# FUNCTIONAL BLOCKS AND BIQUADRATIC ARC FILTERS USING TRANSIMPEDANCE AMPLIFIERS

Tomáš DOSTÁL, Roman PROKOP,René ŠARMAN
Dept. of Radioelectronics
Faculty of Electrical Engineering
Technical University of Brno
Purkyňova 118, 618 00 Brno
Czech Republic

## Abstract

*The aim of the article are design and analysis of modern circuits including high performance functional blocks and biquadratic filters using transimpedance amplifiers. Here are given various types of these circuits, that works in classical voltage, current or hybrid mode. In this paper are also compared various possibilities of connection of single amplifier filters as for reduction of influence of transimpedance amplifier parasitic elements.*

## Keywords:

transimpedance amplifier, functional block, filter, adjoint transformation, voltage mode, current mode, hybrid mode

## 1. Introduction

A commercially available high-speed monolithic transimpedance operational amplifier (TOA) was originally destined for video-applications, for fast and quality analogue-digital convertors, buffers or high-speed communication circuits. The popularity of transimpedance opamps (technically classified as current-feedback opamps) has increased, as they were found to be able to overcome the limitations that arise with using of conventional operational amplifiers (OAs). The biggest advantage of the TOAs are high gain values and simultaneously large bandwidths against OAs. Owing to their current-mode operation are usual slew rates as high as 2000 V/s. Therefore transimpedance amplifiers are very useful for high-performance applications. We can use these transimpedance opamps for design of high-performance biquadratic filters. Favourable course of the frequency characteristic and particularly the presence of a compensation pin Z (originally meant only for a transimpedance compensation) enables to make the best of the circuit as a building element of functional blocks and high-performance filters.

## 2. Mode types

At first from principle of methodology we would recommend to distinguish more modes in which the given circuit can operate. There can be especially applied basic modes from [3], namely the classical voltage mode (VM) and the adjoint current mode (CM), when all subnetworks operate either with voltage or current signals. However if certain subcircuit (usually an active element) operates in a complementary mode (opposite to other parts), we will talk about hybrid modes, namely the voltage-current mode (V/CM) or the current-voltage mode (C/VM) respectively. Let us recall, that the conventional opamp operates in the VM, while the current conveyor CC II and the transimpedance amplifier in the CM.

It may be useful to outline how the filters in the current and hybrid modes can be reached from already known classical filters, operating in the VM and using the opamps. Assuming ideal case the nullor model of the opamp can be used there. The corresponding CM can be obtained applying the adjoint transformation given in [3] - simply by interchanging the nullator and norator and also reversing the input and output of the network. The current transfer function $H(p) = I_{OUT}/I_I$ of the resulting ideal CM filter is identical to the voltage expression $K(p) = V_{OUT}/V_I$ of the prototype VM, and the given design equations must valid too. Also the both frequency responses have the ideal form . Note once more that in the ideal case the identical modes VM and CM can be obtained, but it is not truth for the real circuits.

A practical CM implementation will be discussed now, namely the nullor model from the ideal CM must be implemented by real active component. One possibility is the classical opamp - to obtain the hybrid mode C/VM. Nevertheless for the full CM, the grounded nullor can be ingeniously implemented by the current conveyor, or by the transimpedance amplifier and or by the current amplifier respectively.

## 3. About transimpedance amplifier

Transimpedance amplifier is equivalent to a second - generation current conveyor with positive transfer (CCII+), which is followed by a voltage buffer. Fig. 1 shows the equivalent circuit for a transimpedance operational amplifier using ideal active elements and including its parasitic impedances. *Rx* is the parasitic input resistance on port X of the CCII+. *Rs* is the output impedance of the voltage follower, and $(R_Y||C_Y)$ is the equivalent impedance of the noninverting input. The noninverting port (Y) exhibits high impedance, whereas the inverting one (X) is characterised by low impedance values (ideally zero). Two complementary current mirrors convey to port Z the current which goes through this inverting input, and so the resulting voltage $V_Z = -(R_Z||C_Z)I$ is transferred to the output by means of the voltage follower. The transfer function $A(s) = (R_Z||C_Z)$ is the transimpedance gain of this device. There in the brackets $(R_Z||C_Z)$ can be the existing parasitic impedances at port Z, also including an internal compensation capacitor $C_c$, which is sometimes added.

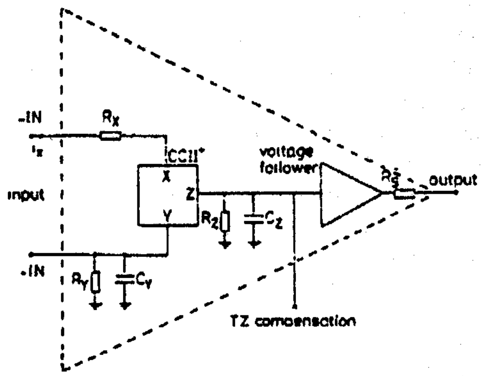



Fig. 1 Equivalent circuit model for a transimpedance opamp, including its parasitic impedances

In some existing TOA, the output Z (Fig. 1) is buried in the integrated circuit. In others, as for example the AD 844 and AD 846 from Analog Devices, output Z constitutes the compensation pin, which gives the circuit much more versatility.

## 4. Function blocks and synthetic elements

### 4.1 Simple implementations

Basic functional blocks in Table 1, serving as a building elements for a realisation of more complex circuit-structures, we can undoubtedly involve the controlled sources. First two of these are namely well known the voltage (Table 1.5) and current amplifiers. Considering the gain A = 1 we can talk about a voltage (Table 1.4) and current (Table 1.1) followers. There are two variants on offer for a realization of the voltage follower. The first considered as input pin Y and as output pin X. At the second variant we can directly take advantage of the inner structure of the transimpedacne operational amplifier integrated voltage follower. There we consider pin Z as input and pin O as output.

Other two controlled sources represent combined types, voltage controlled current source (Table 1.2) and current controlled voltage source (Table 1.3). We call them also voltage-current and current-voltage convertor. These four basic types can help for a building of various imitance convertors or invertors utilized by synthesis of concrete circuit-structures like a gyrator or a frequency dependent resistor.

Among basic functional blocks in Table 1 are also the integrators serve as a building block of several filters. Below introduced voltage integrator (Table 1.6) was realized with the help of the current-voltage convertor (Table 1.3) with respect of the input current was obtained through conversion of input voltage at resistor R. Furthermore in Table 1.8 is the current integrator described by eq. (8). Note that by replacing there R and C we obtain a derivator.

### 4.2 Applications

In Table 1 is shown the circuit with two transimpedance operational amplifiers (T-1.7), whose input impedance is given by relation (7), what makes possible to realize generalized imitance convertor or invertor with frequency dependent parameters of defined $Z_{IN}(p)$. Towards gateway $Z_2$ is possible to see this circuit as invertor and towards gateway $Z_3$, contingently $Z_1$ as convertor.

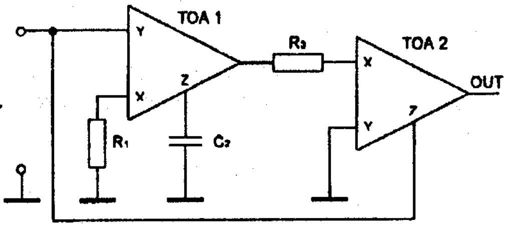



Fig. 2 A circuit simulating the synthetic inductor

On the basis of this circuit is in Fig. 2 given one of the possible implementations of the synthetic inductor-simulation. Because we need to move the operator p from the denominator to the numerator, it is necessary that particular impedances were selected as follows:

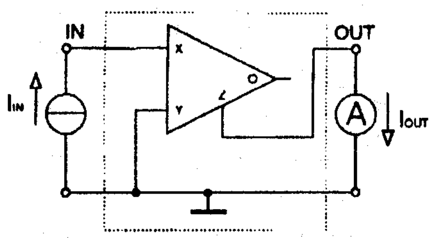
$$Z_1(p) = R_1,\ Z_3(p) = R_3,\ Z_2(p) = 1/pC.$$

then :

$$Z_{IN} = pL_{EQ},\quad L_{EQ} = R_1R_3C \qquad (9), (10)$$

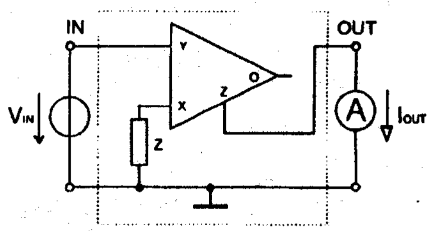
**Table 1** Basic types of functional blocks

**T-1.1 Current follower ( CCCS )**



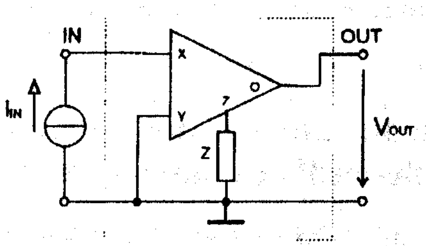

$$I_{OUT}(p) = -I_{IN}(p) \qquad (1)$$

**T-1.2 Voltage - current convertor ( VCCS )**



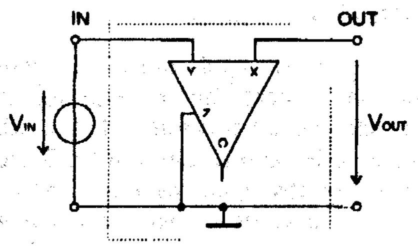

$$I_{out}(p) = \frac{1}{Z(p)} V_{IN}(p) \qquad (2)$$

**T-1.3 Current - voltage convertor ( CCVS )**



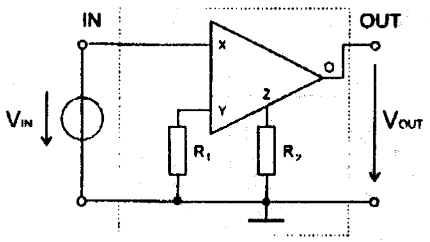

$$V_{OUT}(p) = -Z(p) I_{IN}(p) \qquad (3)$$

**T-1.4 Voltage follower ( VCVS )**



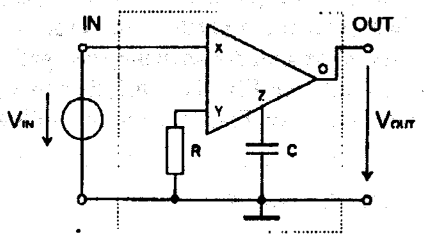

$$V_{OUT}(p) = V_{IN}(p) \qquad (4)$$

**T-1.5 Voltage amplifier ( VCVS )**



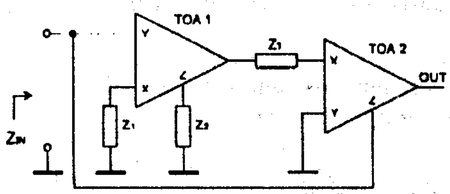

$$V_{OUT}(p) = \frac{R_2}{R_1} V_{IN}(p) \qquad (5)$$

**T-1.6 Voltage integrator**



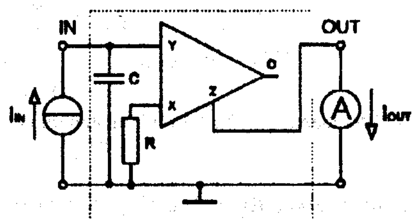

$$V_{OUT}(p) = \frac{1}{pRC} V_{IN}(p) \qquad (6)$$

**T-1.7 General configuration simulating impedance**




$$Z_{IN}(p) = \frac{Z_1(p) Z_3(p)}{Z_2(p)} \qquad (7)$$

**T-1.8 Current integrator**




$$I_{OUT}(p) = \frac{1}{pRC} I_{IN}(p) \qquad (8)$$

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Should we replace in Fig. 2 reciprocally resistors by capacitors $(Z_1(p) = 1/pC_1, Z_3(p) = 1/pC_3, Z_2(p) = R)$, we get a circuit simulating a frequency dependent negative resistor (FDNR), in Fig. 3, with the input impedance given by relation (11):

$$Z_{IN} = \frac{1}{p^2 D_{EQ}}, \quad D_{EQ} = C_1 C_3 R \qquad (11), (12)$$

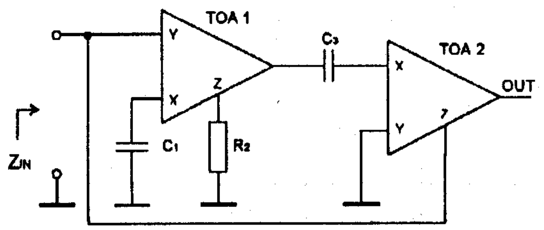


Fig. 3 A circuit simulating FDNR

The above introduced applications of synthetic elements and functional blocks can be employed for a realization of synthetic circuit-structures. The synthetic inductors are possible to be used in classical RLC-circuits at that, the favourable sensitive qualities of RLC-prototype are preserved too (by comparison. with the analogical elements arranged from usual operational amplifiers). Likewise previously stated FDNR is used for example in filters arranged on the basis of DCR-structures.

## 4.3 Filter with synthetic inductor

As a practical illustration of the possible usage of the above-mentioned synthetic inductor was proposed in PSPICE program is a second-order bandpass with the parallel resonance circuit (see Fig. 4). An inductance was simulated from the circuit in Fig. 2 with the following values:

$R_1 = R_3 = 1\ \mathrm{k\Omega}$, $C_2 = 10\ \mathrm{nF}$.

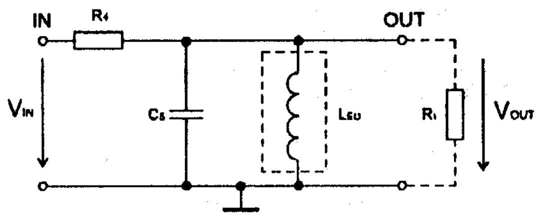


Fig. 4 Second-order bandpass with the parallel resonance circuit

The calculation gives the value $L_E = 10$ mH. Then we get for $f_{mez} = 100$ kHz : $C_5 = 253$ pF, $R_4 = 1\ \mathrm{k\Omega}$. As the output is possible to use the pin "OUT" of the second TOA and to separate thereby the endurancing resistor $R_L$. The frequency response is shown in Fig. 5.

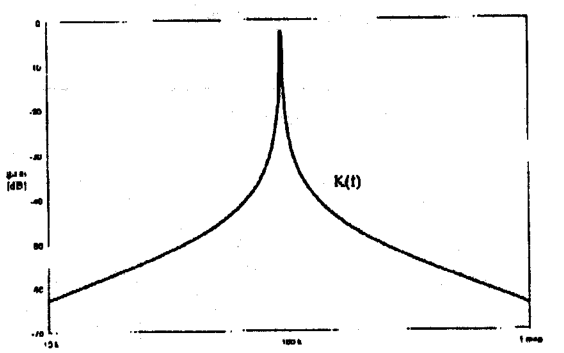


Fig. 5 Frequency response of second-order bandpass

The additional possibilities of this circuit we get in the case that we take away the output from the first TOA on the pin Y (we obtain the bandpass) or on the pin O (we obtain the lowpass). The same variants we get in the case that the output pin is the pin O of the second TOA (bandpass) or the pin Z of of the first TOA (lowpass).

# 5. Modification of single-amplifier multiple-feedback biquadratic filter

## 5.1 Rauch's structure in voltage-mode with classical op. amp

Filters with TOA can be reached from already known classical networks operating in voltage-mode. It's very advantageous to use the Rauch's structure with a conventional operational amplifier for design of these filters. (Fig. 6)

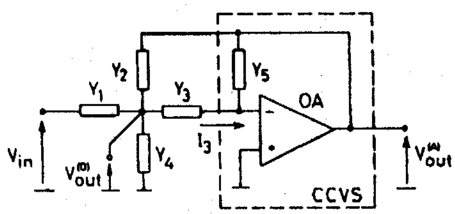


Fig. 6 Bridgman-Brennar double-ladder multiple-loop feedback biquad in classical voltage mode with opamp

Voltage transfer function of the circuit in the symbolic form is following.

$$K_A(p) = \frac{V_{out}^{(A)}}{V_{in}} = \frac{Y_1 Y_3}{Y_5(Y_1 + Y_2 + Y_3 + Y_4) + Y_2 Y_3}. \qquad (13)$$

It's possible also to use output B, then transfer function of this circuit is

$$K_B(p) = \frac{V_{out}^{(B)}}{V_{in}} = -\frac{Y_5}{Y_3} K_A(p) = \frac{-Y_1 Y_5}{Y_5(Y_1+Y_2+Y_3+Y_4)+Y} \tag{14}$$

Advantage of this configuration are two types of transfer function (for example BP and LP) obtained only by one circuit. Unfortunately the output B can not be much loaded.

## 5.2 On the choice of admittances

For the general transfer function (Eqn. 13) of filter shown in Fig. 6, we can easily determine all the various combinations of the admittances, that gives a second-order polynomial in p for the denominator of the transfer function. (We assume for each admittance a single R or C component.) Then a second-order filter will only be obtained when

(a) $Y_2$ and $Y_3$ are of the same nature

(b) $Y_5$ and $(Y_2, Y_3)$ are of a different nature

(c) $(Y_4$ and (or) $Y_1)$ and $(Y_2, Y_3)$ are of a different nature

Nevertheless, the various possibilities above will not be practically equivalent. This is because of presence of non ideal active circuit and its parasitic qualities in the filter. With a conventional OA for example, the limitations appear principally owing to its non ideal open-loop frequency response. With a transimpedance opamp on the contrary, they principally result from its parasitic impedances. Various possibilities of connection of filter using TOA will be described below.

## 5.3 Hybrid voltage-current mode using transimpedance amplifier

These filters can be reached from already known networks operating in voltage mode. Prototype was taken from the Rauch's structure of a Bridgman-Brennar double-ladder multiple-loop feedback biquad displayed in Fig.6. The procedures and rules of an adjoint transformation given in [3] and [4] can be used for solution. The subnetwork denoted in Fig. 6 with a dashed line can be presented as a current-controlled voltage source described by a transfer impedance

$$Z_T(s) = \frac{V_{out}^{(A)}}{I_3} = -\frac{1}{Y_5}\,, \tag{15}$$

when $I_3$ is its input current. The subnetwork can be ingeniously replaced by a commercially available transimpedance opamp (TOA) using a compensation pin (Z) where the admittance $Y_5$ is connected. The change keeps the voltage transfer functions from previous original network working in classical voltage mode. In such a way, the general structure of the hybrid mode V/CM for TOA is obtained in Fig. 7.

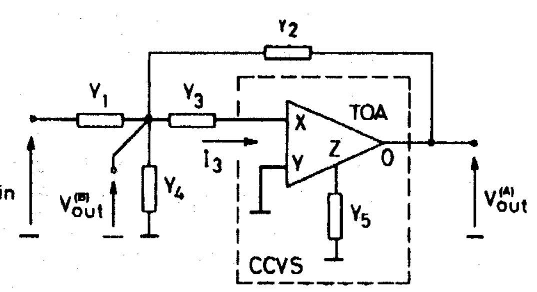


Fig. 7 Bridgman-Brennar double-ladder multiple-loop feedback biquad in hybrid voltage-current mode V/CM with TOA

The transimpedance amplifier, owing to its good frequency qualities (as high gain value, large bandwidth which is relatively independent of closed-loop gain,slew rate as high as 2000 V/μs), provides to use this filter for higher frequency than a classical filter using OA. Parasitic elements limiting performance of TOA are shown in chapter 3.

## 5.4 Adjoint current mode

The circuit was obtained from the filter shown in Fig. 7 by the adjoint transformation given in [3] , when was mutually changed input and output(A) of this circuit and simultaneously was changed the input X and the output of the TOA. The new circuit is shown in Fig. 8.

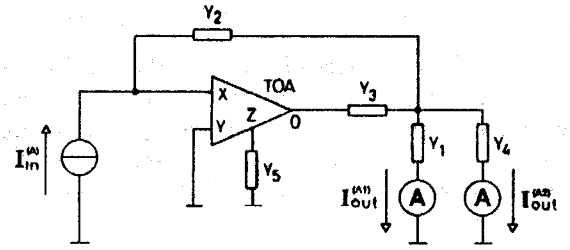


Fig. 8 Bridgman-Brennar double-ladder multiple-loop feedback biquad in current mode CM with TOA

We will obtain circuit with current input and output, but its current transfer function (16) is identical as voltage transfer function (13) of the filter working in voltage mode. Other possibility is using of output (A2) ,that is displayed in the scheme. It's possible to prove, that current transfer function (17) is identical as $H_{A1}(p)$ with the mutual change of symbols $Y_1$ and $Y_4$ .

$$H_{A1}(p) = \frac{I_{out}^{(A1)}}{I_{in}^{(A)}}\,, \quad H_{A2}(p) = \frac{I_{out}^{(A2)}}{I_{in}^{(A)}} \tag{16),(17}$$

## 5.5 Modification of this filter

Using adjoint transformation for the circuit in V/CM (Fig. 7) and taking output B, the new circuit in Fig. 9 is obtained.

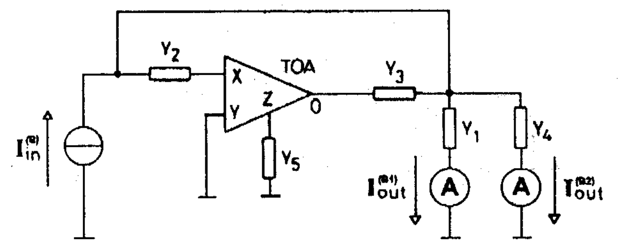


Fig. 9 Biquad in current mode CM with TOA obtained by adjoint transformation from V/CM for output B

For this case, the current transfer function has the symbolic form (18), that is equivalent to the transfer function (14), or (19), respectively, after the mutual change of the symbols $Y_1$ and $Y_4$ .

$$H_{B1}(p) = \frac{I_{out}^{(B1)}}{I_{in}^{(B)}}, \quad H_{B2}(p) = \frac{I_{out}^{(B2)}}{I_{in}^{(B)}}, \qquad (18),(19)$$

## 5.6 Choice of network structure

The conditions of locating $R_i$ and $C_i$ as $Y_i$ ,to obtain the required type of filter were shown in the chapter 5.2. According to these conditions, there exist only two significant possibilities for the choice of the admittances above $Y_2 = 1/R_2, Y_3 = 1/$ and $Y_5 = C_5$ (this first will be called as case A), and $Y_2 = C_2 s$, $Y_3 = C_3 s$ and $Y_5 = 1/R_5$ (case B). The admittances $Y_1$ and $Y_4$ are chosen as indicated in condition (c). These two possibilities will not be equivalent if we consider real TOA modeled in [1],[2].

The port (Y) is grounded, therefore $R_Y$ and $C_Y$ will not exert one's influence. The resistor $R_Z$ is a high resistance, then capacitance character of $C_Z$ is dominant. Furthermore we have to calculate with parasitic resistors $R_X$ and $R_S$ (output resistance of the TOA) into the ports (X) and the output too.

For the case A, the resistors $R_X$ and $R_S$ interact with $R_2$ and $R_3$ ,respectively. Then it will be possible to calculate the values for $\omega_0$,Q and the gains, taking the values of these parasitic resistances into account, especially for the circuit in Fig. 9. The capacitor $C_5$ (assuming $C_5 >> C_Z$ ) induces incorrect frequency responses at frequencies lower than $\omega_{min} = 10/R_Z C$ . For the case B, the resistors $R_X$ and $R_S$ interact with $C_2$ and $C_3$ ,respectively, giving incorrect frequency responses at high frequencies. This is a similar for $R_5$ and $C_Z$ . It is evident that the case A must be used in preference to the case B, when high frequency filters are implemented. The admittances $Y_1$ and Y have to be determine according to conditions above. Type of the filter depends on the choice of these admittances. The transfer functions for case A, depending on the choice of $Y_1$ and $Y_4$ for the circuits from Fig. 8 and Fig. 9 are given in Table 2.

| Admittances | Circuit in Fig.8 | | Circuit in Fig.9 | |
|---|---|---|---|---|
| | $H_{A1}(p)$ | $H_{A2}(p)$ | $H_{B1}(p)$ | $H_{B2}(p)$ |
| $Y_1 = C_1 p$, $Y_4 = C_4 p$ | Bandpass | Bandpass | Highpass | Highpass |
| $Y_1 = 1/R_1$, $Y_4 = C_4 p$ | Lowpass | Bandpass | Bandpass | Highpass |
| $Y_1 = C_1 p$, $Y_4 = 1/R_4$ | Bandpass | Lowpass | Highpass | Bandpass |

**Table 2**: Various transfer function for case A, depending on the choice of $Y_1$ and $Y_4$ .

## 6. Conclusion

Voltage, current and hybrid modes of the ARC biquadratic filters have been analysed, compared and experimentally tested. In any case an important conclusion may be generally pointed out as follows. The hybrid current-voltage mode and specially full current one are closer to the ideal and over a much wider bandwidth than the corresponding voltage mode.

It is evident that a previously designed and optimised VM filter can be directly transformed into the CM filter, without losing its optimum characteristics. Due to the adjoint transformation which is used, the CM filter has identical network functions and their sensitivities, as the VM prototype.

It is now apparent that transimpedance amplifiers including a compensation pin are the right choice to implement second-order filters, when better performances than those obtained for circuits with conventional opamps have to be obtained.

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## About authors...

**Tomáš DOSTÁL** was born in Brno, in 1943. He received the CSc. and DrSc. degree in electrical engineering from the Technical University Brno in 1976 and 1989 respectively. From 1973 to 1978, and from 1980 to 1984, was with Military Academy Brno, from 1978 to 1980 with Military Technical College Baghdad. Since 1984 he has been with the Technical University Brno, where he is now Professor of Radioelectronics. His present interests are in the circuit theory, filters, switched capacitor networks and circuits in current mode.

**Roman PROKOP** was born in Velké Meziříčí, in 1971. At present, he is the PhD Student at TU Brno, Institute of Radioelectronics. His research interest include circuit theory and applications and computer-aided analysis.

**René ŠARMAN** was born in Nový Jičín, in 1971. At present, he is the PhD Student at TU Brno, Institute of Radioelectronics. His research interest modern filters design and synthetic function blocks and computer-aided analysis.

# DOCTORAL (PHD) THESES

## Means of Fast Image Information Processing Systems

author Petr Vítek, MSc

*Abstract:*

Theses deals with parallel approach to image information processing and its application to special mathematic operation. Parallel algorithms based on this attitudes are implemented into both suitable microelectronics parallel structures and into optical means. Efficiency evaluation of proposed processors has been performed using several fundamental parameters of parallel processing, e.g. Speed-up, Utilisation etc. The practical part of the thesis is devoted to the implementation of parallel processing principles in a modern TV coding method called PALplus.

***This work was conducted and successfully defended at the CTU in Prague.***