CDTA – Building Block for Current-Mode Analog Signal Processing

Dalibor Biolek*

Abstract **- A new active element with two current inputs and two kinds of current output, namely the Current-Differencing Transconductance Amplifier (CDTA) is proposed. This element is a synthesis of the known DCBA (Current-Differencing Buffered Amplifier) and OTA (Operational Transconductance Amplifier) elements to facilitate the realization of current-mode analog filters. The basic system features of CDTA are shown, as well as some of its applications.**

1 INTRODUCTION

The CDBA (Current-Differencing Buffered Amplifier) circuit element is introduced in [1]. The CDBA converts the current flowing into a pair of low-impedance inputs into a difference current, which flows out of so-called *z* terminal into the outside load. The voltage across the *z* terminal is then copied by an internal unity-gain buffer to a low-impedance terminal *w*. The current inputs enable a simple addition of the input currents, which can be generated by connecting impedances, driven by voltage sources. This element is thus appropriate for the synthesis of particularly voltage-mode filters.

Replacing in the CDBA the voltage buffer by a current source that will be controlled by the voltage of terminal *z*, yields a circuit with only current inputs and outputs. The current of the last-mentioned source will be a current replica of the voltage across the impedance connected to the *z* terminal. While choosing a reasonably low impedance level, the voltage levels in the circuit will be adequately low. Thus we will approach the optimum regime of the current mode.

The paper has the following structure: In Section 2, the behavioral model of the CDTA element is presented together with simple flow graphs for its modeling. Section 3 shows some possible applications of CDTA element, with a view to the synthesis of current-mode filters. The final Section 4 deals with computer simulation of the proposed CDTA-based filters.

2 CDTA AND ITS MODELS

A simple model of ideal CDTA element is in Fig. 1. Analogously to the CDBA, 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 the *x* terminals. This last element part is the familiar transconductance operational amplifier (OTA). In general, the transconductance is controllable electronically through an auxiliary port that is not shown in Fig. 1.

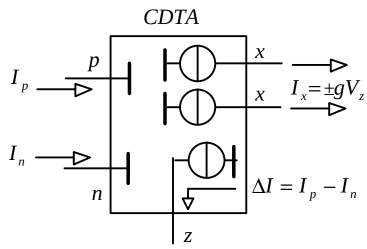

Figure 1: Behavioral model of CDTA element.

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 inside the CDTA element. Then we talk 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. 2 (a).

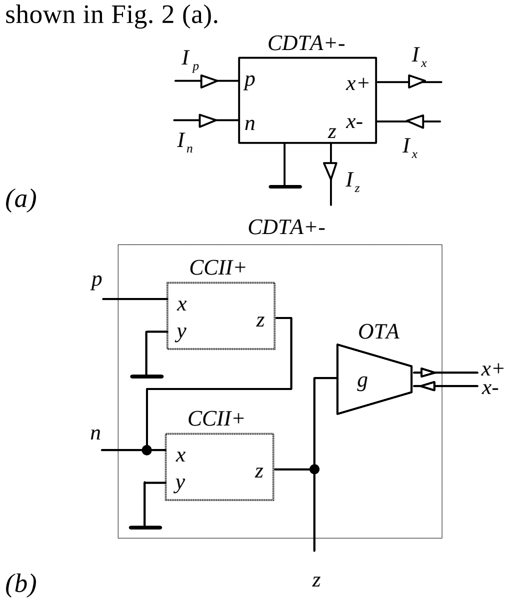

Figure 2: (a) Symbol of the CDTA element, (b) its implementation by current conveyors and by OTA with double current output.

* Department of Electrical Engineering, Military Academy Brno, Kounicova 65, 612 00 Brno, Czech Republic, e-mail: dalibor.biolek@vabo.cz, tel.: +420 9732487, fax: +420 9732888.

The proposed symbol of CDTA is in Fig. 2 (a). Also in Fig. 2 (b) is given a possible implementation of CDTA using the familiar CCII+ and OTA components. Marking the voltages of *p*, *n*, *x*, and *z* terminals in Fig. 2 (a) with symbols V_p, V_n, V_x, and V_z, then for the CDTA+- element the following equations are true:

$$\begin{pmatrix} I_z \\ I_{x+} \\ I_{x-} \\ V_p \\ V_n \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & -1 \\ g & 0 & 0 & 0 & 0 \\ -g & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_z \\ V_{x+} \\ V_{x-} \\ I_p \\ I_n \end{pmatrix} \qquad (1)$$

As shown below, the *z* terminal is loaded by a grounded impedance *Z* in most applications. For the analysis and the synthesis of such circuits, there are useful special signal flow graphs, which we will call „IVI“ graphs (Current-Voltage-Current). It is an analogy of the „VIV“ graphs introduced in [2]. The „IVI“ graph of CDTA element is in Fig. 3 (a): the difference current *DI* is generated as the difference of currents I_p and I_n. The flow through impedance *Z* results in voltage V_z. This voltage is converted to current I_x via transconductance *g*. When observing primarily the current relations without necessarily knowing voltage V_z, we can use the simplified flow graph in Fig. 3 (b).

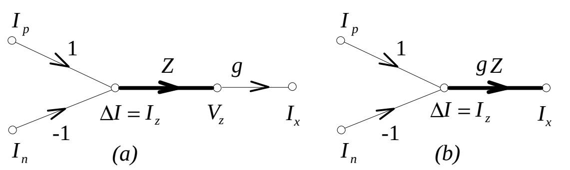

Figure 3: (a) „IVI“ flow graph of CDTA element with grounded load across the *z* terminal, (b) simplified graph after skipping the voltage node.

3 APPLICATIONS OF CDTA ELEMENT

Connecting a grounded capacitor or capacitor and resistor in parallel across the *z* terminal yields the ideal or lossy current integrator, inverting and noninverting, with the possibility of summing the input currents directly on low-impedance terminals *p* and *n*. Summing the current signals is accomplished by simply connecting the corresponding wires. A prospective current division can be realized by impedance dividers. In this way we can simulate the operation of a number of familiar voltage-mode biquads. The CDTA elements are also appropriate for the leapfrog simulation of passive ladder filters, for the synthesis of immittance inverters, etc. Depending on the circuit topology, we can obtain various effects of electronic control of filter parameters by means of transconductances.

The following examples illustrate the above facts.

3.1 Biquadratic filters

The familiar Tow-Thomas biquad [3] is in Fig. 4 (a). Its simulation by means of two CDTAs is shown in Fig. 4 (b). 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 and by the input current that drives the *n* terminal. The conductances of resistors R_1 and R_3 are replaced by the transconductance g_1 of the first CDTA.

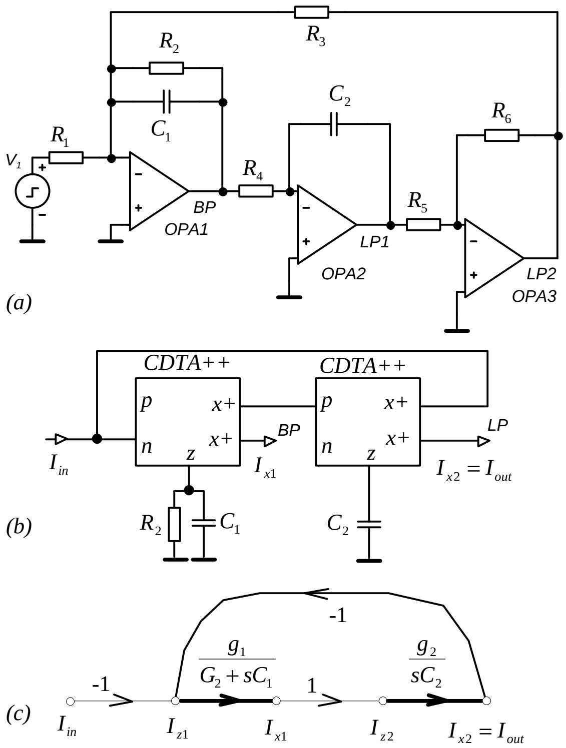

Figure 4: (a) 2nd-order Tow-Thomas filter, (b) implementation by two CDTAs, (c) reduced „IVI“ flow graph.

The following integrator and inverting amplifier with OPA2 and OPA3 are implemented by a single CDTA and by a capacitor C_2. Evaluating the reduced „IVI“ graph in Fig. 4 (c) yields the transfer functions of BP (current I_{x1}) and LP (current I_{x2}) filters. The frequency ω_0 and the quality factor Q are:

$$w_0 = \sqrt{\frac{g_1 g_2}{C_1 C_2}}\,,\ Q = \sqrt{\frac{C_1}{C_2}} R_2 \sqrt{g_1 g_2}\,.$$

The noninverting variant can be obtained by applying the input current to terminal *p* instead of *n*.

In Fig. 5 (a) are 2nd-order LP or BP filters that use a combination of active and passive integrators [4]. The current-mode LP filter in Fig. 5 (b) simulates the passive integrator by the current divider R_2-C_2, which divides current from the *x*-terminal analogously to the voltage divider R_2-C_2 in Fig. (a), which divides the output voltage of OPA1.

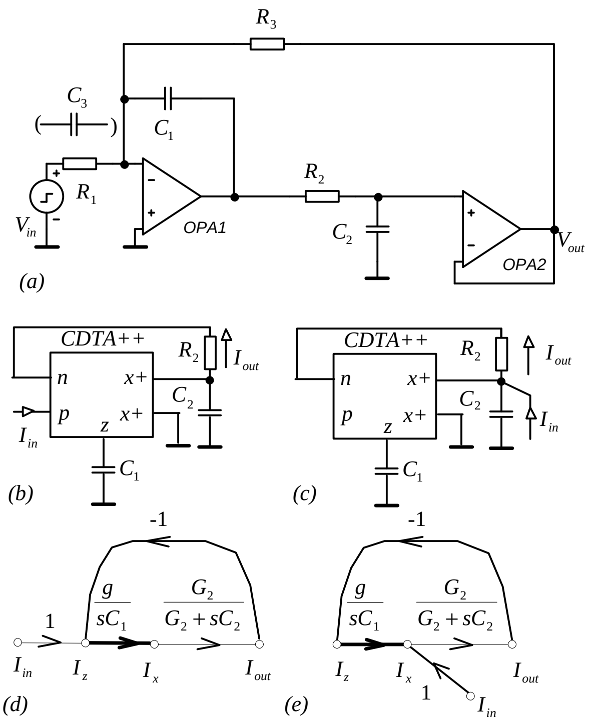

Figure 5: (a) LP (with R_1) or BP (with C_3) biquad, (b) CDTA-based LP filter, (c) CDTA-based BP filter, (d), (e) the corresponding reduced „IVI“ graphs.

In the case of BP filter (C_3 instead of R_1), the input voltage of the filter in Fig. 5 (a) is transferred into the OPA1 output by real gain C_3/C_1. The current input of CDTA-based filter cannot be led into the p terminal (this would be an integration). This current will be simply led into the x terminal. Here it will be added to the output current of the OTA. As shown in the flow graph in Fig. (e), this case corresponds to the equality C_3=C_1. The w_0 and Q parameters are now

$$w_0 = \sqrt{\frac{g}{R_2 C_1 C_2}},\ Q = \sqrt{\frac{C_1}{C_2}}\sqrt{R_1 g}\ .$$

3.2 Leapfrog CDTA-based simulation of passive ladder structures

For the ladder filter in Fig. 6 (a), let us write equations for nodal voltages V_1 and V_2. Capacitance C_3 is not considered in the first step:

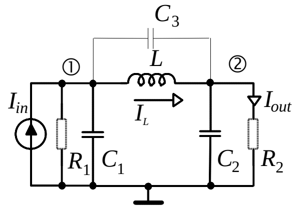

Figure 6: Third-order ladder filter.

$$gV_1 = g\frac{1}{(sC_1 + G_1)}[I_{in} - I_L],\ I_L = \frac{gV_1 - gV_2}{sLg},$$
$$gV_2 = g\frac{1}{sC_2 + G_2}I_L\ . \tag{2}$$

The symbol g denotes an auxiliary conductance introduced in the equations to convert nodal voltages into currents. These currents will be implemented by CDTAs, which will convert terminal voltages into currents via transconductances g.

Equations (2) are modeled by the „IVI“ graph in Fig. 7 (a). The resulting CDTA-based filter is in Fig. 7 (b). A simple method of creating transfer zero by appending capacitor C_3 is indicated both in the flow graph and in the schematic.

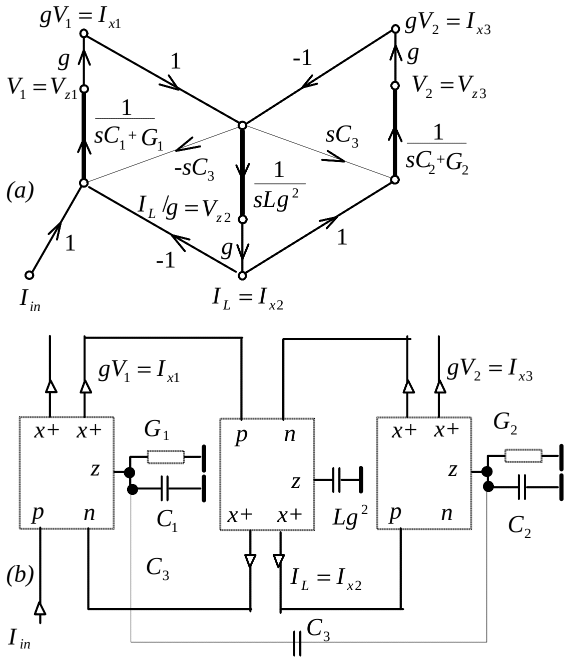

Figure 7: (a) „IVI“ filter flow graph, accordant with equations (2), (b) the synthetized filter.

For a symmetrically terminated ladder filter (R_1=R_2=R), the CDTA+- element offers a simpler implementation, which is shown in Fig. 8. Applying resistive current dividers, this approach can also be used to implement non-symmetrical terminations.

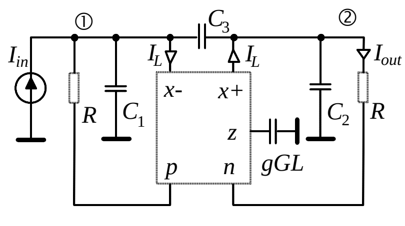

Figure 8: Economical simulation of the ladder filter in Fig. 6 with symmetrical termination.

3.3 CDTA-based impedance inverters

The impedance inverters can be realized, for instance, by a couple of OTA elements [3]. A similar principle is exploited in the circuit in Fig. 9 (a). The corresponding "IVI" flow graph is in Fig. 9 (b), where Z_1 is an auxiliary grounded impedance. Evaluating the graph, we obtain the well-known formula for the input impedance of impedance inverter

$$Z_{in} = \frac{V_1}{I_1} = \frac{Z_1}{1 + g_1 g_2 Z_1 Z} \xrightarrow{Z_1 \to \infty} \frac{1}{g_1 g_2 Z} \cdot$$

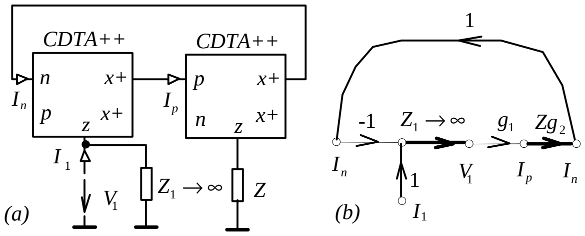

Figure 9: (a) impedance inverter with two CDTAs, (b) the corresponding „IVI“ graph.

4 COMPUTER SIMULATIONS

To provide computer simulations, we have created a SPICE model of 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 SPICE model of 275MHz commercial amplifier MAX435.

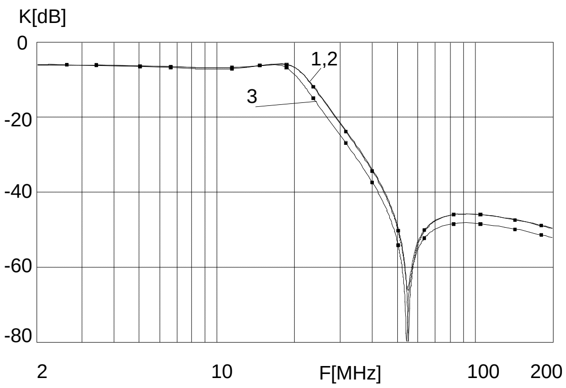

Figure 10: Frequency response of ladder filter in Fig. 6 (1) and the simulated responses of CDTA-based leapfrog structures in Fig. 7 (b) (2) and Fig.8 (3).

The simulation of the circuits from Section 3 has verified their operation up to tens of MHz. The attainable bandwidth of OTA decreases when its current outputs do not work into low impedances. From this point of view, the Tow-Thomas (Fig. 4 b) and leapfrog (Fig. 7 b) structures seem to be better than filters that simulate passive RC cells (Figs. 5 b, c) because the last mentioned filters use the principle of impedance division of OTA output current.

One result of the computer simulation of active filters in Fig. 7 (b) and Fig. 8 is shown in Fig. 10. These filters are designed as a Cauer LP filter with 1dB ripple, 20MHz cutoff frequency, and with an attenuation of 40 dB above 50 MHz. The ladder filter in Fig. 6 has the following parameters: C_1=C_2=151pF, C_3=11.5pF, L=719nH, R_1=R_2=100Ω. The OTA transconductances were set to 10mS.

5 CONCLUSIONS

The proposed CDTA element enables an easy implementation of multiple-input current integrators. That is why it seems to be a promising building block of current-mode filters. In the ideal case, such filters would be built only from the CDTA elements and grounded working impedances for necessary conversions of working currents into frequency-dependent voltages.

Compared with CDBA, the CDTA element is less universal in the sense that – to avoid all additional current-to-voltage-to-current conversions- it does not enable setting the summing coefficients simply by means of outside R and C components. The voltage-mode prototypes provide more design freedom. In the paper, some possibilities are shown how to overcome these limitations.

Acknowledgments

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