Universal biquads using CDTA elements for cascade filter design

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Abstract – A 2nd-order universal filter, utilizing CDTA (Current-Differencing Transconductance Amplifier) elements, is proposed. These elements, having pairs of current inputs and outputs, enable an easy synthesis of current-mode filters. The procedure of high-order filter synthesis and results of computer simulation are shown.

Key-Words: - CDTA, active filter, current mode.

1 Introduction

A new circuit element named CDTA (Current-Differencing Transconductance Amplifier) is introduced in [1]. This element converts currents into a pair of low-impedance inputs into a difference current, flowing from so-called *z*-terminal into an outside load. The *z*-terminal voltage is then converted into a couple of output currents into the *x*-terminals by internal operational transconductance amplifier (OTA). The current gain of the whole circuit will be given by the product of the outside z-terminal impedance and the OTA transconductance. That is why the CDTA is suitable especially for the synthesis of current-mode active filters.

The paper is structured as follows: In Chapter 2, which follows the introduction, the behavioral model of CDTA is presented. Chapter 3 describes its signal flow graph for the check analysis of filters containing CDTAs. In Chapter 4, a universal 2nd-order filter will be introduced which offers current gains of LP, BP and HP types. Associating individual current outputs yields further combinations of these gains. The procedure of cascade synthesis of high-order filters based on CDTAs is shown in Chapter 5. In Chapter 6, results of computer simulation are demonstrated. Other possibilities of biquad optimization are indicated in Chapter 7.

2 CDTA and its behavioral model

A simple model of ideal CDTA element is in Fig. 1. It has difference current inputs *p* and *n*. The difference of these currents flows from terminal *z* into an outside load. The voltage across the *z* terminal is transferred by a transconductance *g* to a current that is taken out as a current pair to *x* terminals. This last element part is the familiar OTA element. In general, its transconductance can be controlled electronically through an auxiliary port or it can be done by an outside two-port. These possibilities are not indicated in Fig. 1.

The pair of output currents from the *x* terminals, shown in Fig. 1, may have three combinations of directions: 1. Both currents can flow out. 2. The currents have different directions. 3. Both currents flow into the CDTA element. Then we speak about the CDTA++, CDTA+-, and CDTA-- elements. It is suitable to mark the current directions in the circuit symbol by the signs + (outside) and – (inside) as shown in Fig. 1 (b).

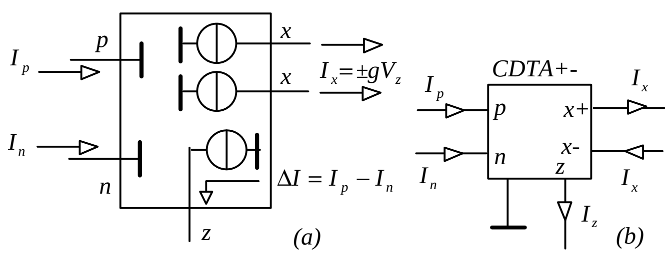

Fig. 1: (a) Behavioral model, (b) schematic symbol of CDTA element.

3 M-C flow graph of CDTA element

For a checking analysis of CDTA-based circuits, there are useful flow graph techniques. Described below are concrete Mason-Coates' (M-C) flow graphs with undirected self-loops [2], which enable the analysis of circuits, operating in the voltage, current and mixed modes.

Let us consider a CDTA element which is included in a general circuit according to Fig. 2(a). The following equations are true:

$$I_p = I_1 + Y_1 V_1,\ I_n = I_2 + Y_2 V_2,\ I_z = I_p - I_z,\ I_x = gV_x$$

$$V_x Y_3 = V_3 Y_3 + I_x + I_3, V_z Y_4 = V_4 Y_4 + I_z + I_4 \quad (1)$$

Following from these equations, the Mason-Coates' (M-C) flow graph [2] in Fig. 2 (b) is compiled. The bold subgraph of CDTA element has a simple structure: input currents I_p and I_n create a difference current I_z, which is one of the causes of voltage V_z. The voltage node V_z is completed by a self-loop whose gain is equal to the sum of all the impedances connected to the z terminal. The output current I_x is derived from the voltage V_z through a transconductance g. The direction of current I_x can be modeled by its sign. Current I_x is one of the causes of voltage V_x.

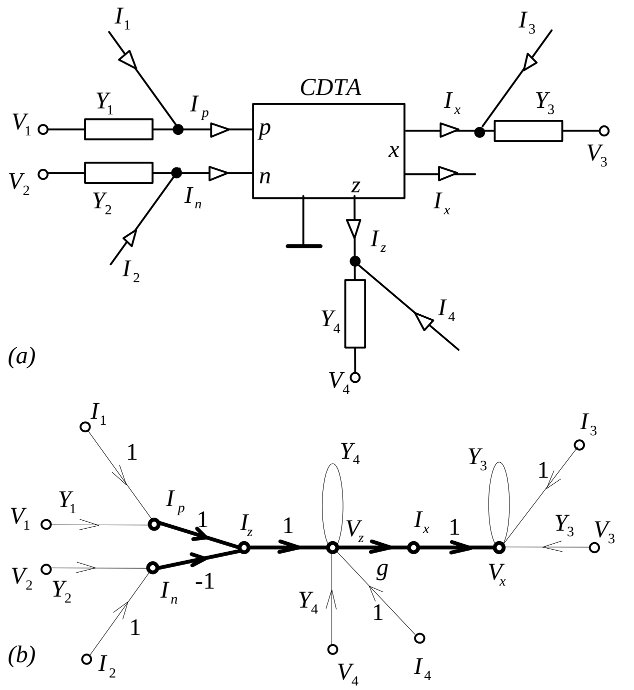

Fig. 2: (a) Inclusion of CDTA element into a circuit, (b) Mason-Coates' flow graph corresponding to Eqs. (1). The CDTA subgraph is shown in bold type.

If some of the circuit variables are outside our interest during the analysis, e.g. the x-terminal voltage or some of the currents I_z and I_x, the flow graph can be further simplified by omitting the corresponding voltage or current node.

4 Biquads with two CDTA elements

Connecting a grounded capacitor or R and C elements in parallel to the z terminal yields an ideal or lossy integrator, inverting and noninverting, with the possibility to sum input currents directly on low-impedance p and n terminals. Adding up the current signals can be done easily by joining the corresponding current-carrying wires. Possible current division can be performed by impedance current dividers. Using this approach, the operation of a number of familiar voltage-mode biquads can be simulated.

Depending on the circuit topology, various effects of electronic control of filter parameters can be achieved by varying the transconductances.

The dynamic parameters of CDTA elements are determined decisively by the construction of internal transconductance amplifier. Typically, the maximum bandwidth is achieved while operating into a low-impedance load. That is why we find such biquad topologies where the OTA outputs are connected directly to other CDTA low-impedance inputs, or where a small number of OTAs appear in the feedback loop.

The first requirement is fulfilled in the two-CDTA structure in Fig. 3 (b), which is deduced from the familiar Tow-Thomas biquad [3] in Fig. 3 (a). There are OTA elements of the two CDTAs in the feedback loop. The version utilizing only the OTA of the second CDTA is in Fig. 3 (c).

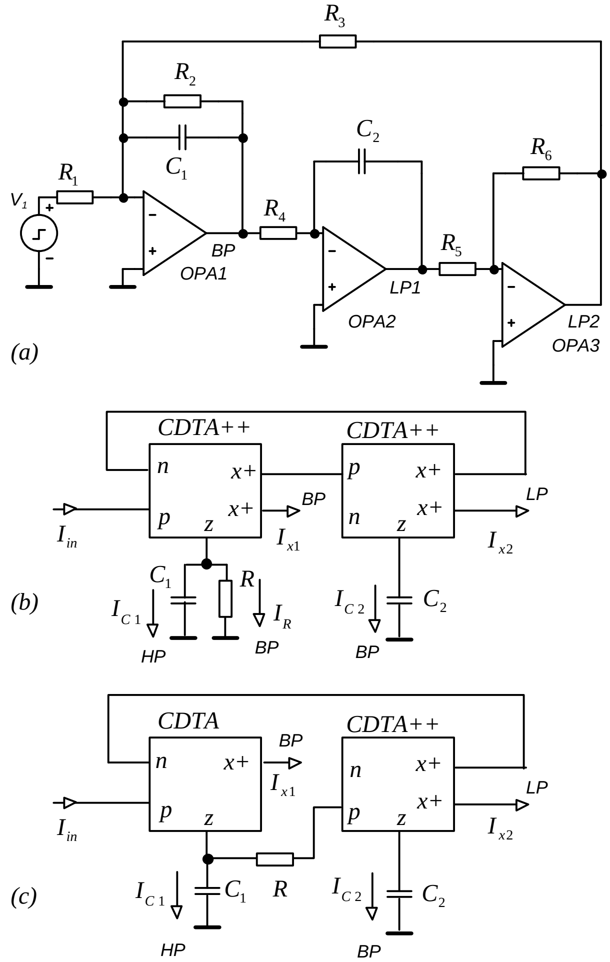

Fig. 3: (a) Tow-Thomas biquad, (b), (c) its realizations using two CDTA elements.

OPA1 along with R_1, R_2, and C_1 form an inverting lossy integrator. In the current mode, it is implemented by one CDTA and R_2, C_1. The current driving the p

terminal of the second CDTA is an equivalent of the OPA1 output voltage. The second CDTA element together with capacitor C2 forms an noninverting integrator, and it replaces the original inverting integrator with OPA2 and the inverter with OPA3.

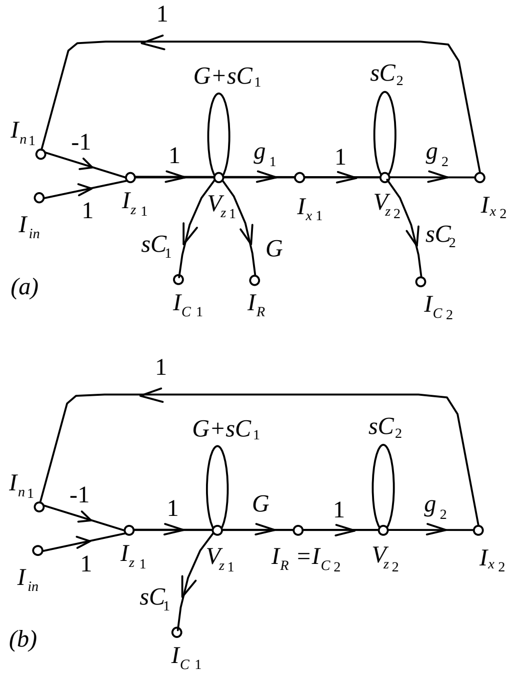

Fig. 4: M-C graphs of circuits in Figs. 3 b (a) and 3c (b).

In the M-C graphs in Fig. 4, the subscripts $x1$, $x2$, $z1$ and $z2$ denote the voltages and currents of x and z terminals of the left and the right CDTA element in Figs. 3 (b) and 3 (c). Evaluating these graphs yields the transfer functions given in Table 1.

Symbols g_1 and g_2 in the equations denote the transconductances of the left and the right CDTA element in Figs. 3 (b) and (c).

From the viewpoint of outputs I_{X2} or I_{C1}, this circuit behaves as a lowpass or highpass filter, while outputs I_{X1}, I_{C2} and I_R provide a bandpass filter. As capacitors C_1 and C_2 are grounded, their currents can be linked up with further cascade sections by connecting them to the CDTA low-impedance current inputs. Joining the currents and utilizing the current dividers can yield further transfer functions, e.g. lowpass notch filters.

	biquad (b)	biquad (c)
$\frac{I_{x1}}{I_{in}}$	$s\frac{w_0/Q}{D}$	
$\frac{I_{x2}}{I_{in}}$	$\frac{w_0^2}{D}$	
$\frac{I_{C1}}{I_{in}}$	$\frac{s^2}{D}$	
$\frac{I_{C2}}{I_{in}}$	$s\frac{g_1 R w_0/Q}{D}$	$s\frac{w_0/Q}{D}$
$\frac{I_R}{I_{in}}$	$s\frac{w_0/Q}{D}$	
D	$s^2+s\frac{w_0}{Q}+w_0^2$	
w_0	$\sqrt{\frac{g_1 g_2}{C_1 C_2}}$	$\sqrt{\frac{g_2}{R C_1 C_2}}$
Q	$R\sqrt{g_1 g_2 \frac{C_1}{C_2}}$	$\sqrt{R g_2 \frac{C_1}{C_2}}$

Table 1: Transfer functions of biquads in Fig. 3 (b) (biquad (b)) and Fig. 3 (c) (biquad (c)).

Comparing the equations for ω_0 and Q of both variants, one can see that we have more degrees of freedom while designing variant (b). It will result in more advantageous ratios of parameters R, C and g, as well as in the possibility of independent setting of Q by R for variant (b). These features are compensated by a certain drawback, which consists in two OTA elements acting in the feedback loop.

5 Method of cascade synthesis

Consider a bandpass filter with a central frequency of 10MHz, 1dB passband ripple, 5MHz bandwidth, and with an attenuation of at least 50dB for frequencies below 4.5MHz and above 22MHz. The Cauer

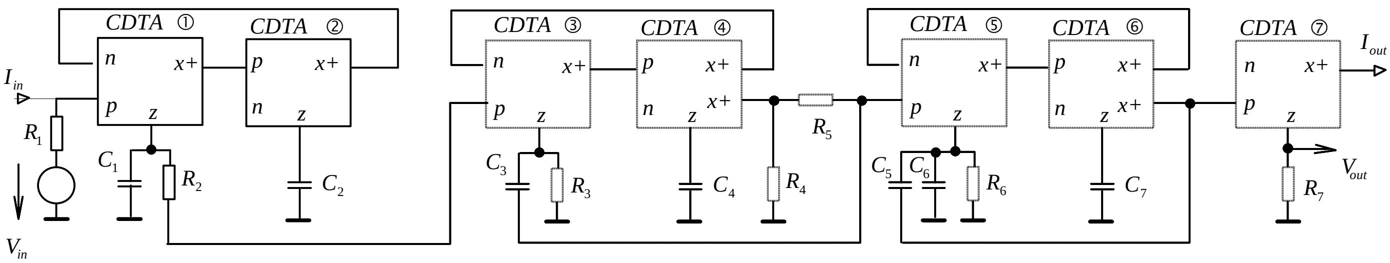

Fig. 5 : Designed elliptic bandpass filter. R_1=4.4kΩ, R_2=627Ω, R_3=1.75kΩ, R_4=50Ω, R_5=129Ω, R_6=1.08kΩ, R_7=1kΩ, C_1=C_2=C_3=C_4=C_7=100pF, C_5=28pF, C_6=72pF, transkonductance of CDTA elements No. 1 to 7: g_1=g_2=6.28mS, g_3=g_4=4.94mS, g_5=g_6=8mS, g_7=1mS.

approximation leads to the 6th- order filter, which can be implemented as a cascade of biquads with the parameters according to Table 2. The zero-gain frequency is denoted by the symbol f_n. The design was performed by the NAF program [4].

Section No.	f_0 [MHz]	Q [-]	f_n [MHz]
1	10	3.9392	-
2	7.85964	8.6557	4.16084
3	12.7232	8.6557	24.0335

Table 2: Parameters of cascaded biquads of elliptic 10MHz bandpass filter.

The cascade filter designed is in Fig. 5. The filter can be excited either from a current source I_{in} or from a voltage source V_{in} through resistor R_1. The last CDTA element enables choosing the output signal as either voltage V_{out} or current I_{out}. The individual biquads operate in the current mode. The first biquad, comprising CDTAs No. 1 and 2, represents a bandpass filter (see Table 1, section 1). The corresponding output current through resistor R_1 is thus led into the low-impedance input of the second section. This section, comprising the CDTAs No. 3 and 4, operates as a highpass notch filter. That is why the output currents from this section flowing into the third section are joined from current outputs „HP“ (current through C_3) and „LP“ (current I_x). Current I_x is divided by the R_4-R_5 current divider to respect the ratio of frequencies f_0 and f_n. For the last section (CDTAs No. 5 and 6), it was necessary to split the capacitor into C_5 and C_6, because frequency f_0 is – unlike section No. 2 – less than f_n.

6 Checking computer simulation

To provide computer simulations, we have created a SPICE model of the CDTA element. This model consists of two parts: The current source controlled by the difference I_p - I_n is modeled as a part of CDBA element, which is published in [5]. The transconductance amplifier is modeled by a SPICE model of 275MHz commercial amplifier MAX435.
An illustration of computer simulation of the filter in Fig. 5 is shown in Fig. 6. The inclination of ripple at frequencies aroud 12MHz is caused by parasitic capacitances of z terminals of CDTA elements which can be as much as 1pF.

7 Additional possible optimization

The pre-designed biquads are appropriate to be optimized, especially from the point of view of impedance levels, R, C and g ratios, and the voltage and current dynamic ranges. So-called VERTEX graphs [6] can be useful for such optimization. They put the global biquad characteristics (e.g. ω_0 and Q) and parameters of filter components into relationships. Let us illustrate the procedure for the biquad in Fig. 3 (b). The following equations can be written from Table 1:

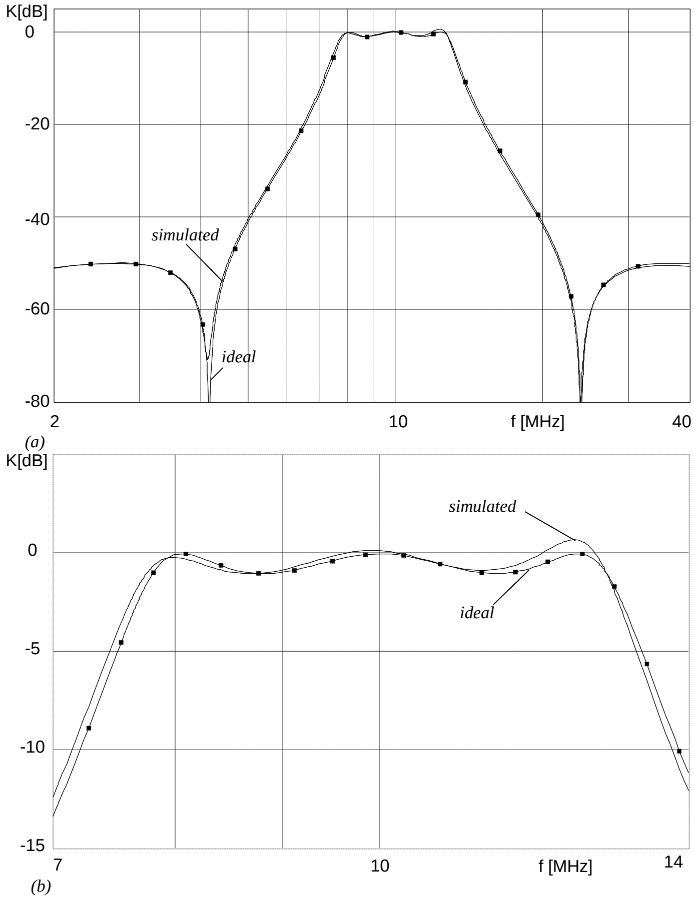

Fig. 6: (a) Frequency response of the filter in Fig. 5 (voltage gain), (b) bandpass detail.

$$g_1 g_2 D_1 D_2 = w_0^2\,,\; GD_1 = B\,, \qquad (2)$$

where B=ω_0/Q is the bandwidth and the symbols D=1/C denote inverse capacitances.
A graph representation of equations (2) is in Fig. 7 (a). The graph consists of two vertices with gains w_0^2 and B, which correspond to the right sides of (2). Branches from individual vertices are terminated in the graph nodes, which correspond to the left-side variables in (2). The VERTEX graph illustrates how to modify already designed element parameters to keep global biquad parameters unchanged. For example, increasing transconductances g_1 and g_2 has to be compensated by decreasing D_2 or D_1 or D_2 and D_1. The possible decrease of D_1 has to be accompanied by an increase of G.

It is obvious from Table 1 that – to keep ω_0 and Q unchanged – the values of current gains, with the exception of I_{C2}/I_{in}, cannot be modified by changing the element parameters. To equate current transfer I_{C2}/I_{in} to the gain level of I_R/I_{in}, it is convenient to choose g_1=G. Then the graph can be modified step by step, as shown in Figs. 7 (b) and (c). As evident from the last graph, there exist two degrees of freedom for the optimization that can be used, for instance, to optimize the upper bound of the voltage dynamic range.

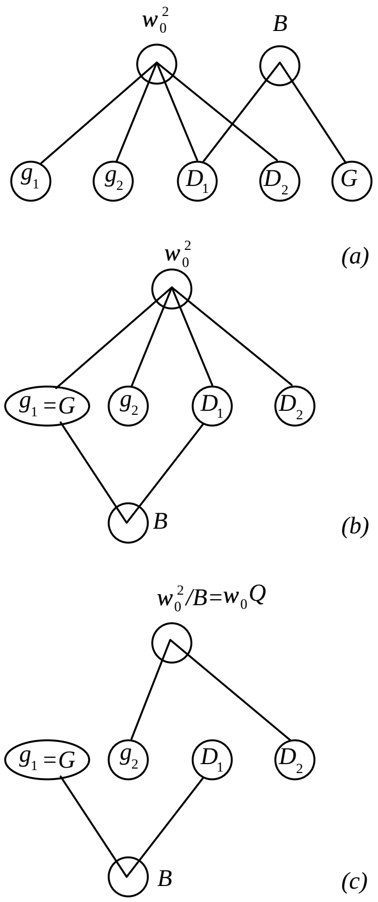

Fig. 7: (a) VERTEX graph according to Eqs. (2), (b), (c) graph modified on the assumption g_1=G.

However, it should be noted that fulfilling the condition g_1=G can result in an unacceptable ratio of C_1 and C_2. Then a compromise solution must be considered.

If all the current outputs of CDTAs in Fig. (b) operate into low-impedance loads, then the only nonzero voltages are voltages V_{Z1} and V_{Z2} accross the z terminals. For these voltages, the transfer functions are as follows:

$$\frac{V_{z1}}{I_{in}} = R\frac{sw_0/Q}{D}, \quad \frac{V_{z2}}{I_{in}} = \frac{1}{g_2}\frac{w_0^2}{D}. \qquad (3)$$

For inconveniently designed elements, the z-terminal voltages can be of exceedingly large values and unacceptable ratios of maximum peaks. As follows from Eqs. (3), the level of V_{Z1} can be modified by R (or by G), and the level of V_{Z2} by transconductance g_2. All the necessary modifications of other elements will be done according to the VERTEX graph in Fig. 7.

In the case of the filter in Fig. 5, the condition g_1=G has not been performed because of the large capacitance ratio. It follows from computer simulation that the current-gain maxima have a spread of 4dB, and the voltage-gain maxima only 2dB.

8 Conclusions

The proposed biquads containing two CDTA elements will enable an easy implementation of all the types of current-mode 2nd-order transfer functions. The CDTA output current and currents flowing through the grounded R and C elements have the frequency dependence of basic LP, BP a HP filter blocks. An arbitrary 2nd-order transfer function can be obtained by applying a linear combination of these currents, i.e. their simple summation, current division and inversion. In the paper, these possibilities are demonstrated on the example of a 6th-order 10MHz elliptic bandpass filter.

Acknowledgments

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References

[1] BIOLEK,D.: CDTA – Building Block for Current-Mode Analog Signal Processing. Submitted to ECCTD2003, Krakow, 2003.

[2] BIOLKOVA,V.-BIOLEK,D.: Stamp-Based M-C Graphs of Current Conveyors. Internet Journal ElectronicsLetters.com, 2002, http://www.electronicsLetters.com.

[3] SCHAUMANN,R.-GHAUSI,M.S.-LAKER,K.R.: Design of Analog Filters. Prentice Hall, 1990.

[4] HAJEK,K.-SEDLACEK,J.: A New Second Order Building Block with Minimised Parasitic Transfer Zero Influence. ECCTD'99. Stresa, Italy, 1999, pp. 811-814.

[5] LATTENBERG,I.-VRBA,K.-BIOLEK,D.: Bipolar Current Differencing Buffered Amplifiers and its Application. IASTED-SIP2001 Int. Conference, Honolulu, Hawaii, pp. 376-379.

[6] BIOLEK,D.-BIOLKOVA,V.: Optimization of Frequency Filters via VERTEX Graphs. ISCAS'01, Sydney, Australia, May 2001, pp. I- 188-191.