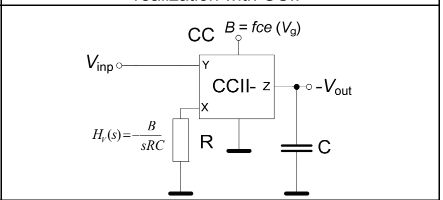
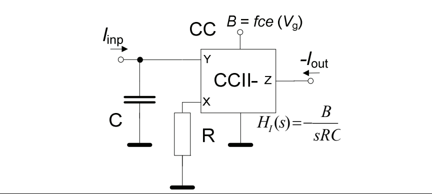
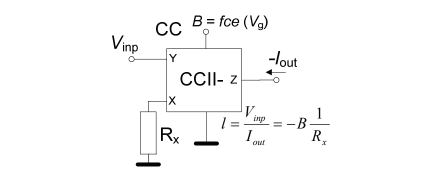
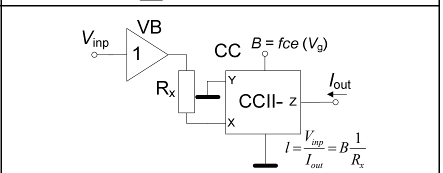
$$\begin{bmatrix} V_X \\ I_Y \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ -B & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_X \\ V_Y \\ V_Z \end{bmatrix}. \tag{5}$$

Note that for the classical CC the parameter $B = 1$, but there the current gain B is controllable via DC voltage V_G. The adjustable parameter $B = \mathrm{fce}(V_g)$ is employed in our two-port applications (Table 2) to control and invert the current

$$I_Z = -I_X \cdot B(V_g). \tag{6}$$

The CCII- is commercially available under designation EL 2082 [23] and also called as current mode multiplier. This product is a little obsolete, but it is still sufficient for our experimental verification of the theory given in this paper. Nevertheless to practically propose these filters the CCII- as a novel implementation on chip would be more usefulness, what is not problem for microelectronic experts.

Table 2. Basic blocks for SFG realization with CCII-

block component	realization with CCII-
inverting voltage integrator	
inverting current integrator	
Inverting voltage to current converter	
non-inverting voltage to current converter	

Synthesis of two-loop full adjustable biquads

The determinant of the SFG in Fig. 2 is defined as

$$\Delta = 1 - (S_1 + S_2) = 1 + F_2 H_1(s) + F_3 H_1(s) H_2(s), \tag{7}$$

where the integrators are described by

$$H_1(s) = k_1 \frac{1}{s}, \quad H_2(s) = k_2 \frac{1}{s}, \quad k_1 = -\frac{B_1}{R_1 C_1}, \quad k_2 = -\frac{B_2}{R_2 C_2}. \tag{8}$$

In case where the amplifiers are used in the feedback and the integrators are in the direct paths, there is necessary five voltage buffers, but in the CM the input summation point (in Fig. 2 designed as 1) will be realizing by KCL only and there are necessary three buffers only (separating high impedance outputs). Modified SFG is given in Fig. 4a and a concrete variant is in Fig. 4b. Supposing that here is used voltage inverting integrators from Table 2, we can evaluate the branch transfers to this node 1 from the input (V_{INP}), from the nodes 3 and 4 and transfer from node 1 to node 2 by the voltage to current conversion constants (given Table 1) as follows

$$g_1 = -\frac{1}{R_3} B_3, \quad g_2 = \frac{1}{R_4} B_4, \quad g_3 = -\frac{1}{R_5} B_5, \quad r_1 = R_6. \tag{9}$$

This procedure will be more cleared from Fig. 5, where the circuit realization and the corresponding subgraph are shown. Note that a classical way with one opamp as the summer (the point 1) is simple but there is not easy an implementation of the electronic adjusting of the gain in the specified paths.

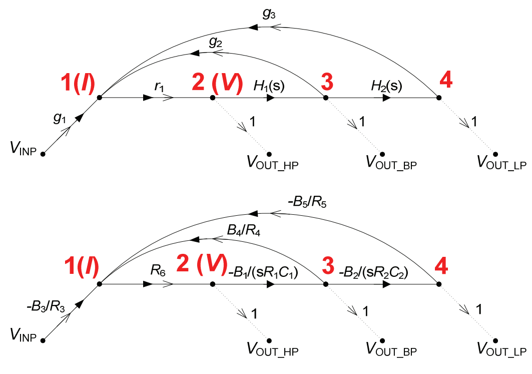


Fig.4. a) Modified SFG with input voltage to current conversion, current mode summation and adjustable parameters, b) concrete variant

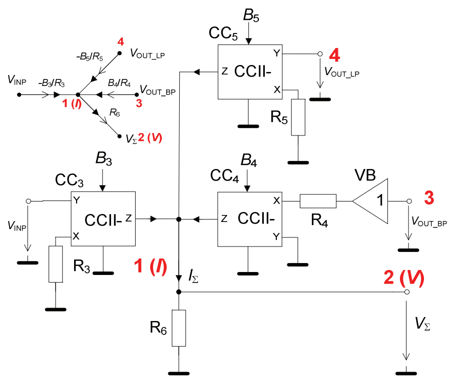


Fig.5. Voltage to current transformation, current summation and conversion of current to voltage at input summation point

Evaluating the SFG in Fig. 4b the determinant (7) is now resulting in

$$\Delta = 1 + r_1 g_2 \frac{k_1}{s} + r_1 g_3 \frac{k_1 k_2}{s^2} = 1 + \frac{R_6 B_1 B_4}{s R_1 R_4 C_1} + \frac{R_6 B_1 B_2 B_5}{s^2 R_1 R_2 C_1 C_2 R_5}, \tag{10}$$

and the voltage transfer functions are determined as

$$K_{HP}(s) = \frac{V_{OUT\_HP}}{V_{INP}} = \frac{P(V_{INP} \to V_{OUT\_HP}) \Delta (V_{INP} \to V_{OUT\_HP})}{\Delta(V_{INP})} = \tag{11}$$
$$= \frac{g_1 r_1}{\Delta} = \frac{-\frac{B_3}{R_3} R_6}{\Delta} = \frac{-\frac{B_3}{R_3} R_6 s^2}{s^2 + \frac{R_6 B_1 B_4}{R_1 R_4 C_1} s + \frac{R_6 B_1 B_2 B_5}{R_1 R_2 C_1 C_2 R_5}},$$

(12) $$K_{BP}(s)=\frac{V_{OUT\_BP}}{V_{INP}}=\frac{P(V_{INP}\to V_{OUT\_BP})\Delta(V_{INP}\to V_{OUT\_BP})}{\Delta(V_{INP})}=,$$

$$=\frac{g_1 r_1 H_1(s)}{\Delta}=\frac{-\frac{B_3}{R_3}R_6\left(-\frac{B_1}{sR_1C_1}\right)}{\Delta}=\frac{\frac{B_1B_3}{R_1R_3C_1}R_6 s}{s^2+\frac{R_6B_1B_4}{R_1R_4C_1}s+\frac{R_6B_1B_2B_5}{R_1R_2C_1C_2R_5}}$$

(13) $$K_{LP}(s)=\frac{V_{OUT\_LP}}{V_{INP}}=\frac{g_1 r_1 H_1(s)H_2(s)}{\Delta}=\frac{-\frac{B_1B_2B_3}{R_1R_2R_3C_1C_2}R_6 s}{s^2+\frac{R_6B_1B_4}{R_1R_4C_1}s+\frac{R_6B_1B_2B_5}{R_1R_2C_1C_2R_5}}.$$

From the denominator of these transfer functions (11-13) is clear that the characteristic frequency f_C is given by

(14) $$f_C=\frac{1}{2\pi}\sqrt{\frac{R_6B_1B_2B_5}{R_1R_2R_5C_1C_2}},$$

the quality factor Q and the basic gain K_0 are

(15), (16) $$Q=\frac{R_1R_4C_1}{R_6B_1B_4}\sqrt{\frac{R_6B_1B_2B_5}{R_1R_2R_5C_1C_2}},\quad K_0=-\frac{B_3}{R_3}R_6 .$$

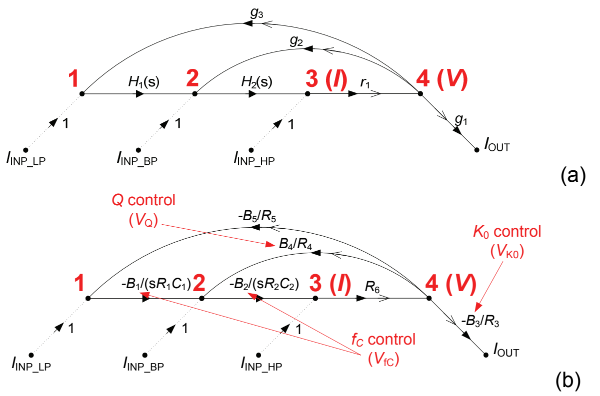


Fig.6. a) Transformed SFG with output voltage to current conversion, current mode distribution and adjustable parameters, b) concrete variant

The described way for the synthesis and design allows to obtain the adjustable biquad with f_C tuning, Q adjusting, gain (K_0) adjusting or orthogonal ω_C/Q control (adjusting BP bandwidth). However, there are necessary quite a lot of active elements (first of all buffers for voltage mode applications).

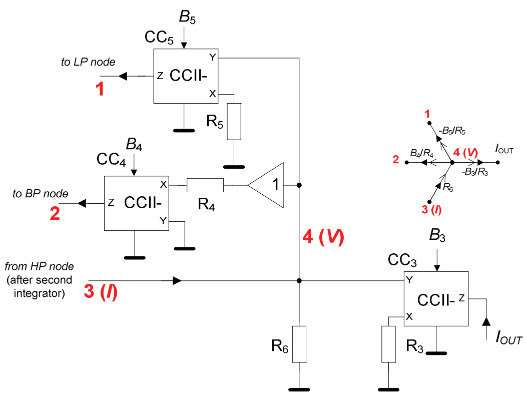


Fig.7. Current to voltage transformation, current distribution point and iterative conversion to output current

The other approach supposes a using of the adjoint transformation from [14] to obtain the CM, where is necessary less voltage buffers. There is necessary only one in path between node 4 and 2 (Fig. 7) if only CCII-s are used. We can save this buffer if in this path CCII+ (positive) is used. The adjoint transformation reverses the SFG (Fig. 3) and swaps the inputs to the outputs and the signal direction in the direct and feedback paths (Fig. 6a). From external view the circuit is now working in current mode with current excitation and output response. There is output distribution instead the input summation. This function is realized with CCs conceived also as voltage to current converters. One conversion is realized via grounded resistor from current to voltage. This equivalent has the same advantages and possibilities as previous solution (Fig. 4), therefore transfer functions are very similar (practically the same). Difference is in order of integrators in loops. The distribution point is shown in Fig. 7. Transfer functions of the structure in Fig. 6b are

(17) $$K_{LP}(s)=\frac{I_{OUT}}{I_{INP\_LP}}=\frac{-\frac{R_6B_1B_2B_3}{R_1R_2R_3C_1C_2}}{s^2+\frac{R_6B_2B_4}{R_2R_4C_2}s+\frac{R_6B_1B_2B_5}{R_1R_2C_1C_2R_5}},$$

(18) $$K_{BP}(s)=\frac{I_{OUT}}{I_{INP\_BP}}=\frac{\frac{R_6B_2B_3}{R_2R_3C_2}s}{s^2+\frac{R_6B_2B_4}{R_2R_4C_2}s+\frac{R_6B_1B_2B_5}{R_1R_2C_1C_2R_5}},$$

(19) $$K_{HP}(s)=\frac{I_{OUT}}{I_{INP\_HP}}=\frac{-\frac{R_6B_3}{R_3}s^2}{s^2+\frac{R_6B_2B_4}{R_2R_4C_2}s+\frac{R_6B_1B_2B_5}{R_1R_2C_1C_2R_5}}.$$

Only small difference is evident in the middle coefficient in numerator (band pass function) and denominator (B_2/R_2C_2 instead B_1/R_1C_1).

Experimental results

Features of designed structure in Fig. 6 using proposed distribution point in Fig. 7 were measured and results are in Fig. 8 - Fig. 10. The complete proposed circuit structure with positive and negative CCII was published in [24, 25] but experimental results were not available until now. There was used Agilent E5071C network analyzer for measurements. Parameters of passive element are in Fig. 8. The voltage follower was used BUF 634 [26] type.

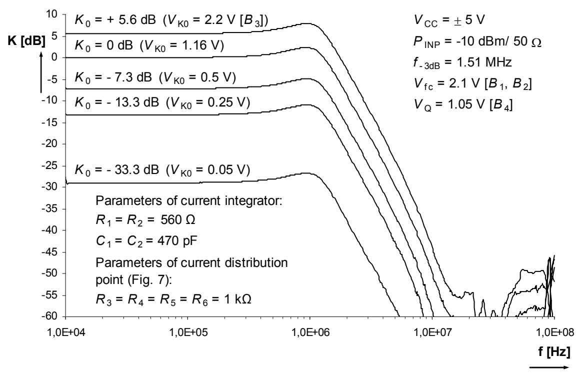


Fig.8. Experimental results of K_0 adjusting on LP response

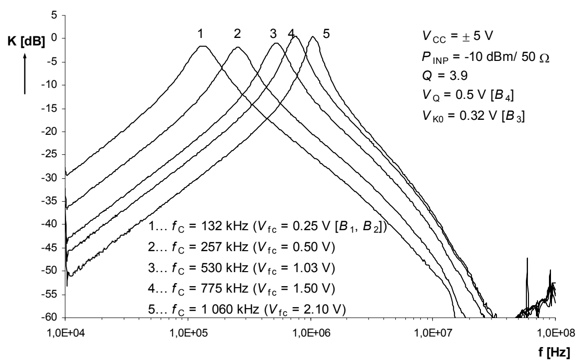


Fig.9. Experimental results of f_C tuning on BP response

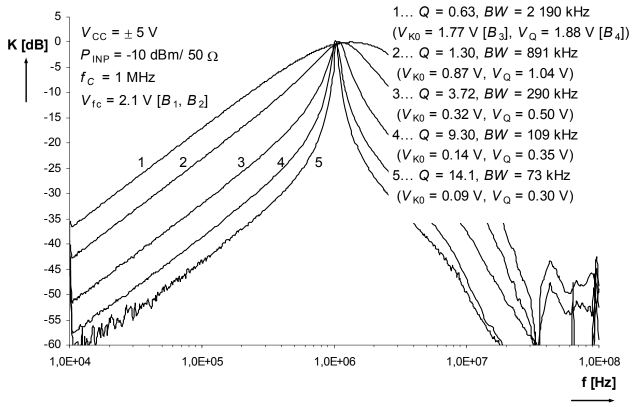


Fig.10. Experimental results of orthogonal control ω_C/Q of the bandwidth of BP response

Conclusion

There was shown that SFG modified method without self-loops for block approach to the circuit design are very suitable for block synthesis and analysis of complicated functional structures (high order active filter, oscillators, more staged amplifier, etc.). Presented approach is very suitable for various modifications of adjustable biquadratic structures, e.g. [27-30]. Described method was shown for two-loop structures only but it is suitable also for theoretically any higher order multi-loop filter. There were shown some advantages of conversion between voltage and current on electronic adjusting of proposed circuits. With standard opamps this features are also possible. However in such solution are necessary electronically adjustable resistors or digital potentiometers and total result is in many cases worse (more additional components). First of all frequency responses and bandwidth of application are worse and it is suitable mainly for low frequency purposes.

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