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PLNĚ DIFERENČNÍ KMITOČTOVÉ FILTRY S MODERNÍMI AKTIVNÍMI PRVKY

FULLY-DIFFERENTIAL FREQUENCY FILTERS WITH MODERN ACTIVE ELEMENTS

ZKRÁCENÁ VERZE PH.D. THESIS

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INTRODUCTION

Despite the fact that the technology is working with digital signals these days, analog frequency filters are a vital part of electronic circuits which we can encounter in a broad range of industry such as measurement technology, radio-technology, telecommunication, electro-acoustics etc. In case that the processed signal is represented by the voltage amplitude, the filter operates in the voltage mode. Lately, we can experience tendency of reducing the size of integrated circuits in order to decrease their requirements of power supply voltage and energy consumption which decreases the level of processed signals. This subsequently results in a reduction of signal-to-noise ratio and limits the dynamic range of the circuit. Therefore, the design of electrical circuits is currently focused on active elements operating in the current mode due to its advantages such as better signal-to-noise ratio, greater dynamic range, wider frequency bandwidth and lower power consumption in particular cases [1]. The design of frequency filters is also more and more focused on the design of these filters in the fully-differential form because of the advantages that the differential signal processing brings in comparison to single-ended structures greater dynamic range of the processed signals, better power supply rejection ratio, lower harmonic distortions and greater attenuation of common-mode signals [2].We can mention controllable active elements which allow us to adjust the characteristic frequency filter parameters, e.g. the pole frequency, quality factor, bandwidth and gain in the pass band area of any filter, or sometimes only of particular type of the filter.

1 STATE OF THE ART REVIEW

In case of the proposal of frequency filters, there are two basic trends. The first one is the proposal of more complex filtering structures using simpler active elements. The structure of these filters is characterized by higher circuit complexity and higher number of used active elements, but provide a greater variability of the proposal. Among the filters that use simpler active elements there are filters employing a variety of Current Conveyors (CCs) [3-17], It was firstly introduced in 1968. There are totally three generations of current conveyors. Individual generations are, from the outside, only distinguished by orientation and derivation of the currents at the Y gate of this element. Slightly different variants of the current conveyor such as current conveyors with various amount and orientation of the input and output terminals e.g. [3], [4], [6], [9], [17], inverting versions [7], [8] and current controlled versions [5], [10], [11], [14], [15] etc gradually emerged. Furthermore, we can mention filters employing Current Followers (CFs) [18-24]. Current follower is the simplest current-mode active element. Filters employing current followers can have a large bandwidth range thanks to a simple internal structure of these elements. We can frequently encounter current followers with two outputs (double-output current followers (DO-CFs)) [21-24] and three and more outputs (multiple-output current followers (MO-CFs)) [18], [20], [21], [25]. There are also filters with Operational Transconductance Amplifiers (OTAs) [26], [27], [23], [28], [29-33]. Depending on the number of outputs of this active element, it is possible to come across OTA [27], [29] (having one output), balanced operational transconductance amplifier (BOTA) [23], [26], [32], (having two outputs of mutually opposite polarities) and multiple-output transconductance amplifier (MOTA) [23], [28], [30-33] with three or more outputs. Filters using Digitally Adjustable Current Amplifiers (DACAs) can be found in [18], [21], [34], [35], [36], for instance. The other approach is opposite to the first one when we use more complex active elements so the number of used active elements can be lower and the proposed filtering structures appear to be simpler. These active elements are usually a particular composition of the simpler elements mentioned above. The disadvantage of this approach is more complex and more expensive proposal and implementation of given active elements on a chip. The literature presents filters which use different types of active elements based on Transconductance Amplifiers such as filters with Current Controlled Transconductance Amplifiers (CCTAs) [37-41], Current Differencing Transconductance Amplifiers (CDTAs) [42-48] etc.

There are two general ways how to propose fully-differential frequency filters. The first one is to directly propose the filter in its F-D form. Such a procedure requires an experienced designer who designs the F-D structures intuitively. The other easier way how to propose the F-D filters is by transformation of the S-E filters into their F-D form by mirroring passive components around the active elements based on particular transformation method [49]. The number of passive components will increase approximately two times in comparison to the number of passive components used in the S-E structure. Active elements are either replaced by their F-D equivalents with differential inputs and outputs, or they are also being mirrored which will again increase their number by twice. The values of the passive components after they were mirrored have to be determined all over when this is dependent on what type of transformation is used.

In comparison to standard (integer-order) filters, the slope of attenuation of the fractional-order filters is given by the equation $20\cdot(n + \alpha)$, where n is an unsigned non-zero integer number and α is a real number in the range $0 < \alpha < 1$ [50]. The design of fractional-order filters is rather more complicated than the proposal of standard (integer-order) filters. There are two basic ways how to propose a fractional-order filter. The first way is based on creation of a special fractional-order element (FOE) [51-55]. Usually it is a capacitor. These fractional-order elements are then used in a conventional filter structure. The other possible way is an approximation of fractional-order Laplacian operator $\mathbf{s}^{\alpha}$ using an integer-order transfer function of higher order. The second-order approximation is most commonly used [50], [52], [56], but it is also possible to use an approximation of higher orders than the second-order approximation [50].

2 THESIS GOALS

The main aim of the work is the proposal and analysis of fully-differential frequency filters operating in the current-mode. Great emphasis will be paid to a comparison of the F-D structures and their corresponding S-E forms. The thesis is possible to divide into three parts.

The first part is to propose new second-order current-mode filtering structures especially fully-differential ones using non-standard active elements such as current conveyors, operational transconductance amplifiers, current amplifiers, current followers and their fully-differential equivalents. The proposed filters are going to be firstly designed in their S-E form using signal-flow graphs method and then transformed into the F-D structures using the transformation of horizontal structures so a mutual comparison of the S-E and F-D structures is possible. One of the main goals of this thesis is the emphasis laid upon the versatility of the proposed filters and the ability to control some of the typical filter parameters such as the pole frequency, or the quality factor of the filter by suitable use of controllable active elements. The design correctness and functionality of the proposed filters are going to be supported by simulations and in some cases also by experimental measurements. The simulations will be carried out using accurate second and third level simulation models of used active elements which are based on the measurement of characteristics of the real elements. The experimental measurements will be performed by measurements of implemented filters in a form of printed circuit boards (PCBs) using simple V/I, I/V converters [57] and chips of available active elements, in particular the universal current conveyor which can be used to implement a variety of active elements such as the current follower and operational transconductance amplifier, for instance. Subsequently, a comparison of the properties of S-E and F-D filters will be made. Each S-E filter and corresponding F-D filter will be presented together in the same chapter because of their easier comparison. Furthermore, the sensitivity [58] and parasitic [23] analysis of chosen proposal is going to be carried out.

The second part is the proposal and analysis of fractional-order frequency filters when also the possibility of creation of these filters in their fully-differential forms and following comparison of the S-E and F-D structures will be analyzed. One of the chosen conditions is again the ability to control some of the characteristic filter parameter, in this case, its order and pole frequency. The design procedure is the same as for the previous part. The filters are firstly designed in their S-E forms and then transformed into the F-D structures.

The last part consist of the analysis of existing design methods used for the proposal of frequency filters especially differential filters and subsequent modification of a chosen existing design method with respect to the specific needs and characteristics of differential structures. A practical applicability and versatility of this method is going to be also analyzed.

3 DEFINITION OF SINGLE-ENDED AND FULLY-DIFFERENTIAL CURRENT TRANSFERS

There are two basic convention how to represent the direction of the currents. According to the convention in [59], the currents flow inside a block both at input and output. In this case, the output current is presented flowing inside a block however, the current transfer contains a minus sign, which means that the output current is actually flowing out which is in consistency with the representation of the current transfer used by signal-flow graphs where the transfer from the input to the output is always considered going in one direction. The other definition [60] represents the output currents flowing outside a block when the current transfer is positive. This definition of the current transfer is also consistent with signal-flow graphs. This particular representation of the current transfer is used in this thesis. Figure 3.1 shows the second of above mentioned definitions of the simple current transfer. The current transfer from Figure 3.1 is given as $K_{\mathrm{i}} = i_{\mathrm{OUT}}/i_{\mathrm{IN}}$.

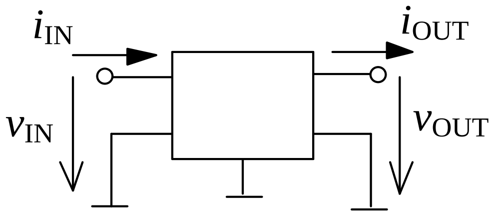

Figure 3.1 Structure used to illustrate the single-ended general current transfer

The fully-differential current transfer is defined as the proportion of the differential output and differential input current. Figure 3.2 shows the definition from [60] when the output currents flow outside the block which respects the current transfer of the signal-flow graphs method where the transfer from the input to the output is, as already mentioned, always considered going in one direction.

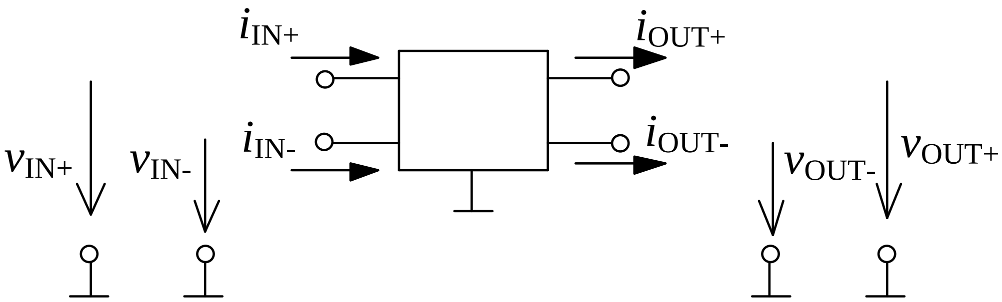

Figure 3.2 Structure used to illustrate the fully-differential general current transfer

The differential input and output current and the current transfer are given as:

$$i_{IN\,DIF} = i_{IN+} - i_{IN-}, \quad i_{OUT\,DIF} = i_{OUT+} - i_{OUT-}, \quad K_i = \frac{i_{OUT\,DIF}}{i_{IN\,DIF}}. \tag{3.1}$$

4 SIGNAL-FLOW GRAPHS DESIGN METHOD

This well recognized method was used in the proposal of filters presented in chapter **Chyba! Nenalezen zdroj odkazů.**. Therefore, it would be appropriate to describe this method in more detail. Signal-flow graphs were originally proposed by S. J. Mason in 1953 in order to describe and solve linear algebraic equations [61]. Later on, generalized Coates graphs [62] have appeared. Mixed Mason-Coates' (M-C) graphs [63] can be used for the analysis and synthesis of linear electrical networks. These graphs can be understood as diagrams of nodes which represent variables and directed branches defining mutual relationships between nodes of the analyzed structure. The signal-flow graphs need only Mason formula to obtain the transfer function.

Manson's gain formula is given by the following relation:

$$K = \frac{1}{\Delta}\sum_i P_i \Delta_i, \tag{4.1}$$

where P_i is gain of i-th forward path and Δ stands for the determinant of the graph. The determinant is given by the following equation:

$$\Delta = P - \sum_i P_i \Delta_i + \sum_j P_j \Delta_j - \sum_k P_k \Delta_k + ..., \tag{4.2}$$

where P represents self-loop products, P_i stands for individual loop gains, Δ_i are then loop gain terms which do not touch the i-th forward path, P_j are products of two non-touching loops, Δ_j symbolizes loop gain terms which do not touch the j-th forward path, P_k interprets products of three non-touching loops, Δ_k represents loop gain terms which do not touch the k-th forward path etc.

The proposed filters were designed using simplified M-C graphs. These simplified graphs are used for easier and more transparent presentation especially of the F-D structures which would be rather complex and difficult to follow in case of using modified M-C graphs.

5 DESCRIPTION OF USED ACTIVE ELEMENTS

5.1 CURRENT FOLLOWERS

Current followers are used to create either lossless or lossy integrators which are basic building blocks used in design of frequency filters. Additional outputs of this active element can used to create feedbacks, which allow us to cancel out undesired terms of the denominator of the filter, or to obtain particular transfer function right from the high-impedance outputs of this element. The MO-CF was originally presented in [64]. A schematic symbol, M-C graph, simplified M-C graph and possible implementation of the MO-CF element with four outputs can be seen in Figure 5.1 a), b), c), d) respectively. The MO-CF element has one input and four output terminals. The relations between the input and output terminals of this active element are described by the following relations:

$$i_{OUT1} = i_{OUT3} = i_{IN}\,, \quad i_{OUT2} = i_{OUT4} = -i_{IN}\,. \tag{5.1}$$

The FD-CF from Figure 5.1 e) has a differential input and its behavior can be described by:

$$i_{OUT1} = i_{OUT3} = i_{IN}\,, \quad i_{OUT2} = i_{OUT4} = -i_{IN}\,. \tag{5.2}$$

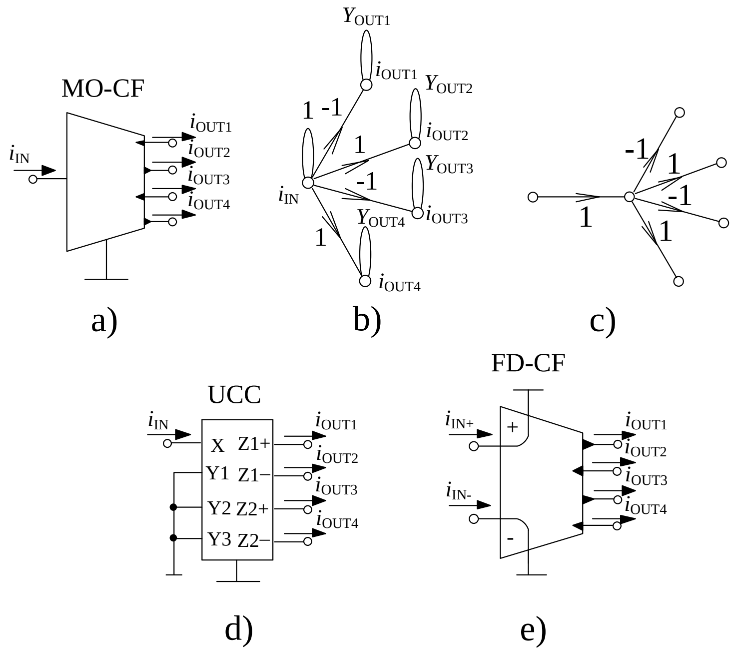

Figure 5.1 a) schematic symbol of the MO-CF, b) modified M-C graph of the MO-CF, c) simplified M-C graph of the MO-CF, d) possible implementation of the MO-CF using the UCC, e) schematic symbol of the FD-CF

5.2 OPERATIONAL TRANSCONDUCTANCE AMPLIFIERS

This active element [27] is not working purely in the current mode, but it is frequently used in current-mode circuits as a basic building element. The operational transconductance amplifiers have a voltage differential input and either one current output (OTA) two current outputs with mutually opposite polarities (balanced operational transconductance amplifier (BOTA)), or three or more current outputs (MOTA). A schematic symbol, modified M-C graph and simplified M-C graph of the BOTA element are shown in Figure 5.2 a), b) and c). A schematic symbol and possible implementation of the MOTA element using the UCC are depicted in Figure 5.2 d), e). In case of the implementation of the MOTA using the UCC, Y_1 and Y_2 terminals serve as inputs, Y_3 is grounded, X is connected to a grounded resistor. Transconductance of this type of implementation is then inversely dependent on the value of the resistor *R* which is connected to X terminal.

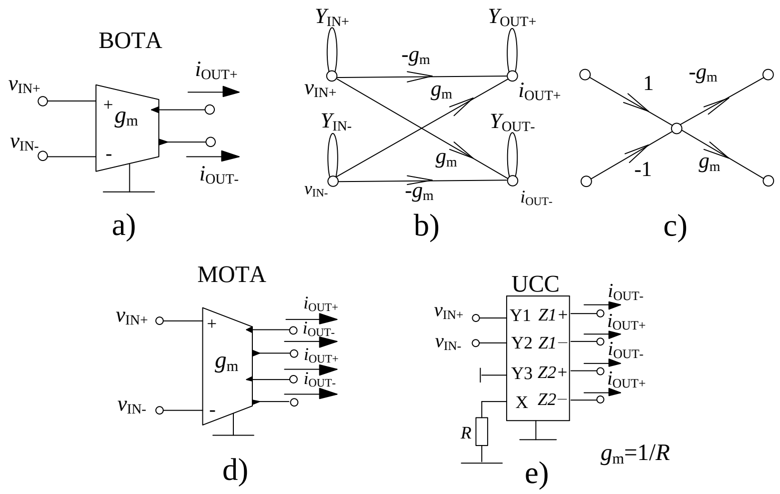

Figure 5.2 a) schematic symbol of the BOTA, b) modified M-C graph of the BOTA, c) simplified M-C graph of the BOTA, d) schematic symbol of the MOTA, e) possible implementation of the MOTA using the UCC

The BOTA and MOTA consist of a voltage differential input and two or more current outputs. Relations between input and output terminals are described as:

$$i_{OUT+} = -i_{OUT-} = g_m(v_{IN+} - v_{IN-}). \tag{5.3}$$

5.3 ADJUSTABLE CURRENT AMPLIFIERS

Adjustable current amplifiers are current-mode active elements with a low-impedance current input(s) and current high-impedance current output(s) with ability to control their gain. A schematic symbol of the ACA element is depicted in Figure 5.3 a). Figure 5.3 b) c) and d) shows a schematic symbol of the digitally adjustable current amplifier, modified M-C graph of this element, simplified M-C graph respectively. The DACA element [21] was developed in cooperation of Brno University of Technology and ON Semiconductor design center in CMOS 0.35 µm technology. The DACA consists of a differential input and differential output and its gain is controlled via 3-bit word in range from 1 to 8 with step of 1. An alternative circuit solution of the DACA element is presented in Figure 5.3 e). It consists of two inputs and four outputs and it is formed by one universal voltage conveyor (UVC) [65], one EL2082 [66] and one UCC. The gain of this circuit can be controlled continuously in range of 0 to 5 by DC voltage.

The DACA element can be described by the following relations:

$$i_{ID} = i_{IN+} - i_{IN-}, \quad i_{OD} = i_{OUT+} - i_{OUT-}, \tag{5.4}$$

$$i_{OD} = 2Ai_{ID}, \quad i_{OUT+} = A(i_{IN+} - i_{IN-}), \quad i_{OUT-} = -A(i_{IN+} - i_{IN-}), \tag{5.5}$$

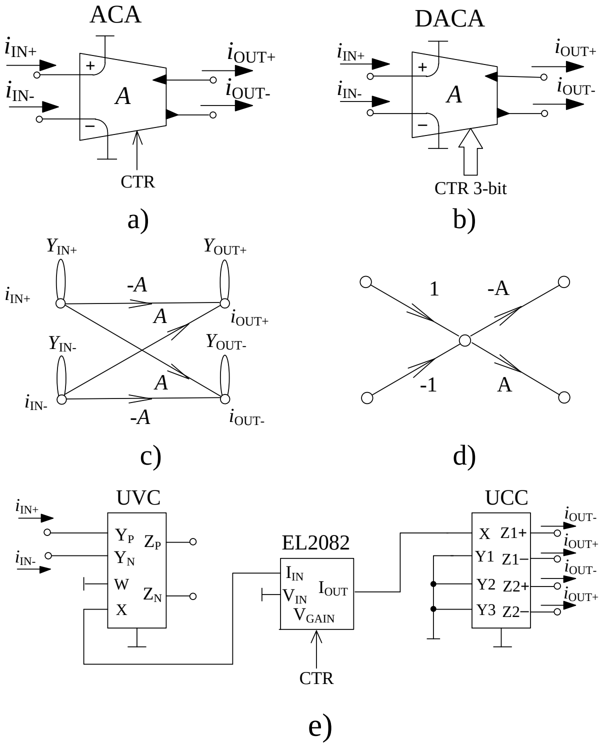

Figure 5.3 a) schematic symbol of the ACA, b) schematic symbol of the DACA, c) modified M-C graph of the DACA, d) simplified M-C graph of the DACA, e) alternative implementation of the DACA using one UCC, UVC and EL2082

6 NEWLY PROPOSED FILTERING STRUCTURES

All S-E filters are firstly design using signal-flow graph design method. The F-D filters are then created from the corresponding S-E filters by the transformation of horizontal structures. All the proposed filters are the second-order current-mode filters. The proposals are then verified using SNAP program and PSpice simulations using available simulation models of used active elements. The actual functionality of the proposed filters is, in some cases, also supported by experimental measurements. The measurement has been performed using network analyzer Agilent 4395A together with simple V/I and I/V converters.

6.1 UNIVERSAL FILTER WITH TWO OTAS, ONE CF AND ONE DACA

The aim of the proposal was to design a second-order universal current-mode frequency filter using transconductance amplifiers (one BOTA and one MOTA elements) as basic building blocks. The DACA element was added in the circuit structure to control the quality factor of the filter. The proposed filter enables to control the pole frequency without disturbing the quality factor of the filter by simultaneous change of transconductances g_{m1}, g_{m2}. The quality factor of the filter can be electronically controlled by adjusting the current gain of the DACA element. I have presented the research from this chapter in [66]. The S-E form of the filter is shown in Figure 6.1.

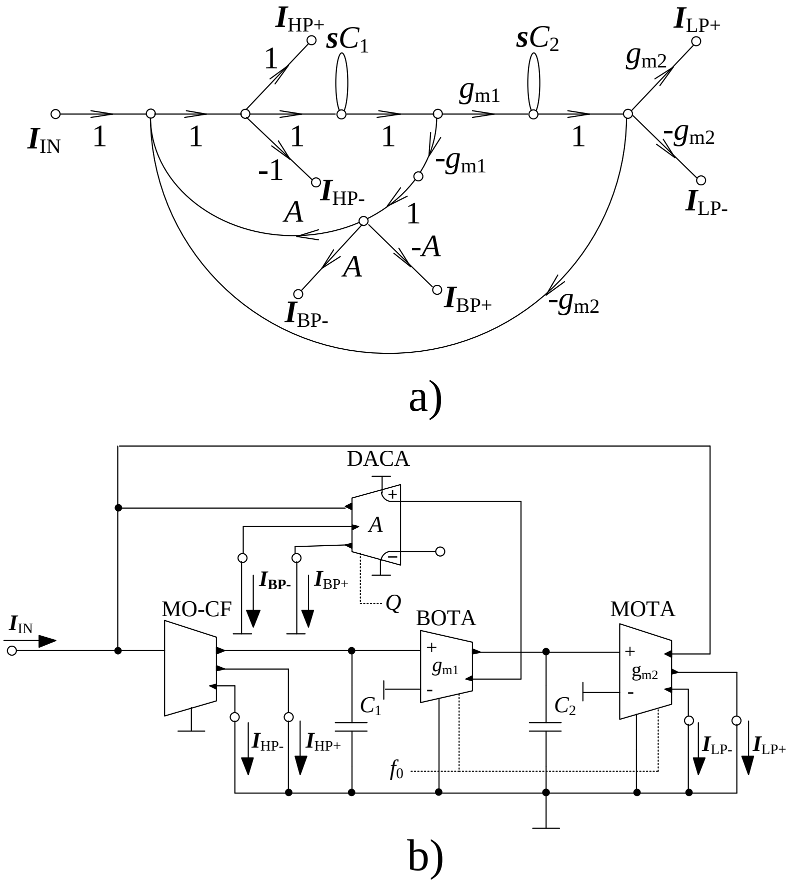

Figure 6.1 Single-ended form of the filter with two OTAs, one DACA and one MO-CF: a) simplified M-C graph, b) circuit structure

The denominator of transfer functions of the S-E and F-D filter is described by:

$$D(\boldsymbol{s}) = \boldsymbol{s}^2 C_1 C_2 + \boldsymbol{s} C_2 g_{m1} A + g_{m1} g_{m2}. \tag{6.1}$$

The pole frequency and the quality factor can be described by the following relations:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}}, \quad Q = \frac{1}{A}\sqrt{\frac{g_{m2} C_1}{g_{m1} C_2}}. \tag{6.2}$$

The F-D form of the filter can be seen in Figure 6.2. Floating capacitors are replaced by grounded capacitors the way shown in Figure 6.2 c). These capacitors are twice as high as capacitors used in the S-E filter. In order to obtain the same transfer functions for both the S-E and F-D filter, factor A used for the F-D structure is replaced by $2A$. The values of g_{m1}, g_{m2} of the F-D filter must be twice higher than in case of S-E transconductances.

The proposed S-E and F-D filter provides the following transfer functions:

$$\frac{\boldsymbol{I}_{LP+}}{\boldsymbol{I}_{IN}} = -\frac{\boldsymbol{I}_{LP-}}{\boldsymbol{I}_{IN}} = \frac{g_{m1}g_{m2}}{D}, \quad \frac{\boldsymbol{I}_{BP+}}{\boldsymbol{I}_{IN}} = -\frac{\boldsymbol{I}_{BP-}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s}C_2 g_{m1} A}{D}, \tag{6.3}$$

$$\begin{gathered} \frac{\boldsymbol{I}_{HP+}}{\boldsymbol{I}_{IN}} = -\frac{\boldsymbol{I}_{HP-}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s}^2 C_1 C_2}{D}, \\ \boldsymbol{I}_{BS} = \frac{\boldsymbol{I}_{HP+} + \boldsymbol{I}_{LP+}}{\boldsymbol{I}_{IN}} = -\frac{\boldsymbol{I}_{HP-} + \boldsymbol{I}_{LP-}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s}^2 C_1 C_2 + g_{m1}g_{m2}}{D}, \end{gathered} \tag{6.4}$$

$$\begin{aligned} \boldsymbol{I}_{AP} &= \frac{\boldsymbol{I}_{HP+} + \boldsymbol{I}_{BP-} + \boldsymbol{I}_{LP+}}{\boldsymbol{I}_{IN}} = -\frac{\boldsymbol{I}_{HP-} + \boldsymbol{I}_{BP+} + \boldsymbol{I}_{LP-}}{\boldsymbol{I}_{IN}} = \\ &= \frac{\boldsymbol{s}^2 C_1 C_2 - \boldsymbol{s}C_2 g_{m1} A + g_{m1}g_{m2}}{D}. \end{aligned} \tag{6.5}$$

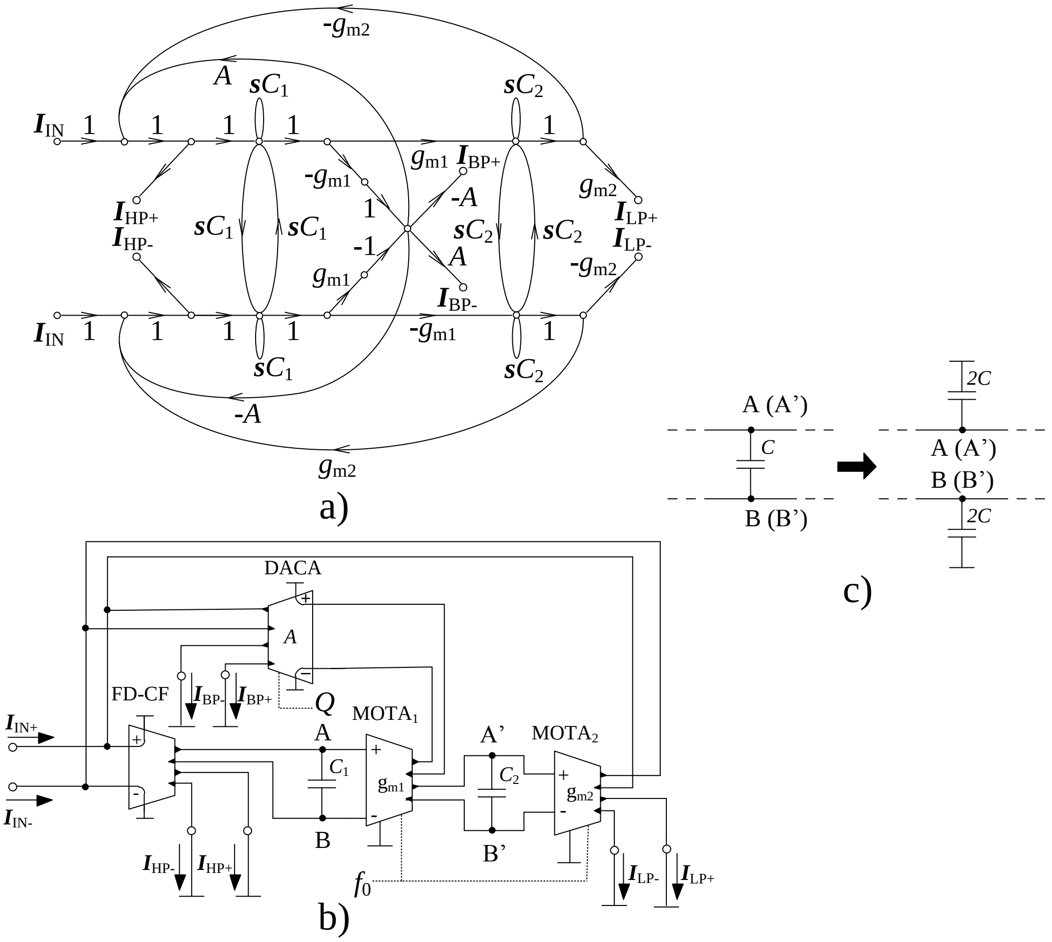

Figure 6.2 Fully-differential form of the filter with two OTAs, one DACA and one CF: a) simplified M-C graph, b) circuit structure, c) implementation of non-floating capacitors

The values of passive elements and specific filter parameters were set as follows: the starting pole frequency equals 500 kHz, the starting quality factor Q = 0.707 (Butterworth approximation), values of conductances g_{m1}, g_{m2} were set to 1 mS, the starting current gain of DACA element has been chosen A = 1. Only values of capacitors C_1 and C_2 remain to be determined. These values were calculated as follows: $C_1 = (g_{m1}QA)/(2\pi f_0) = 225$ pF, $C_2 = g_{m2}/(2\pi f_0 AQ) = 450$ pF. Hence, for the simulations and experimental measurement $C_1 = 220$ pF and $C_2 = 440$ pF have been used. The alternative circuit solution of the DACA element has been used. Therefore, the values used to control the quality factor of the S-E and F-D filter are solely demonstrational and do not necessary correspond with values which can be obtained using a real element of the DACA amplifier. The reason why the alternative solution of the DACA element is used instead of the DACA chip is that in case of the F-D we need 4 outputs otherwise it would not be possible to obtain the band-pass transfer function. It would be possible to use a current follower in order to copy and multiply the output signal of the DACA element, but that would increase the number of active elements on the PCB. Another advantage is that the quality factor of the filters can be controlled continuously instead of being limited by discrete steps.

A comparison of the experimental measurement of low-pass, band-pass, high-pass and band-stop transfer functions of the S-E and F-D filter are shown in Figure 6.3. From the graph can be seen that the F-D transfer functions have slightly higher attenuation than in case of the S-E functions, which is mainly given by that the values of conductances used in F-D structures must be twice the values used in case of S-E structures in order to obtain the same pole frequency for both filters.

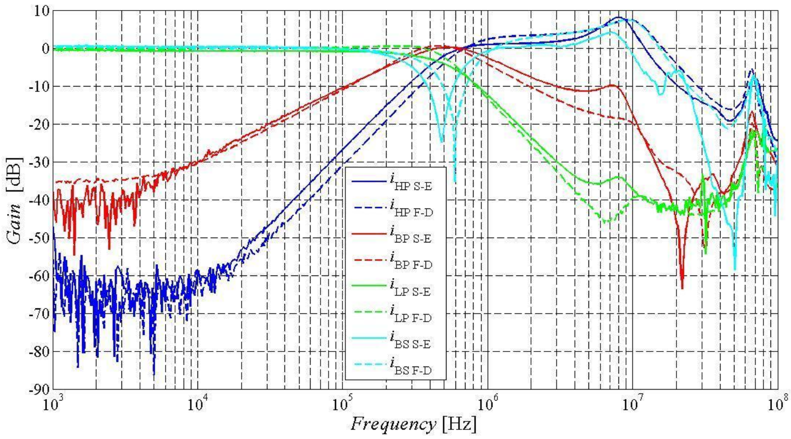

Figure 6.3 Comparison of transfer functions high-pass, band-pass, low-pass and band-stop of experimental results: the S-E filter from Fig. 6.1 (solid lines) and the F-D filter from Fig. 6.2 (dashed lines)

Figure 6.4 compares the experimental results of the ability to control the pole frequency of the S-E and F-D filter without disturbing the quality factor by changing values of transconductances g_{m1}, g_{m2}. Obtained values of measured pole frequencies can be compared in Table I. The values of transconductances used in the S-E filter (before the slash) and the F-D filter (after the slash) are given in the table. The pole frequencies of the F-D filter are at lower frequencies closer to calculated values than values obtained from the S-E filter. The slopes of attenuation are greater in case of the F-D filter.

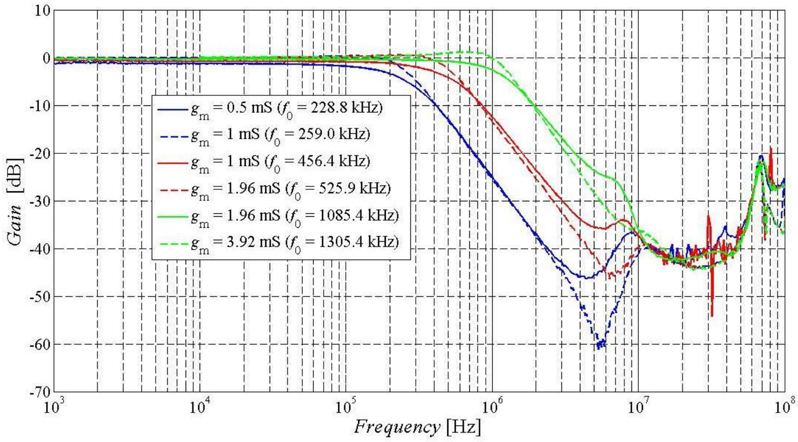

Figure 6.4 Comparison of possibility to control the pole frequency when comparing experimental results: S-E filter from Fig. 6.1 (solid lines), F-D filter from Fig. 6.2 (dashed lines)

Table I Comparison of obtained values of the pole frequency

	$g_{m1,2}$ S-E/$g_{m1,2}$ F-D [mS]		
Frequency [kHz]	0.5/1	1/1.96	1.96/3.92
Calculated	255.8	511.5	1003.0
Measured S-E	228.8	456.4	1085.4
Measured F-D	259.0	525.9	1305.4

The experimental results showing the ability to control the quality factor of the S-E and F-D filter without disturbing the pole frequency by changing the value of the current gain A are illustrated in Figure 6.5. Table II provides a comparison of measured quality factors obtained from the S-E and F-D filter. The values of the quality factor obtained from the S-E are closer to the theoretical values. The values obtained from the F-D filter are significantly higher than the calculated values. Also the pole frequency of the F-D is slightly shifting for higher values of the quality factor.

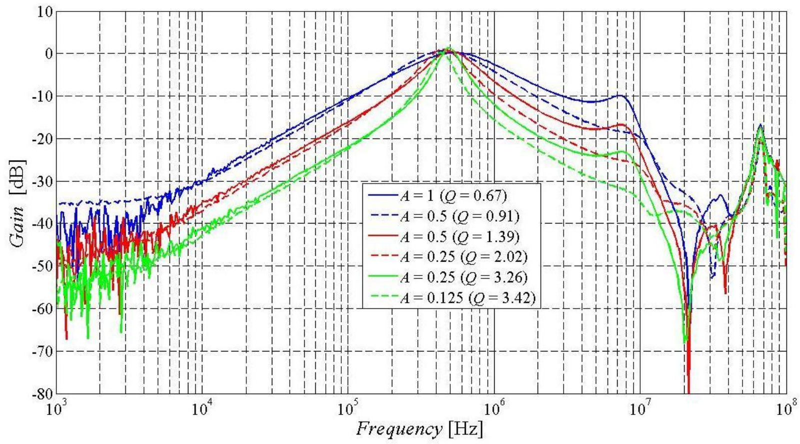

Figure 6.5 Comparison of possibility to adjust the quality factor when comparing experimental results: S-E filter from Fig. 6.1 (solid lines), F-D filter from Fig. 6.2 (dashed lines)

Table III Comparison of obtained values of the quality factors

	A S-E/*A* F-D [-]		
Q [-]	0.25/0.125	0.5/0.25	1/0.5
Calculated	2.83	1.41	0.71
Measured S-E	3.26	1.39	0.67
Measured F-D	3.42	2.02	0.91

Other proposed filter from this chapter can be found in [68-71] for instance.

7 PROPOSAL OF FRACTIONAL-ORDER FILTERS

The proposed filters in this chapter were simulated using the transistor-level simulation models. Simulation models of all used active elements are implemented with 0.18 µm CMOS technology and the supply voltage for all these models is ±1 V.

7.1 (1+*A*)-ORDER LOW-PASS FILTER WITH THREE OTAS TWO ACAS AND ONE CF

The proposal is focused on the design of a S-E and F-D (1+α)-order low-pass filter with Butterworth characteristics which employs three OTAs two ACAs and one CF. I present this research in [72]. The proposed filter is based on Inverse Follow-the-Leader Feedback topology.

The transfer function of a (1+α)-order low-pass Butterworth filter is given as [50]:

$$K_{1+a}^{LP}(\boldsymbol{s}) = \frac{k_1}{\boldsymbol{s}^a(\boldsymbol{s}+k_2)+k_3}, \tag{7.1}$$

where $k_1 = 1,\ k_2 = 1.0683\alpha^2 + 0.161\alpha + 0.3324,\ k_3 = 0.2937\alpha + 0.71216.$

Coefficients k_1, k_2 and k_3 are used in order to shape the pass band region while keeping the desired fractional-order slope of attenuation of the stop band region [50].

Using the second-order approximation of fractional Laplacian operator, a (1+α)-order low-pass transfer function turns into [50]:

$$K_{1+a}^{LP}(\boldsymbol{s}) \cong \frac{k_1}{a_0}\frac{a_2\boldsymbol{s}^2 + a_1\boldsymbol{s} + a_0}{\boldsymbol{s}^3 + b_2\boldsymbol{s}^2 + b_1\boldsymbol{s} + b_0}, \tag{7.2}$$

where $a_0 = \alpha^2 + 3\alpha + 2$, $a_1 = 8 - 2\alpha^2$, $a_2 = \alpha^2 - 3\alpha + 2$, and $b_0 = \dfrac{a_0k_3 + a_2k_2}{a_0}$, $b_1 = \dfrac{a_1(k_2+k_3)+a_2}{a_0}$, $b_2 = \dfrac{a_1 + a_0k_2 + a_2k_3}{a_0}$.

Using the transfer function given in (7.2), it is possible to create a block diagram of a fractional-order low-pass filter.A possible block diagram of a (1+α)-order low-pass filter based on IFLF topology is illustrated in Figure 7.1.

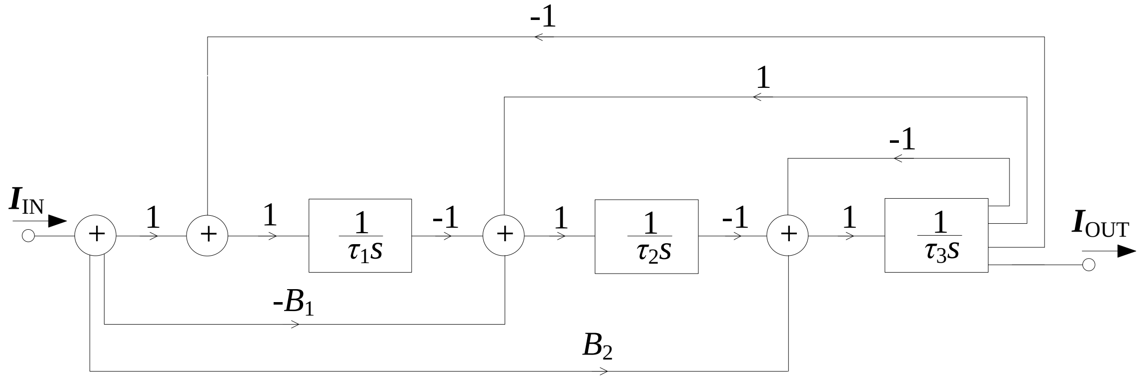

Figure 7.1 Block diagram of the third-order IFLF topology filter leading to (1 + α)-order low-pass filter

The transfer function of this block diagram is given as:

$$K(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN}} = \frac{\frac{B_2}{\tau_3}\boldsymbol{s}^2 + \frac{B_1}{\tau_2\tau_3}\boldsymbol{s} + \frac{1}{\tau_1\tau_2\tau_3}}{\boldsymbol{s}^3 + \frac{1}{\tau_3}\boldsymbol{s}^2 + \frac{1}{\tau_2\tau_3}\boldsymbol{s} + \frac{1}{\tau_1\tau_2\tau_3}}. \tag{7.3}$$

The values of B and τ parameters can be determined when comparing particular terms of equations (7.2) and (7.3). Figure 7.2 shows the circuit structure of the S-E fractional (1+α)-order low-pass filter which is based on the block diagram from Figure 7.1. It consists of two OTAs, two ACAs, one MOTA and one MO-CF.

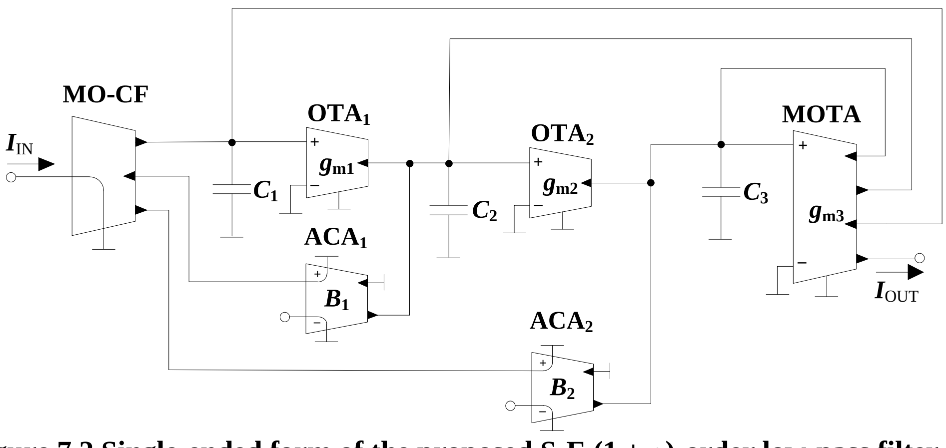

Figure 7.2 Single-ended form of the proposed S-E (1 + α)-order low-pass filter

The transfer function of the proposed S-E and F-D filter is given by the following relation:

$$K(s) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN}} = \frac{N(\boldsymbol{s})}{D(\boldsymbol{s})}, \tag{7.4}$$

where

$$\begin{aligned} N(\boldsymbol{s}) &= C_1 C_2 g_{m3} B_2 \boldsymbol{s}^2 + C_1 g_{m2} g_{m3} B_1 \boldsymbol{s} + g_{m1} g_{m2} g_{m3}, \\ D(\boldsymbol{s}) &= C_1 C_2 C_3 \boldsymbol{s}^3 + C_1 C_2 g_{m3} \boldsymbol{s}^2 + C_1 g_{m2} g_{m3} \boldsymbol{s} + g_{m1} g_{m2} g_{m3} n_{31}. \end{aligned} \tag{7.5}$$

The F-D form of the proposed (1 + α)-order low-pass filter is presented in Figure 7.3. The F-D filter was created from the S-E filter by mirroring of passive parts. The values of current gains B of the F-D filter must be half of the values used for the S-E filter. The F-D filter is proposed with grounded capacitors instead of floating ones. These capacitors must have twice the value of capacitors of the S-E filter.

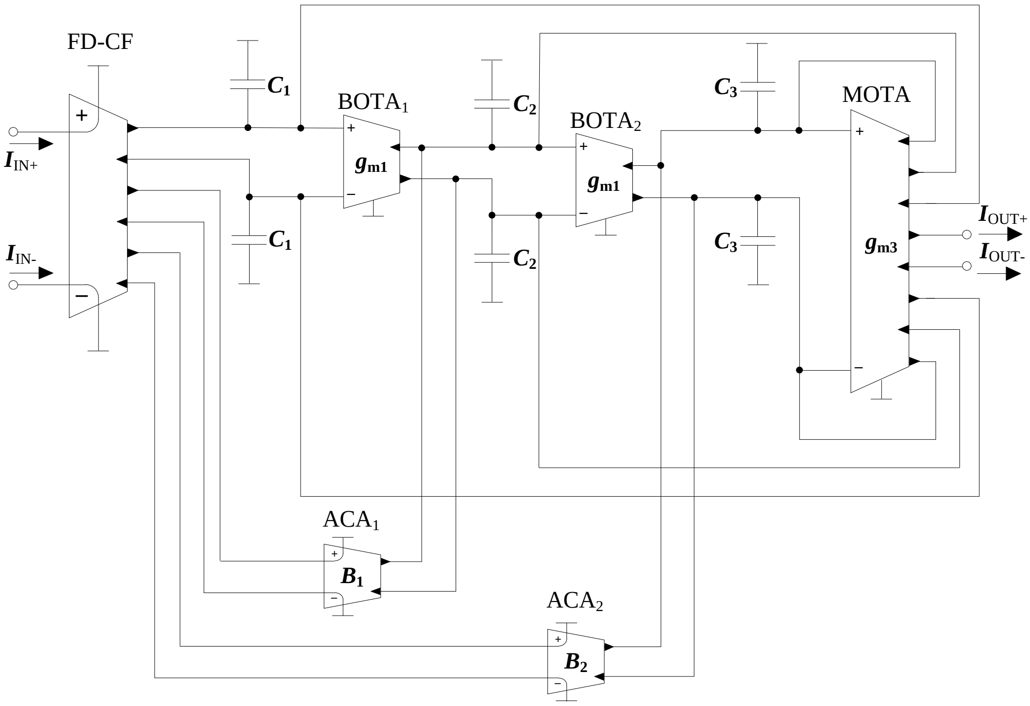

Figure 7.3 Fully-differential form of the proposed (1 + α)-order low-pass filter

The values of passive and active elements were selected accordingly: capacitors C_1 = 820 pF, C_2 = C_3 = 560 pF, the starting pole frequency is equal to 100 kHz, starting value of the filter order is 1.5 (α = 0.5), transconductances g_{m1} = 146 µS, g_{m2} = 376 µS, g_{m3} = 934 µS and current gains B_1 = 0.6 and B_2 = 0.068. The proposed S-E and F-D filter possesses ability to electronically control the order of the filter by changing values of transconductances g_{m1}, g_{m2}, g_{m3} and transfers B_1 and B_2. This ability was simulated for five values of parameter α (0.1, 0.3, 0.5, 0.7, 0.9). Calculated values of passive and active elements for chosen values of parameter α are given in Table III.

Table IIIII Used values of passive and active elements for selected values of parameter *α*

α [-]	0.1	0.3	0.5	0.7	0.9
C_1 [pF]	820				
$C_2 = C_3$ [pF]	560				
g_{m1} [µS]	112	133	147	174	210
g_{m2} [µS]	340	370	370	417	417
g_{m3} [µS]	1499	1181	909	909	954
B_1 [-]	0.76	0.7	0.61	0.515	0.428
B_2 [-]	0.17	0.117	0.07	0.033	0.008

Figure 7.4 shows a comparison of the simulation results of the S-E and F-D filter when changing its order. The values of passive and active elements used for the simulations are summarized in Table III. The obtained slopes of attenuation of the transfer function of the S-E and F-D filter for selected values of parameter α can be compared in Table IV. The values of the slope of attenuation of the F-D filter are closer to the theoretical values.

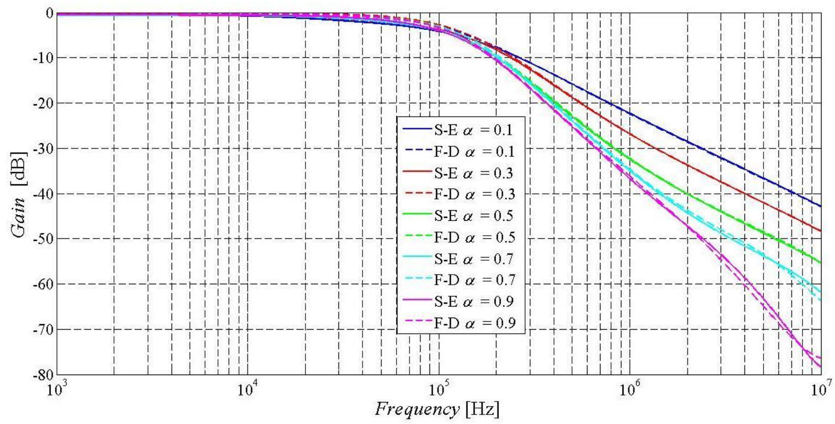

Figure 7.4 Comparison of simulated transfer functions of the S-E filter from Fig. 7.2 (solid lines) and the F-D filter from Fig. 7.3 (dashed lines) when *α* was set to 0.1, 0.3, 0.5, 0.7 and 0.9

Table IVV Comparison of obtained slopes of attenuation

α [-]	0.1	0.3	0.5	0.7	0.9
Theoretical slope of attenuation [dB/dec]	22.0	26.0	30.0	34.0	38.0
Simulated slope of attenuation S-E [dB/dec]	20.8	25.5	30.2	34.5	36.6
Simulated slope of attenuation F-D [dB/dec]	21.2	26.0	30.6	34.4	37.0

A comparison of the simulation results of the S-E and F-D filter when changing the pole frequency can be seen in Figure 7.5. The values of the pole frequency selected for the illustration are 50 kHz, 75 kHz, 100 kHz, 150 kHz and 200 kHz when the order of the filter is fixed to 1.5 (α = 0.5). The used values of passive and active elements are stated in Table V. Obtained values of the pole frequency are compared in Table VI. The obtained pole frequencies of the F-D filter are closer to the theoretical values. The values of the pole frequency of the F-D filter are slightly above the theoretical values when the values of the S-E filter are lower. This fact is being more evident with increasing frequency.

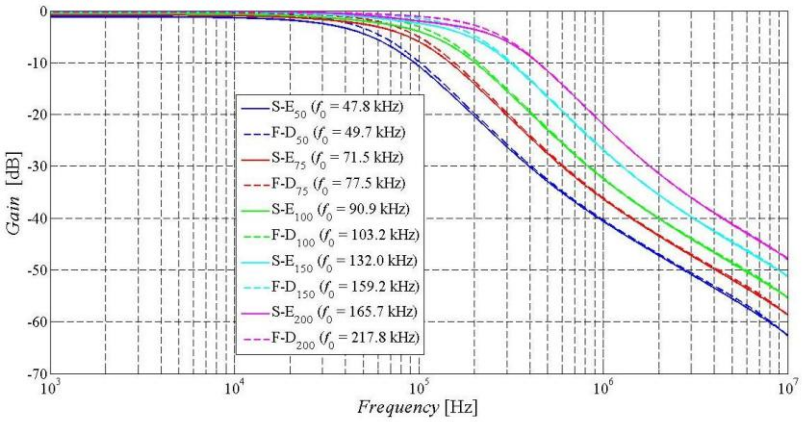

Figure 7.5 Comparison of ability to control the pole frequency of the S-E filter from Fig. 7.2 (solid lines) and the F-D filter from Fig. 7.3 (dashed lines)

Table V Used values of passive and active elements for selected values of f_0

f_0 [kHz]	50	75	100	150	200
C_1 [pF]			820		
$C_2 = C_3$ [pF]			560		
g_{m1} [µS]	74	110	147	220	294
g_{m2} [µS]	182	278	370	556	769
g_{m3} [µS]	465	667	909	1333	1818
B_1 [-]			0.61		
B_2 [-]			0.07		

Table VI Comparison of obtained pole frequencies

f_0 [kHz]	50	75	100	150	200
Simulated pole frequency S-E [kHz]	47.8	71.5	90.9	132.0	165.7
Simulated pole frequency F-D [kHz]	49.7	77.5	103.2	159.2	217.8

Other proposal of a fractional-order filter from this chapter can be found in [73].

8 CONCLUSION

The thesis was mainly aimed at the proposal of fully-differential frequency filters working in the current mode and employing non-standard active elements. Great emphasis was paid to a comparison of the F-D structures and their corresponding S-

E forms. The work was divided into three main parts namely the proposal of new second-order current-mode filtering structures especially fully-differential ones, the proposal of fractional-order frequency filters in both single-ended and fully-differential forms and finally a modification of the transformation of horizontal structures design method with respect to the specific needs and characteristics of differential structures. The design correctness and functionality of the proposed filters are verified by SNAP program, PSpice simulations and in some cases also by experimental measurement.

Chapter 6 contains eight proposed second-order current-mode filtering structures in their S-E and also F-D form. In principle, all proposed filters are SIMO type filters which can provide all (or at least more than one) transfer functions without a necessity to change the circuit structure or position of the input current. From the graphs it is obvious that the transfer functions of the differential filters have slightly higher slope of attenuation than in case of single-ended filters. This is mainly due to the fact that the F-D filters are using resistors of half values than the S-E filters. From the measurement results of the possibility to control the pole frequency and quality factor of the S-E and F-D filter is possible to observe that the obtained pole frequencies of the F-D filters are usually closer to the theoretical values than in case of the S-E filters. Furthermore, the quality factors of F-D transfer functions are higher than the quality factors of S-E transfer function which are closer to the theoretical values.

Chapter 7 presents the proposal of two fractional order filters. One in its F-D and the second one in its S-E and F-D form. The first proposed filter is based on current followers and the second one on operational transconductance amplifiers. The proposal of the F-D structures is made the same way as in chapter 6. The possibility to propose these filters in their F-D form has been proved and the proposed F-D structures provide better properties as shown in case of controllability of the order and pole frequency of the filters when both slope of attenuation for individual values of parameter α and pole frequency of the F-D filter are closer to the theoretical values.

Finally chapter 8 presents the modified horizontal structures transformation method which was adjusted with respect to the specific needs and characteristics of differential structures. The modified method is intended for filtering structures using current followers. Its practical applicability was tested on ten simulated filters and six implemented filters and then compared with results obtained from the corresponding F-D structures created using the original horizontal structures transformation method and the corresponding S-E forms of these filters.

The research described in this work was adequately presented to the scientific community, as an author or coauthor I have published: 4 papers in impact factor journals, 4 papers in proceedings of international conferences, 1 paper in international non-impact journal, 7 papers in national non-impact journals and 6 papers in proceedings of national conferences. Furthermore, I'm an author of 2 pedagogical texts.

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Curriculum Vitae

Lukáš Langhammer

OSOBNÍ INFORMACE

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VZDĚLÁNÍ

2012 - 2016: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií

- Doktorské studium - obor Teleinformatika

2010 - 2012: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií

- Navazující magisterské studium - obor Telekomunikační a informační technika

2007 - 2010: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií

- Bakalářské studium - obor Teleinformatika

2003 - 2007: ISŠ - COP Olomoucká

- střední vzdělání s maturitou - obor mechanik elektrotechnik (26-41-L/01)

PEDAGOGICKÁ PRAXE

- výuka laboratorních cvičení kurzu Komunikační technologie a Pokročilé komunikační techniky na ústavu teleinformatiky

- vedení 6 diplomových a 4 bakalářských prací

ÚČAST NA PROJEKTECH

Projekty podporované Grantovou Agenturou České Republiky:

- GA16-06175S Syntéza a analýza systémů fraktálního řádu využívající netradiční aktivní prvky
- GA102/09/1681 Počítačové automatizování metod syntézy lineárních funkčních bloků a výzkum nových aktivních prvků

Projekty Ministerstva školství, mládeže a tělovýchovy

- LO1401 Interdisciplinární výzkum bezdrátových technologií (INWITE)
- ED2.1.00/03.0072 Centrum senzorických, informačních a komunikačních systémů (SIX)

Projekty Evropské Unie

- CZ.1.07/2.2.00/28.0096 Příprava specialistů pro telekomunikace a informatiku - magisterské studium telekomunikační a informační technika
- CZ.1.07/2.2.00/28.0193 Komplexní inovace studijních programů a zvyšování kvality výuky na FEKT VUT v Brně
- CZ.1.07/2.2.00/28.0062 Společné aktivity VUT a VŠB - TUO při vytváření obsahu a náplně odborných akreditovaných kurzů ICT

Projekty Vysokého učení technického v Brně

- FEKT-S-14-2352 Výzkum elektronických komunikačních a informačních systémů
- FEKT-S-11-15 Výzkum elektronických komunikačních systémů

PUBLIKACE

Celkový počet publikací: 24

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ABSTRACT

This doctoral thesis focuses on research in the field of frequency filters. The main goal is to propose and analyze fully-differential current-mode frequency filters employing modern active elements. Presented filters are proposed using current followers, operational transconductance amplifiers, digitally adjustable current amplifiers and transresistance amplifiers. The proposal is focusing on ability to control some of the typical filter parameter or parameters using controllable active elements suitably placed in the circuit structure. Individual presented filters are proposed in their single-ended and fully-differential forms. Great emphasis is paid to a comparison of the fully-differential structures and their corresponding single-ended forms. The functionality of each proposal is verified by simulations and in some cases also by experimental measurements.

ABSTRAKT

Tato disertační práce se zaměřuje na výzkum v oblasti frekvenčních filtrů. Hlavním cílem je navrhnout a analyzovat plně diferenční kmitočtové filtry pracující v proudovém módu a využívající moderní aktivní prvky. Prezentované filtry jsou navrženy za použití proudových sledovačů, operačních transkonduktančních zesilovačů, plně diferenčních proudových zesilovačů a transrezistančních zesilovačů. Návrh se zaměřuje na možnost řídit některý z typických parametrů filtru pomocí řiditelných aktivních prvků, které jsou vhodně umístněny do obvodové struktury. Jednotlivé prezentované filtry jsou navrženy v nediferenční a diferenční verzi. Velký důraz je věnován srovnání plně diferenčních struktur s jejich odpovídajícími nediferenčními formami. Funkčnost jednotlivých návrhů je ověřena simulacemi a v některých případech i experimentálním měřením.