Filters with Multi-Loop Feedback Structure in Current Mode

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Abstract. *Universal multifunctional (low-pass, high-pass, band-pass, band-reject and all-pass) n^{th}-order active RC filters in current mode are presented in this paper. The filters are based on several multi-loop feedback and state-variable structures. Their modification and implementation using multi-output transconductors (OTA) and current followers are given.*

Keywords

Analogue circuits, filters, current mode, state-variable based structures.

1. Introduction

Continuous-time active filters in current mode have found applications in many areas audio, video and communication systems. New active devices and functional blocks are there used, such as transadmittance amplifiers (OTA), current conveyors, current amplifiers and followers (CF) etc. Many novel filter structures have been proposed and or classical filters based on the opamps have been modified. In recent years the OTA-C filters have received particular interest by Sun, Y., Fidler J. K., Acar, C., Anday, F., Kuntman, H. and others [1], [7], [8], [9].

Current mode (CM) is known [3], which is inherent in simplicity implementing such operations as addition (current summation), subtraction, integration and multiplication by constant. There can be also used simple current replicas (current distribution) and multiple outputs independent of other loading. It is well known, that these circuits can operate at much higher frequencies than the techniques in standard voltage mode with the opamp's.

Classical state variable model (using signal flow graph) of the universal multifunctional (low-pass, high-pass, band-pass, band-reject and all-pass) n^{th}-order filter in standard voltage mode is there modified and transformed to the CM and non-conventionally realized. These filters have an advantage over the cascade and ladder structures, namely in universality of function, simplicity in direct design and independently adjustable coefficients.

2. Canonical State-Variable Multi-Loop Structures in Current Mode

The current transfer function of any n^{th}-order filter can be generally expressed as

$$K = \frac{I_{out}}{I_{inp}} = \frac{a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}{s^n + b_{n-1} s^{n-1} + \ldots + b_1 s + b_0} \quad . \tag{1}$$

State-variable multi-loop structure (MLS) corresponding with the formula (1) in classical voltage mode (VM) is well-known [1], [2]. Usually as an acceptable model of the MLS the signal flow graph (SFG) is used [1]. These VM-SFG can be transformed to the CM using the adjoint VM $\rightarrow$ CM transformation from [3] to obtain the desired current SFG. Four CM-SFG's of the basic canonical MLS's in CM are shown in Fig. 1. There are namely the follow the leader feedback (FLF) structure (Fig. 1a, Fig. 1c) and the inverse follow the leader feedback (IFLF) structure (Fig. 1b, Fig. 1d), with the output summation (OS) (Fig. 1a, Fig. 1b) and with the input distribution (ID) (Fig. 1c, Fig. 1d). All these MLS's from Fig. 1 can be directly implemented using current integrators, current amplifiers (multipliers by constant), current summers and current distributors, what is a little complicated and it is the reason of following modification.

3. Modification of Multi-Loop Structures

MLS structures given in Fig. 1 can be ingeniously modified for the real universal multifunctional n^{th}-order filter as follows. Firstly the denominator of the transfer function (1) keeps the form, but the numerator has a simpler and concrete design with the following coefficients only

$$a_i = \left\langle \begin{matrix} +b_i \\ -b_i \\ 0 \end{matrix} \right. \quad \text{for} \quad i = 0, 1, \ldots n-1, \qquad a_i = \left\langle \begin{matrix} \pm a \\ \pm 1 \\ 0 \end{matrix} \right. \quad \text{for} \quad i = n, \tag{2}$$

what depends on the desired type of this filter. Note that a in (2) is a real number.

For the **low-pass** (LP) filter:

$$a_0 = \pm b_0 \,, \qquad a_1 = a_2 = \ldots = a_n = 0 \,. \tag{3}$$

For the **high-pass** (HP) filter:

$$a_n = \left\langle \begin{array}{c} \pm 1 \\ \pm a \end{array} \right. , \qquad a_i = 0, \qquad i = 0, 1, \ldots n-1 \,. \tag{4}$$

For the **band-pass** (BP) filter if the order n is even:

$$\begin{aligned} & a_i = b_i, \quad \text{for} \quad i = \frac{n}{2}, \\ & a_i = 0, \quad \text{for other} \quad i = 0, 1, \ldots (\frac{n}{2}-1), (\frac{n}{2}+1), \ldots n \,. \end{aligned} \tag{5}$$

For the **band-reject** (BR) filter if the order n is even:

$$\begin{aligned} & a_i = 0, \quad \text{for} \quad i = \frac{n}{2}, \\ & a_i = b_i \quad \text{for other} \quad i = 0, 1, \ldots (\frac{n}{2}-1), (\frac{n}{2}+1), \ldots n \,. \end{aligned} \tag{6}$$

For the **all-pass** filter (APF):

$$\begin{aligned} & a_i = +b_i, \quad \text{for} \quad i = 0,2,4, \ldots n \quad \text{even}, \\ & a_i = -b_i, \quad \text{for} \quad i = 1,3,5, \ldots n \quad \text{odd} \,. \end{aligned} \tag{7}$$

Taking the condition above the SFG from Fig. 1c is transformed in the form shown in Fig. 2, where B_i has the value B_i = -1, 0, +1, what depends on the type of desired filter. Note that the other SFG's from Fig. 1 can be similarly modified. Then resulting circuits have simpler realizations as shown below.

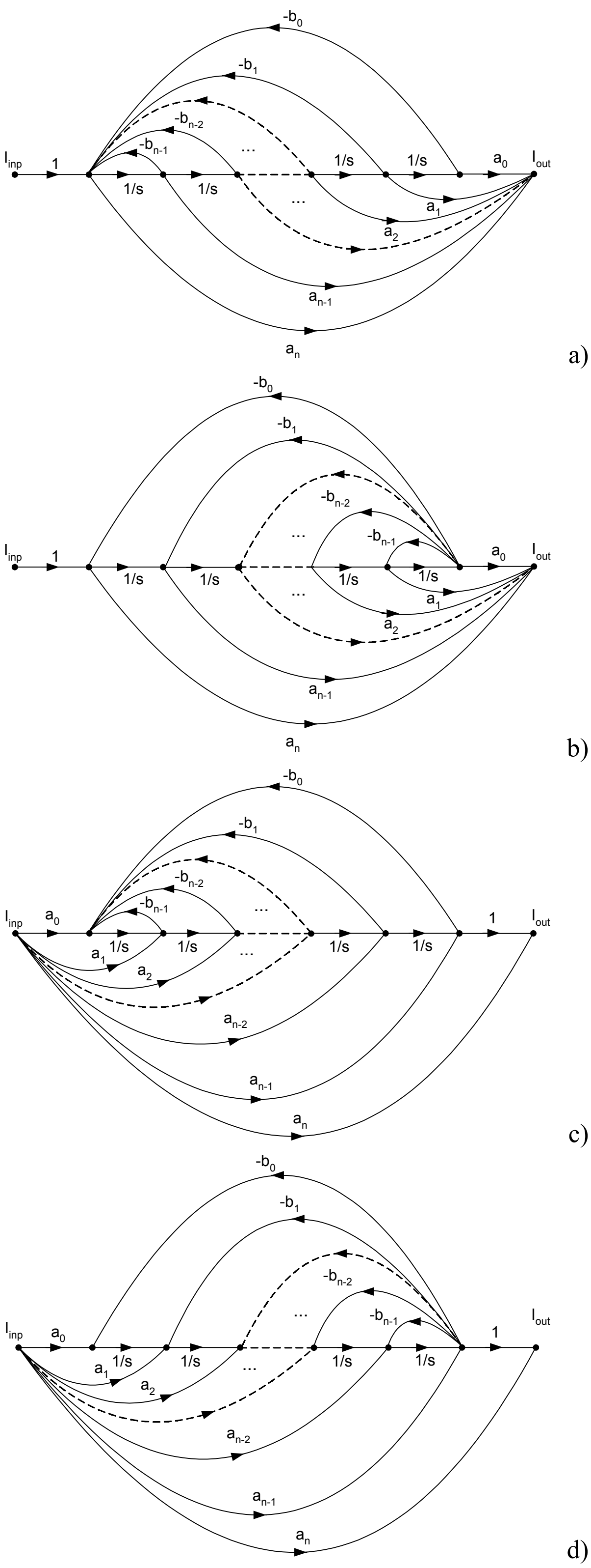

Fig. 1. Basic signal flow graphs of the state-variable multi-loop canonical structures in current mode. Follow the leader feedback (a, c), inverse follow the leader feedback (b, d), with output summation (a, b) and input distribution (c, d).

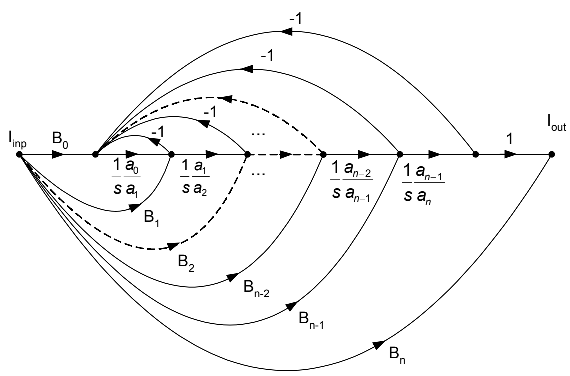

Fig. 2. Modification of the signal flow graph (Fig. 1c) of the multi-loop structure FLF-ID (Follow the leader feedback, with input distribution).

4. Circuit Realizations of the Universal n^{th}-order Filter

Circuit realization of the modified SFG from Fig. 2 requires the following types of basic building blocks:

- Current summer,
- Current distributor,
- Current integrator.

The **summer** of the currents

$$I_{out} = \sum_{i}^{n} I_{inp} \quad , \tag{8}$$

can be realized very easily by the single node only.

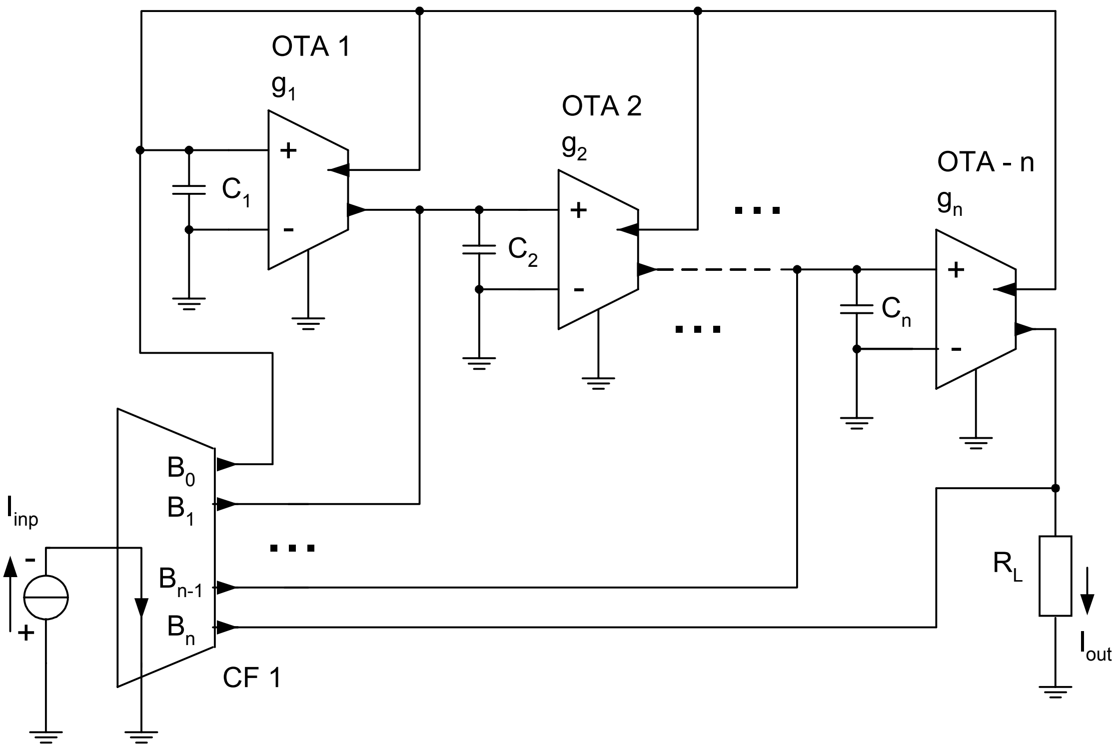

Fig. 3. Circuit diagram of the current mode n^{th}-order universal filter based on the follow the leader feedback multi-loop structure with input distribution (FLF-ID), corresponding with the signal flow graph given in Fig.2 (Fig. 1c).

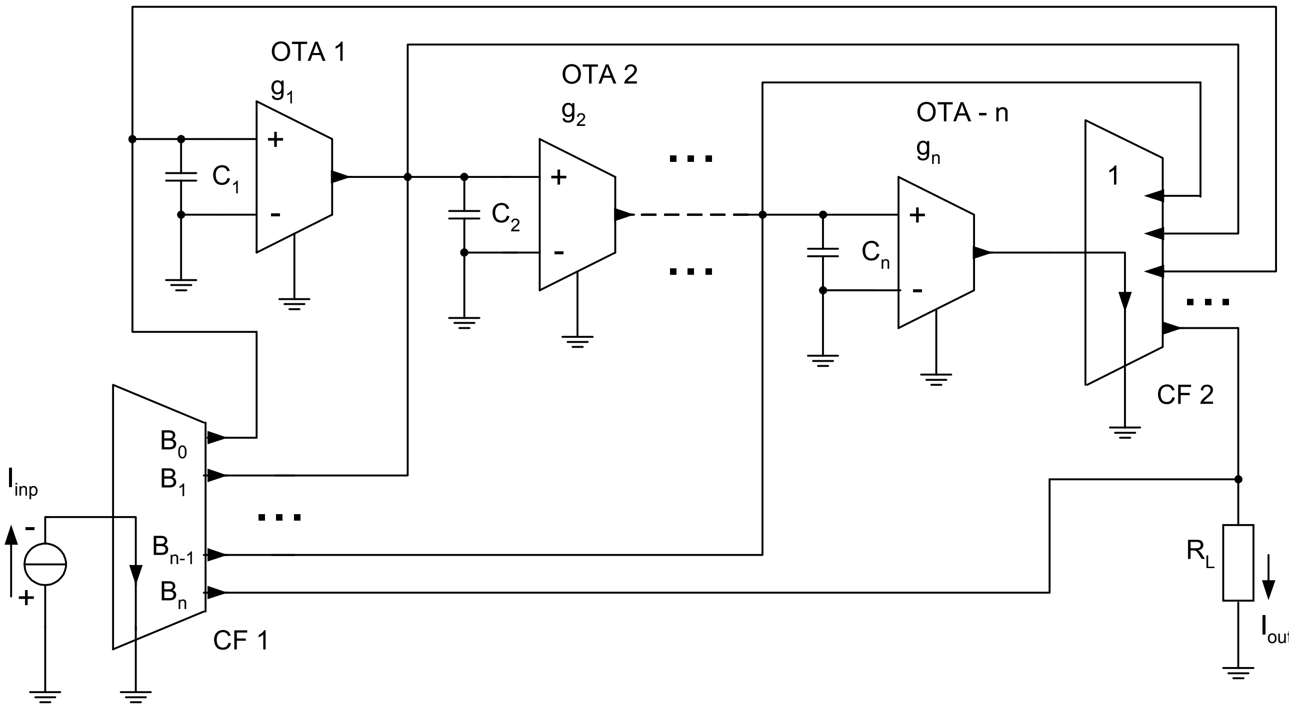

Fig. 4. Circuit diagram of the current mode n^{th}-order universal filter based on the inverse follow the leader feedback multi-loop structure with input distribution (IFLF-ID, Fig. 1d)

The **current integrator** with the transfer function

$$K_i = \frac{I_{out}}{I_{inp}} = \frac{1}{s}\frac{a_n}{a_{n+1}} \quad , \tag{9}$$

can be implemented by single-input double-output (SIDO) transconductor (OTA) and capacitor (OTA-C). There (Fig. 3) are two current replicas with opposite phase required at the output of integrators in the case of the FLF-ID (Fig. 2). Noting that, for the structure FLF-OS three current replicas are needful, as shown below (Fig. 5).

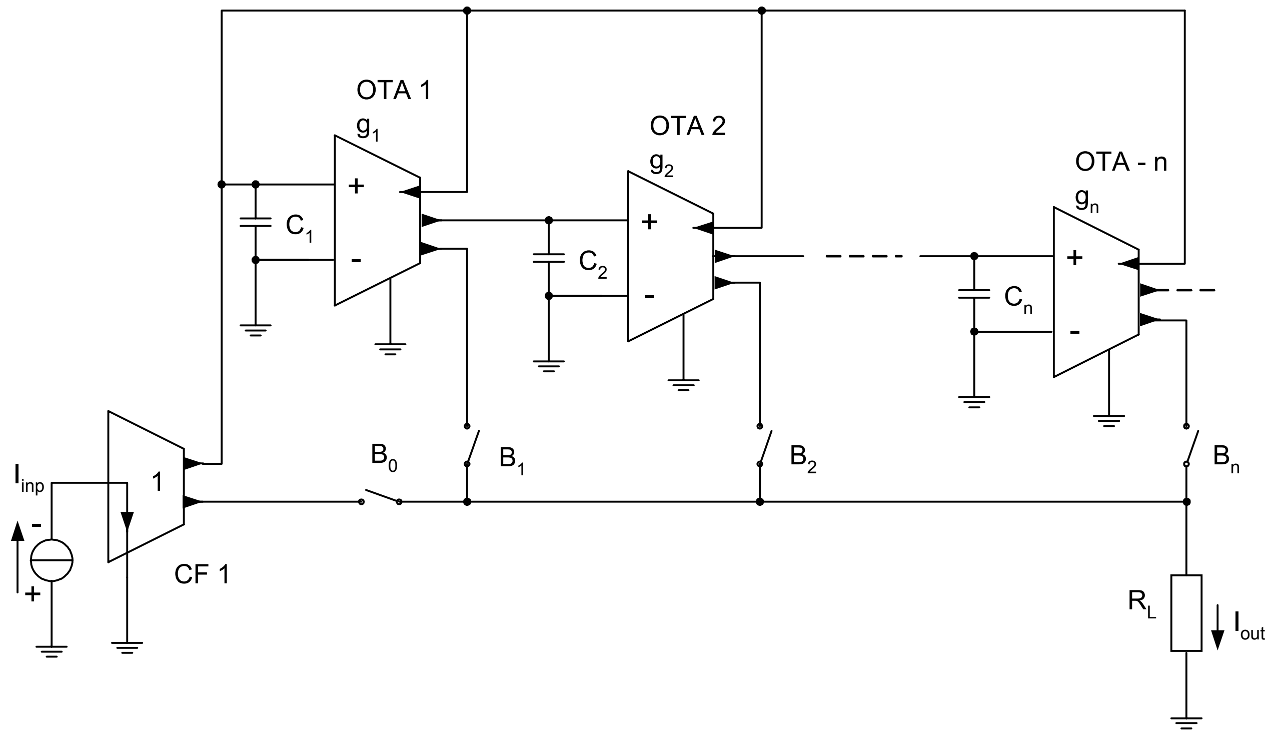

Fig. 5. Circuit diagram of the current mode n^{th}-order universal filter based on the follow the leader feedback multi-loop structure with output summation (FLF-OS, Fig. 1a).

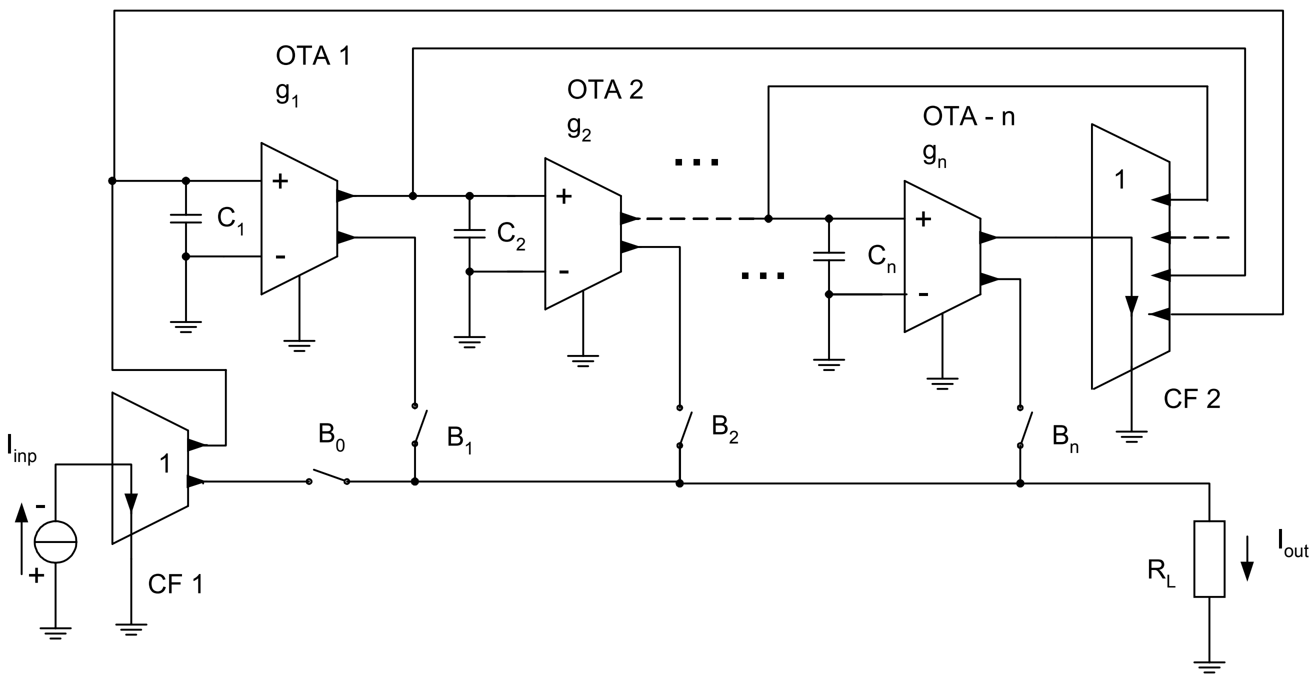

Fig. 6. Circuit diagram of the current mode n^{th}-order universal filter based on the inverse follow the leader feedback multi-loop structure with output summation (IFLF-OS, Fig. 1b).

The **current distributor** (first node of the SFG in Fig. 2) is realized by the single-input multi-output (SIMO) current follower (CF 1 in Fig. 3). The CF1 is producing (n+1) current replicas of the input current, to obtain the designed type of the filter. The resulting circuit diagram of the structure FLF-ID (the SFG in Fig. 1c and after modification in Fig. 2) is shown in Fig. 3.

Similarly the structure IFLF-ID (the SFG in Fig. 1d) can be realized using the same way, to obtain the circuit diagram of the n^{th}-order universal filter in Fig. 4. There are simpler OTA's, namely the SISO type (instead of the SIDO in Fig. 3), but two current followers are needed (CF 1 and CF 2 in Fig. 4).

Modification	Transfer function	Type of filter	Parameters of CF 1			
			B_0	B_1	B_2	B_3
1.	$K=-\frac{a_3 s^3+a_2 s^2+a_1 s+a_0}{s^3+a_2 s^2+a_1 s+a_0}$	General 3rd order filter	1	1	1	1
2.	$K=\frac{-a_0}{s^3+a_2 s^2+a_1 s+a_0}$	Low-pass	1	0	0	0
3.	$K=\frac{-a_3 s^3}{s^3+a_2 s^2+a_1 s+a_0}$	High-pass	0	0	0	1
4.	$K=\frac{-a_1 s}{s^3+a_2 s^2+a_1 s+a_0}$	Unsymmetrical band-pass BP1	0	1	0	0
5.	$K=\frac{-a_2 s^2}{s^3+a_2 s^2+a_1 s+a_0}$	Unsymmetrical band-pass BP2	0	0	1	0
6.	$K=-\frac{a_3 s^3+a_2 s^2+a_0}{s^3+a_2 s^2+a_1 s+a_0}$	Unsymmetrical band-reject BR1	1	0	1	1
7.	$K=-\frac{a_3 s^3+a_1 s+a_0}{s^3+a_2 s^2+a_1 s+a_0}$	Unsymmetrical band-reject BR2	1	1	0	1
8.	$K=-\frac{s^3-a_2 s^2+a_1 s-a_0}{s^3+a_2 s^2+a_1 s+a_0}$	All-pass	1	-1	1	-1

Tab. 1. Modifications of the given universal 3rd-order filter (Fig. 4).

The resulting circuit diagram of the n^{th}-order universal filter based on the structure FLF-OS (Fig. 1a) is shown in Fig. 5 and on the IFLF-OS (Fig. 1b) is in Fig. 6 respectively. The switches (B_n) determine there a type of designed filter, summing some output currents, what is a dual function of the CF 1 in the structure with input current distribution (Fig. 3 and Fig. 4).

5. Illustrative Example of the Universal 3rd-order Filter

To illustrate the given IFLF-ID structure in CM (Fig. 4), a universal (LP, HP, BP, BR, APF) 3rd-order video filter is designed with the following specification:

- The cut-off and center frequency are $f_c = f_o = 1$ MHz,
- For the pass-band with $K_c = -3$ dB,
- The stop-band frequency is $f_s = 3$ MHz,
- For the minimum $K_s = -35$ dB and
- Butterworth approximation.

In the first step the following coefficients of the desired transfer function (1) are obtained using the filter design computer tool NAFID [5]:

$$a_0 = 2.48640 \cdot 10^{20}\ ,\quad a_1 = 7.90819 \cdot 10^{13}\ ,\quad a_2 = 1.25763 \cdot 10^{7}\ ,\quad a_3 = 1\ . \tag{10}$$

The circuit diagram of this filter given in Fig. 4 consists of three OTA-SISO with parameters g_1, g_2, g_3, three capacitors (C_1, C_2, C_3), and two current followers CF-SIMO with four outputs (CF1, CF2).

This circuit (Fig. 4) has been symbolically analyzed by SNAP [6] to obtained the following denominator

$$D(s) = a_0 + s a_1 + s^2 a_2 + s^3 a_3 = = \frac{g_1 g_2 g_3}{C_1 C_2 C_3} + s\frac{g_2 g_3}{C_2 C_3} + s^2\frac{g_3}{C_3} + s^3\ . \tag{11}$$

The resulting numerators for eight several modifications and the types of the 3rd-order filter are simply given by the configuration and the parameters B_i (1, -1, 0) of the block CF 1 (Fig. 4) as shown in detail in Tab. 1.

Following three design equations are obtained substituting the desired coefficients a_i (10) in the equation (11)

$$a_0 = \frac{g_1 g_2 g_3}{C_1 C_2 C_3} = 2.48640 \cdot 10^{20} ,$$
$$a_1 = \frac{g_2 g_3}{C_2 C_3} = 7.90819 \cdot 10^{13} , \quad (12)$$
$$a_2 = \frac{g_3}{C_3} = 1.25763 \cdot 10^{7} .$$

Then choosing $C_1 = C_2 = C_3 = 100$ pF the resulting values of transconductances are:

$$g_1 = 314\ \mu S ,$$
$$g_2 = 628\ \mu S , \quad (13)$$
$$g_3 = 1.26\ mS .$$

A lot of transconductance amplifiers is commercially available these days. The LT 1228 has been chosen. Using this IC, it is possible to set the value of the transconductances in the following range

$$g_m \in <10\mu\ S,\ 10 mS> , \quad (14)$$

namely by DC current I_{SET}, what gives the possibility to set or tune this filter easily.

The multi-output current followers (CF 1, CF 2) can be realized using the improved Wilson's current mirrors and bipolar transistors, modifying circuit given in [4].

6. Simulation Results

To verify the functionality of the proposed universal filter, the PSpice simulation has been carried out. Resulting magnitude responses for LP, HP and BP modification (Tab.1) of the universal 3rd-order filter (Fig. 4) are shown in Fig. 7. They have confirmed the symbolical analysis and theoretical assumptions.

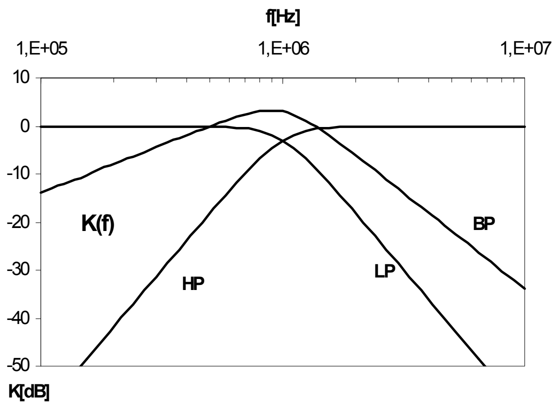

Fig. 2. Magnitude responses of the given 3rd-order filter.

7. Conclusion

The SFG of the universal n^{th}-order filter in standard state variable based voltage form is modified and transformed to the current mode and realized by current OTA-C integrators and multi-output current followers. This filter has advantage in universality of the type or function and simplicity in direct design. Note that similar circuit structures can be obtained using current conveyors instead of the transconductors (OTA) [10].

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Tomáš Dostál was born in Brno, Czech Republic, in 1943. He received the degrees of CSc. (Ph.D) and DrSc. in electrical engineering from Brno University of Technology in 1976 and 1989, respectively. From 1973 to 1978, and from 1980 to 1984, he was with the Military Academy in Brno, from 1978 to 1980 with the Military Technical College in Baghdad. Since 1984 he has been with Brno University of Technology, where he is now Professor of Radio-Electronics. His present interests are in circuit theory, analogue filters, switched capacitor networks and circuits in current mode.