

Single-Input Multi-Output Resistorless Current-Mode Biquad

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Abstract—A universal current-mode 2nd-order filter employing two ZC-CITA (Z-Copy Current Inverter Transconductance Amplifier) active elements and two grounded capacitors is proposed. The filter has one low-impedance current input and several high-impedance current outputs which are easy to combine to yield all basic types of transfer functions. The active element is implemented on the basis of commercial integrated circuits. The filter is manufactured and the results measured are compared with theoretical responses.

Keywords—CDTA; ZC-CITA; current-mode;biquad

I. INTRODUCTION

The synthesis of universal 2nd-order filters remains an up-to-date subject of numerous papers in international journals and conference proceedings. The main interest is particularly focused on such implementations which result in low-voltage and low-power applications. One of the popular methods consists in designing current-mode filters whose input and output signals are currents, not voltages. Concurrently, it is also an effort aimed at decreasing the number of active and passive elements. However, the latter can be in conflict with another design goal, i.e. the circuit universality, particularly the ability to implement several types of transfer functions and the possibility to control independently the filter's natural frequency ω_0 and quality factor Q .

The synthesis of 2nd-order filters is based on two integrators within a feedback loop [1]. It is useful to utilize such active elements which enable a simple implementation of both the noninverting and inverting integrators. Such elements are CDBA (Current Differencing Buffered Amplifier) [2] and CDTA (Current Differencing Transconductance Amplifier) [3], whose input part is formed by the CDU (Current Differencing Unit) [4]. By virtue of the CDU, these elements are provided with difference low-impedance inputs p and n . The difference of currents, flowing into these terminals, then flows out of the high-impedance terminal z , causing a voltage drop at an external impedance. This voltage is then transformed into an output signal. For CDBA, the transforming cell is a unity-gain voltage buffer, and the output signal is thus a voltage. CDTA utilizes an OTA (Operational Transconductance Amplifier), thus the output signals are currents of the same value but of optional directions. It results from the above that after

connecting a grounded capacitor C to the z terminal, we get a transimpedance-type (V_{out} versus I_{in} for CDBA) or current-type (I_{out} versus I_{in} for CDTA) integrator. For CDBA, the noninverting/inverting property of the integrator can be chosen only via selecting the p or n input of the CDU. In the case of CDTA, one additional option is to select the polarity of the output current.

In the case of two CDBA-based integrators, their co-operation in the feedback loop requires a conversion of the output voltage of integrator No. 1 to the input current of integrator No. 2, which is easily accomplished by a resistor R . Integrator No. 2, containing the above resistor, can be considered a voltage-mode integrator with a fixed time constant RC . On the other hand, the co-operation of the CDTA-based integrators does not require any V/I conversion. The time constant of the integrator is determined by the C/g_m ratio, where g_m is the transconductance of the internal OTA of the CDTA, which can be controlled electronically.

From the above point of view, CDTA seems to be more suitable for the biquad synthesis than CDBA, because it offers a resistorless solution, utilizing only CDTAs and grounded capacitors. In addition, the input and output signals are currents.

Quite a number of papers were published on CDTA-based biquads. The biquad is implemented by five [5], four [6], three [7], two [8, 9], or only one [10, 11] CDTA. Two-CDTA biquads appear a well-balanced trade-off between the circuit complexity and universality. In [8], a topology with one input and three outputs of HP, BP, and LP types is proposed. However, the output currents of HP- and BP- types flow through the working capacitors and thus their utilization for driving independent loads is problematic. A modified topology, proposed in [9], represents a multiple-input single-output biquad. Various transfer functions are accomplished via selecting various combinations of current inputs. As a drawback, some of the given combinations require an additional circuitry for implementing the matching conditions among the individual input currents (e.g. the condition of the type $I_1 = -I_2/2 = I_m$ in [9]). Moreover, these matching conditions can be put into effect only with a limited accuracy. As shown in [4] and [12], any inaccuracy generates additional transmission zeros in the transfer functions and the

corresponding corruption of frequency responses. A second drawback of the filter in [9] is that one of the current inputs has a high-impedance character.

This paper starts from the concept of two-CDTA universal biquad and demonstrates a procedure how to overcome the disadvantages of the above circuits in [8] and [9]. The problems generated by a finite precision of implementing the matching conditions for input currents are avoided altogether. The filter is thus designed as a single-input multiple-output device, with low-input and high-output impedances. The problem of the availability of concrete output currents is solved such that a copy of the z -terminal current is made directly on the CDTA chip. This copy is then available as one of the current outputs. Another optimization of the circuit is made possible when the CDTA has bipolar currents I_x . Then the implementation of both the noninverting and the inverting integrator does not necessarily require the complicated CDU, and it can be replaced by a simple current follower or inverter. According to the general methodology, introduced in [4], we speak about a modified circuit element with the abbreviation ZC-CFTA (Z-Copy Current Follower Transconductance Amplifier) or ZC-CITA (Z-Copy Current Inverter Transconductance Amplifier). The latter has a more simple internal construction and thus we use it for the biquad implementation.

II. ZC-CITA

The schematic symbol and behavioral model of the ZC-CITA are shown in Figs 1 (a) and (b). As indicated in Fig. 1, there can be an arbitrary number of the x -type current outputs, and the currents can be of both directions. The following set of circuit equations hold:

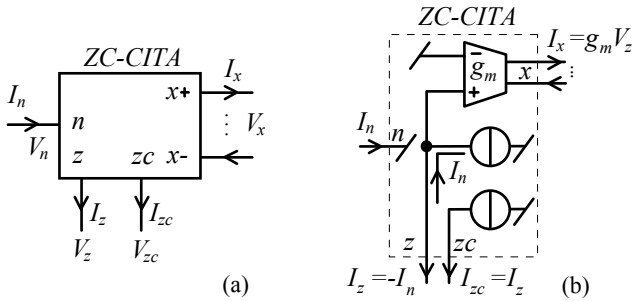


Figure 1. (a) schematic symbol, (b) behavioral model of the ZC-CITA.

$$\begin{pmatrix} I_z \\ I_{zc} \\ I_x \\ V_n \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & -1 \\ g_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_z \\ V_{zc} \\ V_x \\ I_n \end{pmatrix}. \quad (1)$$

It should be noted from Eqs (1) and Fig. 1 (b) that the voltage of the low-impedance n terminal is zero, and that the z -, zc -, and x - type outputs are of high-impedance character. Note that the ZC-CITA comes from the CDTA after leaving out the input terminal p and complementing the circuit with a circuitry for copying the z -terminal current.

III. PROPOSED BIQUAD

The schematic of the proposed universal biquad is shown in Fig. 2. A routine analysis leads to the following transfer functions:

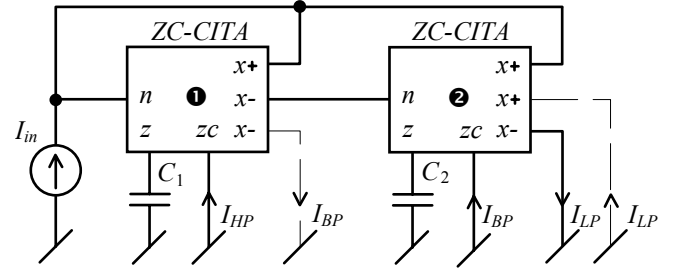


Figure 2. Proposed current-mode 2nd-order filter.

$$\frac{I_{HP}}{I_{in}} = \frac{s^2}{D}, \quad \frac{I_{BP}}{I_{in}} = \frac{sB}{D}, \quad \frac{I_{LP}}{I_{in}} = \frac{\omega_0^2}{D}, \quad (2)$$

where

$$D = s^2 + sB + \omega_0^2. \quad (3)$$

Natural frequency ω_0 , bandwidth B and quality factor $Q = \omega_0/B$ are as follows:

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad B = \frac{g_{m1}}{C_1}, \quad Q = \sqrt{\frac{g_{m2}C_1}{g_{m1}C_2}}. \quad (4)$$

The above results confirm that the circuit in Fig. 2 provides a universal 2nd-order filter with three transfer functions of LP, BP, and HP types with all the three current outputs shown in solid lines in the schematics in Fig. 2. This filter can be implemented by means of two ZC-CITA with a couple of bipolar $x+$ and $x-$ terminals and with two grounded capacitors. The band-reject (BR) output can be obtained by simply connecting the current output I_{HP} and the dashed output I_{LP} , and the allpass (AP) output by joining the above outputs and the dashed I_{BP} output. The accuracy of BR and AP transfer functions implemented in this way will depend on the accuracy of the copies of the currents combined.

IV. EXPERIMENTAL VERIFICATION

The ZC-CITA element was implemented on the basis of integrated circuit OPA860, which contains the so-called diamond transistor and fast voltage buffer [13]. The diamond transistor with its terminals E (emitter), B (base), and C (collector) acts as a current-controlled current conveyor CC-CCII+ [14] with X, Y, and Z terminals, with the resistance $R_x = 1/g_{mT}$ of the x terminal, where g_{mT} is the diamond transistor transconductance, electronically controllable via the bias current.

The circuit diagram is shown in Fig. 3. Transistor T_1 implements the low-impedance input for the current I_n , which

is conveyed to the collector and to the z terminal of the ZC-CITA. A pair of identical resistors R , where $R \gg R_x$, ensures that the current I_n also flows to the emitter of T_2 . It is then conveyed to the zc terminal by T_2 . Transistors T_3 and T_4 operate as a differential-output OTA. In order to increase the linearity, decrease the transconductance, and eliminate the influence of the voltage offset of the transistors on the OTA current offset, a degeneration resistor $R_g \gg R_x$ can be included between the emitters of both transistors. Then the OTA transconductance will be $g_m \approx 1/R_g$. However, the above benefits are achieved at the cost of losing the possibility of electronic control of the transconductance.

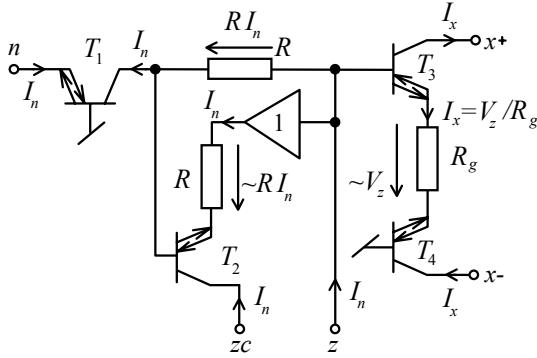


Figure 3. ZC-CITA implementation by diamond transistors.

According to the datasheet [13], the transconductances g_{mT} of all the transistors were set to approx. 100 mA/V via auxiliary resistors $R_{ADJ}=330\Omega$, and the corresponding x -terminal resistances of controlled conveyors are 10Ω . Integrated circuits OPA860 were supplied with $\pm 5V$. Resistances R were designed to be 470Ω . The maximum swing of working currents of the biquad is up to ± 1 mA, which implies an acceptable voltage drop on the resistors of up to $0.47V$. Choosing $R_g = 470\Omega$ and $C_1 = C_2 = 330$ pF, the theoretical values of f_0 , B , and Q according to (4) are 1.026 MHz, 1.026 MHz, and 1, respectively.

The biquad was manufactured according to Fig. 2 with the exception of the dashed alternative outputs IBP and ILP. Its frequency responses were measured by means of an HP4195A network analyzer. The input gate (I_{in}) of the filter was separated from the analyzer by unity-gain buffer (a part of OPA860) with a 50Ω resistor for impedance matching. The voltage/current converter was implemented by a 470Ω resistor. The current/voltage converters for sensing the output current employ the OPA690 OpAmp with 1.5 k Ω feedback resistor in parallel with 1.5 pF capacitor for passband ripple compensation.

Together with the frequency responses, the attenuation of the matching networks and the crosstalk of the input signal to the output through parasitic paths were also measured in order to subtract them and to obtain true biquad responses. They were then exported to the OrCAD PSpice 16 program such that the biquad measured was modeled by E-type controlled sources based on FREQ-type look-up tables. The results are in Fig. 4 (b). Agreement with the theoretical results from Fig. 4 (a) is very good. The anomalies near 100 MHz are induced by the

frequency limitations of diamond transistors. The natural frequency measured, 933 kHz, is 9 per cent below the theoretical value. The dominant cause consists in the decrease of the transconductance g_m in (4) below the value $1/R_g$ due to internal transconductances T_3 and T_4 in Fig. 3, which operate in series, as well as to the fact that capacitances C_1 and C_2 at z terminals of CITA are virtually increased by the parasitic capacitances of voltage buffers (see Fig. 3). These factors can be easily compensated by an adequate decrease of the resistance R_g . Finite low-frequency attenuations, manifested in the HP and BP frequency responses, are caused by the finite internal resistances of z terminals of CITA elements. In conjunction with capacitances C_1 and C_2 , they induce parasitic transfer zeros. As is obvious from Fig. 3, the internal resistance of z terminal is formed dominantly by the internal collector resistance R_c of T_1 in series with resistance R , thus

$$R_z \approx R_c + R. \quad (5)$$

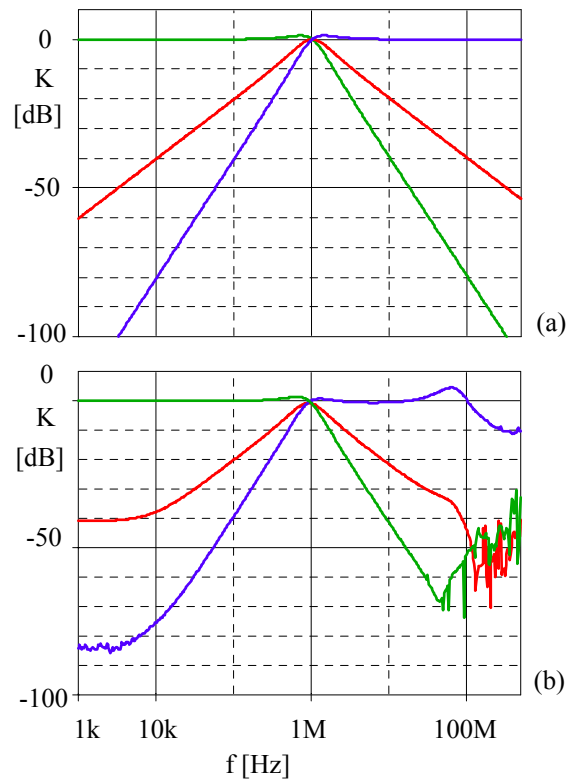


Figure 4. Frequency responses of the biquad: (a) theoretical, (b) measured.

This is because R_c is much less than the input resistance of the voltage buffer and than the base resistances R_b of T_2 and T_3 , since the resistances R_b are increased due to negative feedbacks, introduced by degeneration resistors R and R_g . The collector resistance of T_1 , where the degeneration resistor is omitted by virtue of achieving a low impedance of the n terminal, is rather low, about 50 k Ω . Then $R_z \approx 50.47$ k Ω . An analysis of the filter in Fig. 2 with respect to the z -terminal resistances $R_{z1} = R_{z2} = R_z$ leads to the following low-frequency attenuations of bandpass and highpass sections:

$$\frac{1}{K_{BP,0}} = 1 + \frac{R'_g}{R_z} + \frac{R_z}{R'_g} \approx 104 \approx 40.3 \text{ dB} \quad (6)$$

$$\frac{1}{K_{HP,0}} = 1 + \frac{R_z}{R'_g} + \left(\frac{R_z}{R'_g} \right)^2 = 10713 \approx 80.6 \text{ dB}, \quad (7)$$

where

$$R'_g = R_g + 2/g_{mT} \approx 490 \Omega. \quad (8)$$

The measured attenuations 41 dB and 84 dB confirm the reasonable accuracy of simple formulae (6) - (8). It should be noted that the parasitic BP/HP attenuations can be increased by 20/40 dB via a tenfold increase of the ratio R_z/R_g .

V. CONCLUSIONS

The 2nd-order filter described in the paper works on the well-known principle of two integrators in the feedback loop. Both the noninverting and the inverting integrator are implemented uniformly, using a novel active element ZC-CITA, which is derived from the well-known CDTA by simplifying its input section and adding a circuitry for copying the current of z terminal. The universal biquad has one low-impedance current input and several high-impedance current outputs whereas only two simple active elements operate within the feedback loop. This kind of gate impedance enables easy filter cascading and also direct superposition of LP, BP, and HP output currents in order to generate more complicated transfer functions. The principle is experimentally confirmed through the discrete implementation of the biquad on the basis of diamond transistors.

ACKNOWLEDGMENT

This work has been supported in part by the Czech Grant Agency under grants Nos. 102/08/0784, 102/08/0851, 102/09/1628, and by the research programmes of BUT No. MSM0021630503/513 and UD Brno No. MO FVT0000403, Czech Republic.

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