Active Elements for Analog Signal Processing: Classification, Review, and New Proposals

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Abstract. *In the paper, an analysis of the state-of-the-art of active elements for analog signal processing is presented which support – in contrast to the conventional operational amplifiers – not only the voltage-mode but also the current- and mixed-mode operations. Several problems are addressed which are associated with the utilization of these elements in linear applications, particularly in frequency filters. A methodology is proposed which generates a number of fundamentally new active elements with their potential utilization in various areas of signal processing.*

Keywords

Active element, current conveyor, operational amplifier, OTA, CDBA, CDTA, filter.

1. Introduction

The demand for electronic circuits with extremely low supply voltages and power consumption belongs to important and long-term trends which affect the development of microelectronic technologies [1]. In many applications, additional requirements appear, particularly the extreme speed or the accuracy of signal processing. Simultaneous fulfillment of the above demands is problematic and the trade-off solution should be used in practice.

In the last two decades, the evolution of modern applications of analog signal processing has followed the trends of so-called current mode [2], when signals, representing the information being processed, are in the form of electric currents. In contrast to the conventional voltage mode, which utilizes electric voltages, the current-mode circuits can exhibit under certain conditions – among other things – higher bandwidth and better signal linearity. Since they are designed for lower voltage swings, smaller supply voltages can be used. Simultaneously with the development of current-mode applications, the mixed-mode circuits are also analyzed because of the necessity of optimizing the interface between the sub-blocks, which are working in different modes. The mixed-mode operation and even the comeback to the conventional voltage mode also have another justification: it appears that some generally accepted statements about the advantages of the current mode probably have no real basis [3].

However, the criticism of [3] not withstanding, the current-mode techniques have given way to a number of important analog signal processing/signal generating circuits as is evident from a vast amount of literature on current-mode circuits and techniques published in the recent past (see[1]-[110] and references cited therein). Due to the advances made in integrated circuit (IC) technology during the last two decades, circuit designers have quite often exploited the potential of current-mode analog techniques for evolving elegant and efficient solutions to several circuit design problems. As a consequence, the current-mode approach to signal processing has often been claimed to provide one or more of the following advantages: higher frequency range of operation, lower power consumption, higher slew rates, improved linearity, and better accuracy.

Approximately since 2000, the number of papers, particularly in high-impact international journals from the field, dealing with new circuit principles of active blocks for fast analog signal processing, has continuously been growing. Besides classical active filters, the target applications of the blocks include advanced fully-integrated input blocks of modern communication circuits. With the exception of DC-precise low-pass filters, the requirements on DC precision of the new blocks are not so relevant in comparison with the requirements on their speed.

In the case of oscillators and other generators, some additional requirements regarding their precision (linearity, offset, etc.) have appeared. For non-linear circuits such as rectifiers of weak signals, precise comparators and Schmitt triggers, shaping networks, etc., the demands for accuracy can be considerable.

The initial set of active elements for analog signal processing is currently evolving in two directions.

The first direction is represented by modifying the basic elements such as VFA (Voltage Feedback Amplifier), CFA (Current Feedback Amplifier), OTA (Operational Transconductance Amplifier), and particularly current conveyors (CC). The important motivations for such modifications consist in the effort to increase the application potential of the element. Simultaneously, this element should have a simple internal structure in order to retain low power consumption and high-speed operation. The electronic control requirements can also be an important motivation for modifying the circuit principle.

The second direction of the evolution of the active elements is characterized by the appearance of entirely new elements which extend the original VFA-CFA-OTA-CC set.

There are three motivation objectives for this paper:

1. Mapping the state-of-the-art of the active elements for analog signal processing. Today, there is such an amount of fundamentally different active elements that it may be often confusing also for workers in the field.
2. Addressing several technical problems not frequently analyzed in the literature which are connected with the implementation of current-mode circuits.
3. Outlining another potential direction of generating active elements which would combine the features of basic elements from the VFA-CFA-OTA-CC set.

The paper layout corresponds to the above objectives. Section 2, which follows this Introduction, contains a summary of hitherto developed and employed types of current conveyors, combinations of conveyors and other analog blocks, and elements which extend the original VFA-CFA-OTA-CC set. Ommited in the text, except for one clause in Section 2.2, is the well-known information about conventional operational amplifiers (OpAmps). Section 3 addresses the problem of “analog“ control of the parameters of active elements as well as the problem of utilizing current signals, flowing through the working impedances of the circuit. Also errors which take effect throughout the process of replicating the currents are discussed. In Section 4, with the utilization of the conclusions from Section 3, a practicable method for generating novel active elements is suggested with regard to several simple criteria.

2. The State-of-the-Art

2.1 Current Conveyors

The current conveyor (CC) is the basic building block of a number of contemporary applications both in the current and the mixed modes. The principle of the current conveyor of the first generation was published in 1968 by K. C. Smith and A. S. Sedra [4]. Two years later, today’s widely used second-generation CCII was described in [5], and in 1995 the third-generation CCIII [6]. However, initially, during that time, the current conveyor did not find many applications because its advantages compared to the classical operational amplifier (OpAmp) were not widely appreciated and any IC implementation of Current Conveyors was not available commercially as an off-the-shelf item. An IC CC, namely PA630, was introduced by Wadsworth [7] in 1989 (mass produced by Phototronics Ltd. of Canada) and about the same time, the now well known AD844 (operational transimpedance amplifier or more popularly known as a current feedback op-amp) was recognized to be internally a CCII+ followed by a voltage follower (for instance, see [8]). An excellent review of the state-of-the-art of current-mode circuits prior to 1990, was provided by Wilson in [9]. Today, the current conveyor is considered a universal analog building block with wide spread applications in the current-, voltage-, and mixed-mode signal processing. Its features find most applications in the current mode, when its so-called voltage input y is grounded and the current, flowing into the low-impedance input x, is copied by a simple current mirror into the z output.

Since 1995 in particular, we have witnessed many successive modifications and generalizations of the basic principle of CCII in order to use this circuit element more efficiently in various applications. A summary of the behavioral models of selected conveyors is in Fig. 1.

The demand for a multiple-output current conveyor led to the DO-CCII (Dual-Output CCII), which provides currents I_z of both directions, thus combining both the positive and the negative CCII in a single device [1]. If both currents are of the same polarity, the conveyors are of the CFCCIIp or CFCCIIn types (Current Follower CCII), where the symbol p or n means positive or negative current conveyor [10]. Another generalization is represented by the so-called DVCCII (Differential Voltage Current Conveyor) [11], in which the original “voltage” input y is split into a pair of inputs y_1 and y_2. The voltage of the x terminal is then given by the voltage difference of the voltage inputs. This offers more freedom during the design of voltage- and mixed-mode applications. DVCC with the complementary pair of z_1 and z_2 terminals is known as DVCCC (Differential Voltage Complementary CC) [11]. As a special case of DVCCII for y_1 grounded, the ICCII (Inverting CCII) is described in [12]. On the contrary, DDCC (Differential Diference CCII) [13] is an extension of DVCCII: Voltage at the x terminal is given by a combination of voltages at three terminals y_1, y_2, and y_3. Splitting the z terminal of DDCC into a pair of z terminals with currents $I_z = \pm I_x$ yields DDCCC (Differential Diference Complementary CC) [14]. Another generalization of the classical CCII is DCC (Differential Current Conveyor) [15], in which the x input is replaced by

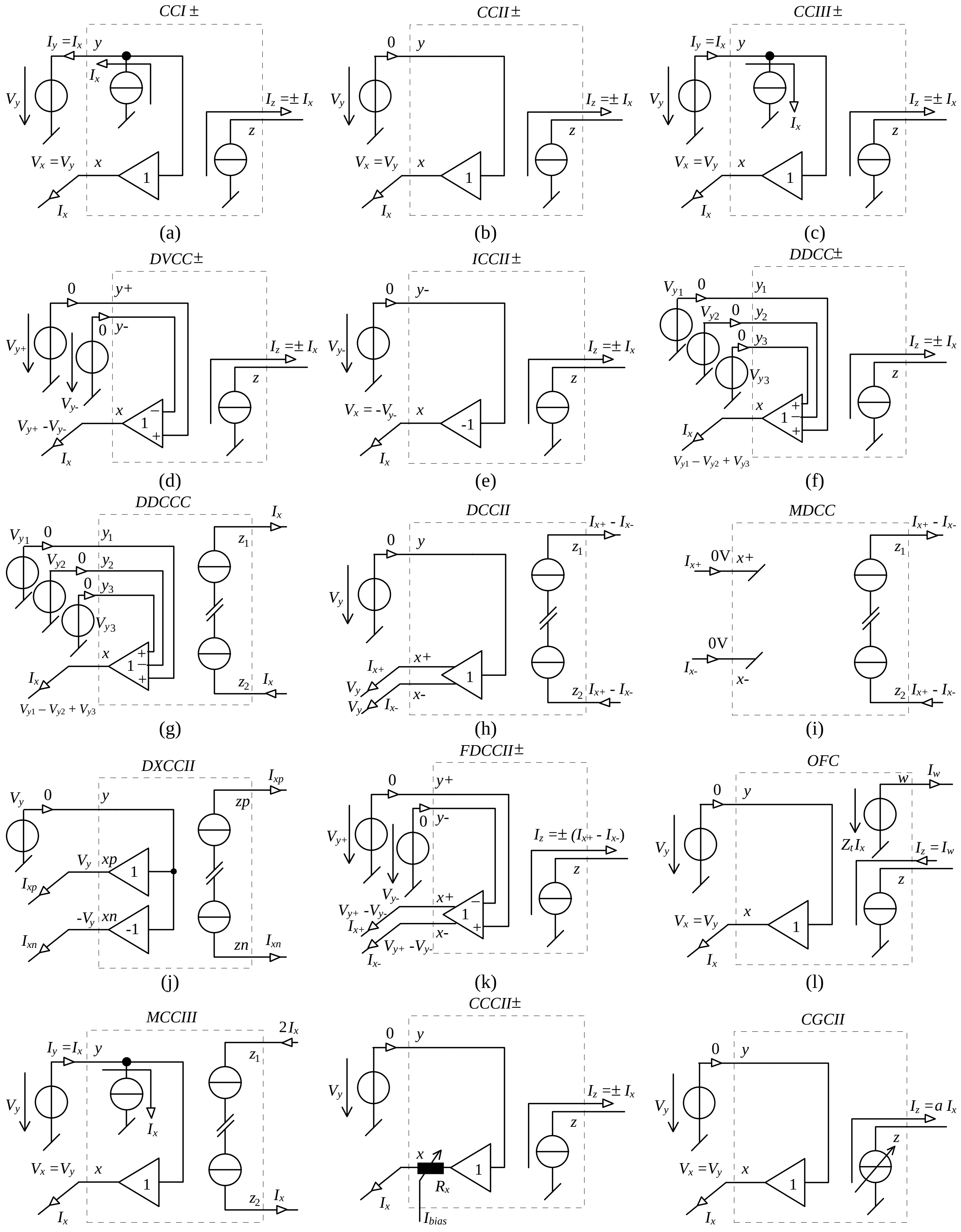

Fig. 1. Survey of current conveyors.

the pair of x_1 and x_2. The current through the z terminal is given by the difference of currents through the x_1 and x_2 terminals. MDCC (Modified Differential Current Conveyor) [15] is a simplification of DCC on the assumption that signal (voltage) at the y terminal is zero.

In [16], Zeki and Toker proposed the Dual-X Second-Generation Current Conveyor (DXCCII) which is a combination of CCII and ICCII. Instead of a single x-terminal, DXCCII has two terminals *xp* and *xn* as outputs of non-inverting and inverting unity-gain amplifiers with their inputs connected to y terminal. Copies of *xp* and *xn* terminal currents are provided at *zp* and *zn* terminals.

FDCCII (Fully Differential CCII) [17] is an important generalization of the conventional CCII. The x, y, and z terminals occur here in pairs. The basic circuit equations of the CCII are now valid for differences of voltages or currents which correspond to these pairs. FDCCII is thus designed for applications with fully differential architecture for fast signal processing. In [18], this type of conveyor is called FBCCII (Fully Balanced CCII).

The so-called modified CCII (MCCII) is published in [19]. Its special internal structure provides such an operation that the current through the z terminal does not depend on the direction of current I_x, i.e. $I_z = \text{abs}(I_x)$. This feature can be used with advantage to implement economically full-wave rectifiers [19]. Joining two current conveyors CCII- yields the so-called Operational Floating Conveyor (OFC) [20]. OFC is a universal differential-input differential-output building block, enabling current-, voltage-, and mixed-mode applications. An extreme embodiment of universality is the so-called UCC (Universal Current Conveyor) [21]. By means of this element, one can implement all the above types of current conveyor. However, such universality is at the cost of non-optimal parameters for a concrete application.

A modification of the third-generation current conveyor is described in [22]. The so-called MCCIII (Modified CCIII) is equipped with a couple of z_1 and z_2 terminals. Currents through these terminals are of opposite directions and the following equalities hold: $I_{z1} = -2I_x$, $I_{z2} = I_x$. Unequal values of the currents enable the design of interesting applications [22].

The non-zero x-terminal impedance is an important parasitic parameter of the current conveyor, which negatively affects its behavior, particularly in filtering applications [2], [23]. However, this phenomenon is paradoxically utilized in a new type of conveyor, namely CCCII (Current Controlled Conveyor) [24-26], where the resistance of x terminal is controlled electronically via the bias current. It can be shown that this active device can be used in filters whose parameters may be controlled electronically [27]. Such a feature has been inherent in the so-called g_mC filters, i.e. filters, compounded only of OTAs and capacitors.

Another method for controlling electronically the parameters of applications employing current conveyors is based on conveyors with variable current gain I_z/I_x. In [1], such a conveyor is identified by the abbreviation CGCCII (Current Gain CCII). The current conveyor of such a type, concretely CCII-, was formerly manufactured by Élantec under the code EL2717 [28]. In [29], the variable gain is implemented via transforming current I_z into voltage by means of resistors, and via back transformation of voltage into current by means of electronically g_m-controlled OTA. The most recent solution is characterized by digital control of the gain, utilizing the so-called CDN (Current Division Network) [82] and DCCF (Digitally Controlled Current Follower) [30].

2.2 Operational Amplifiers (OpAmps), FTFN, and Hybrid OpAmp-CC Elements

68 years have elapsed since the design of the first operational amplifier (OpAmp) [31] and 56 years since the manufacture of the first commercial OpAmp [32]. Over time, the OpAmp internal structure has been modified and two basic OpAmp types – Voltage Feedback Amplifier (VFA) and Current Feedback Amplifier (CFA) have been outlined. However, the well-known input-output behavior of the ideal OpAmp in the linear regime is still the same: zero differential input voltage, zero input currents, and extremely high signal gain. Such characteristic properties can be smartly modeled via a pair of nullator and norator, called nullor [33]. According to [34], the amplifier is called “operational” if it can simulate – with the assistance of the negative feedback – the nullor action at its input and output gates.

Fig. 2 gives the behavioral models of well-known amplifiers and related hybrid elements.

In modern mixed systems, which combine analog and digital parts on a chip, the question of the imunity of analog circuits to digital noise is of much importance. The analog subsystems should therefore be designed with a fully balanced architecture. Such architecture is attained in several steps which can be characterized by the abbreviations DDA (Differential Diference Amplifier), FTFN (Four Terminal Floating Nullor), OFA (Operational Floating Amplifier), DDOFA (Differential Diference OFA), and FBFTFN (Fully Balanced FTFN).

The principle of the DDA was published for the first time by Säckinger in 1987 [35]. In contrast to the conventional OpAmp, DDA has four high-impedance inputs *pp*, *pn*, *np*, and *nn*. Whereas the OpAmp amplifies the difference voltage V_p-V_n and provides the equality V_p=V_n with the help of negative feedback, the DDA responds to the “generalized“ difference voltage $(V_{pp}-V_{pn}) - (V_{np}-V_{nn})$, and maintains the equality $V_{pp}-V_{pn} = V_{np}-V_{nn}$ via the feedback. Among other things, this principle enables an implementation of applications with high signal dynamics with a minimum number of additional elements and without

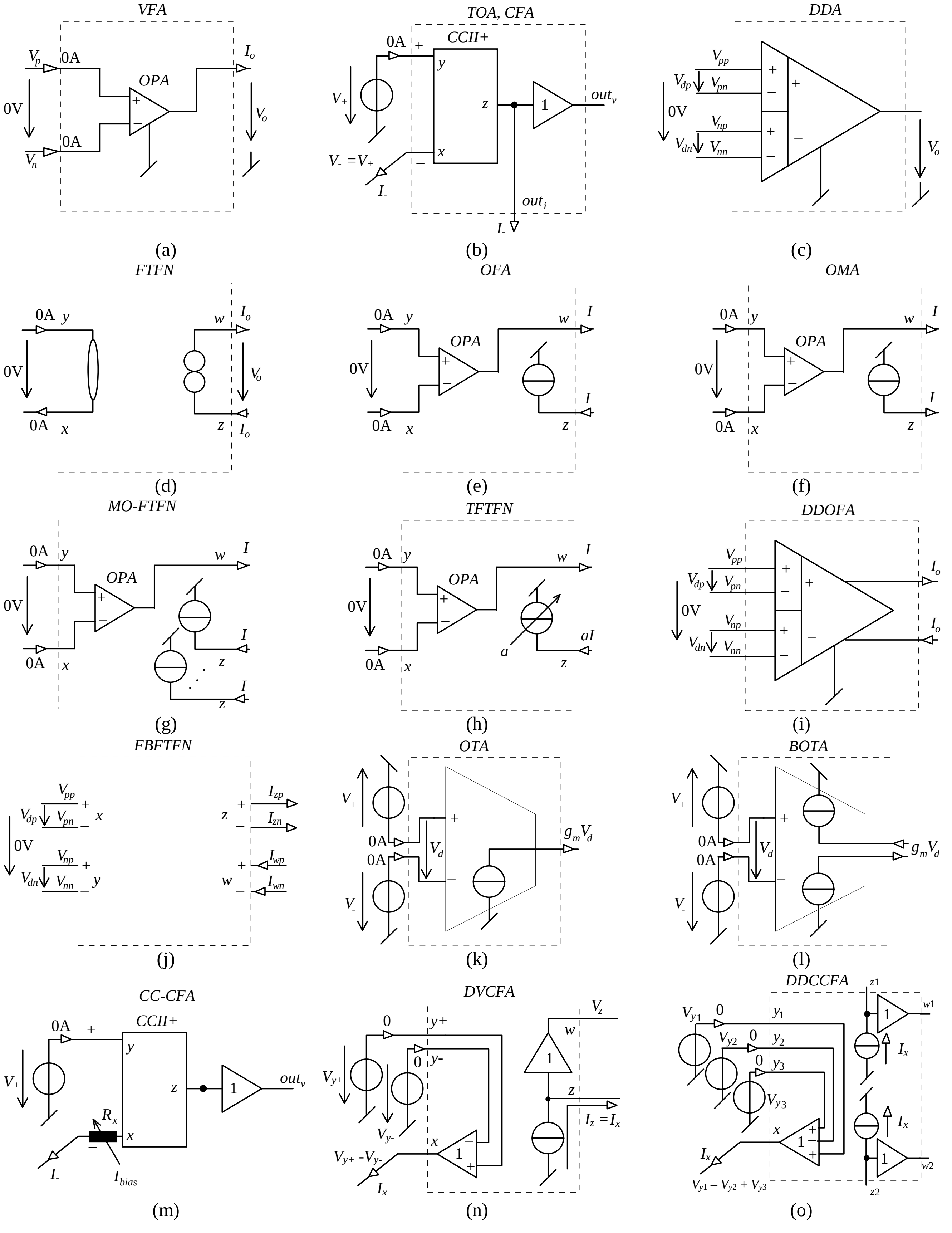

Fig. 2 (a)-(o). Operational amplifiers and hybrid elements (continued on the next page).

(p) (q)

Fig. 2 (p)-(q). Operational amplifiers and hybrid elements (continued from the previous page).

the necessity of satisfying the limiting matching conditions between the parameters of such elements [36].

The need for the floating output in some applications led to the design of monolithic floating nullor [37]. From the point of view of classical works of Tellegen [38] and Carlin [33], it is a four-terminal floating nullor (FTFN). Considering the output voltage and current to be dependent on the external circuits, the FTFN output impedance is not specified and it is given secondarily by the concrete FTFN implementation.

A number of papers have dealt with the FTFN implementation [37, 39, 40]. A general implementation has been described by Huijsing in [41] under the notation Operational Floating Amplifier (OFA). Compared to the conventional OpAmp, OFA has a pair of output terminals. The current, coming into one of them, flows out of the other. In the ideal case, this element can be represented by a bipolar-output operational transconductance amplifier (BOTA) with the transconductance approaching infinity. In this case, the output impedances are theoretically infinite. However, most FTFN implementations are based on the conventional OpAmp with the output terminal labeled *w*, and the current, flowing through this terminal, is replicated by current mirrors to another output terminal, labeled *z* [42, 43]. The outputs are then asymmetrical, with low (*w*) and high (*z*) impedances. The difference, compared to the "BOTA" concept, is obvious: in the case of "BOTA", both output signals are derived symmetrically from the input difference voltage. Now only the signal of the *w* terminal is derived from the input voltage, whereas the signal of the *z* terminal is a consequence – current replica – of the signal of the *w* terminal. Such an FTFN implementation is called OFA (Operational Floating Amplifier, see above) if the current copy is in opposite direction to the original current, or OMA (Operational Mirrored Amplifier) [44], possibly PFTFN (Positive FTFN) [45] if both directions are identical. Increasing the universality can be achieved by increasing the number of current copies. This kind of circuits is called FiTFN (Five Terminal Floating Nullor) [46] or, more generally, MO-FTFN (Multi-Output FTFN) [47]. For example, the extension to a couple of bipolar currents *z*+ a *z*- is done in [48]. Other attempts to increase the universality resulted in the TFTFN element (Tunable current gain FTFN) [49, 50].

Combining the advantages of the fully balanced input of DDA and the symmetrical output of OFA results in the DDOFA (Differential Difference Operational Floating Amplifier) [51] element, which has four high-impedance voltage inputs and two high-impedance current outputs. The FBFTFN (Fully Balanced Four Terminal Floating Nullor) [52] with inputs x_p, x_n, y_p, y_n and outputs z_p, z_n, w_p and w_n represents the completion of the balanced structure. Circuit equations of the FBFTFN are analogous to equations of common FTFN but the differential variables $V_{xd}=V_{xp}-V_{xn}$, $V_{yd}=V_{yp}-V_{yn}$, $I_{zd}=I_{zp}-I_{zn}$, $I_{wd}=I_{wp}-I_{wn}$ figure here instead of the original variables V_x, V_y, I_z, and I_w. An exshaustive bibliography on FTFNs and their applications in circuit analysis and design, covering the period 1961-2000, has been presented in [53].

OTA (Operational Transconductance Amplifier) [54] belongs to the most widespread active elements for on-chip implementation of fast frequency filters. It acts as a voltage-controlled current source with the possibility of electronic adjustment of transconductance g_m. Recently, the MO-OTA (Multiple Output OTA) has appeared as a generalization of BOTA (Bipolar OTA) and its applications in economical biquadratic filters [55], [56]. However, the drawbacks of such applications are not sufficiently emphasized. Some of them are referred to in [57]: the MO-OTA applications embody relatively high sensitivities to the attainable matching error of the current gains of the current mirrors that form the multiple output of the OTA. An error of about 1%, which is common for today's CMOS technologies, often causes unacceptable deviations of circuit characteristics from those that were designed.

Another building block for current- and mixed- mode signal processing, the conventional Transimpedance Operational Amplifier (TOA) [2], is a combination of the CCII and the voltage buffer amplifier. The well-known CFA (Current Feedback Amplifier) has an identical internal structure. In a popular CFA from Analog Devices Inc., namely AD844, the *z*-terminal of the internal CCII+ is brought out which provides more flexibility in its use in several applications [58]. However, in CFAs from other manufacturers (for instance [59]), the *z* terminal of the internal CCII is not led out of the device in order to maximize the parasitic transimpedance and thus the bandwidth. In slower applications, where higher stability is

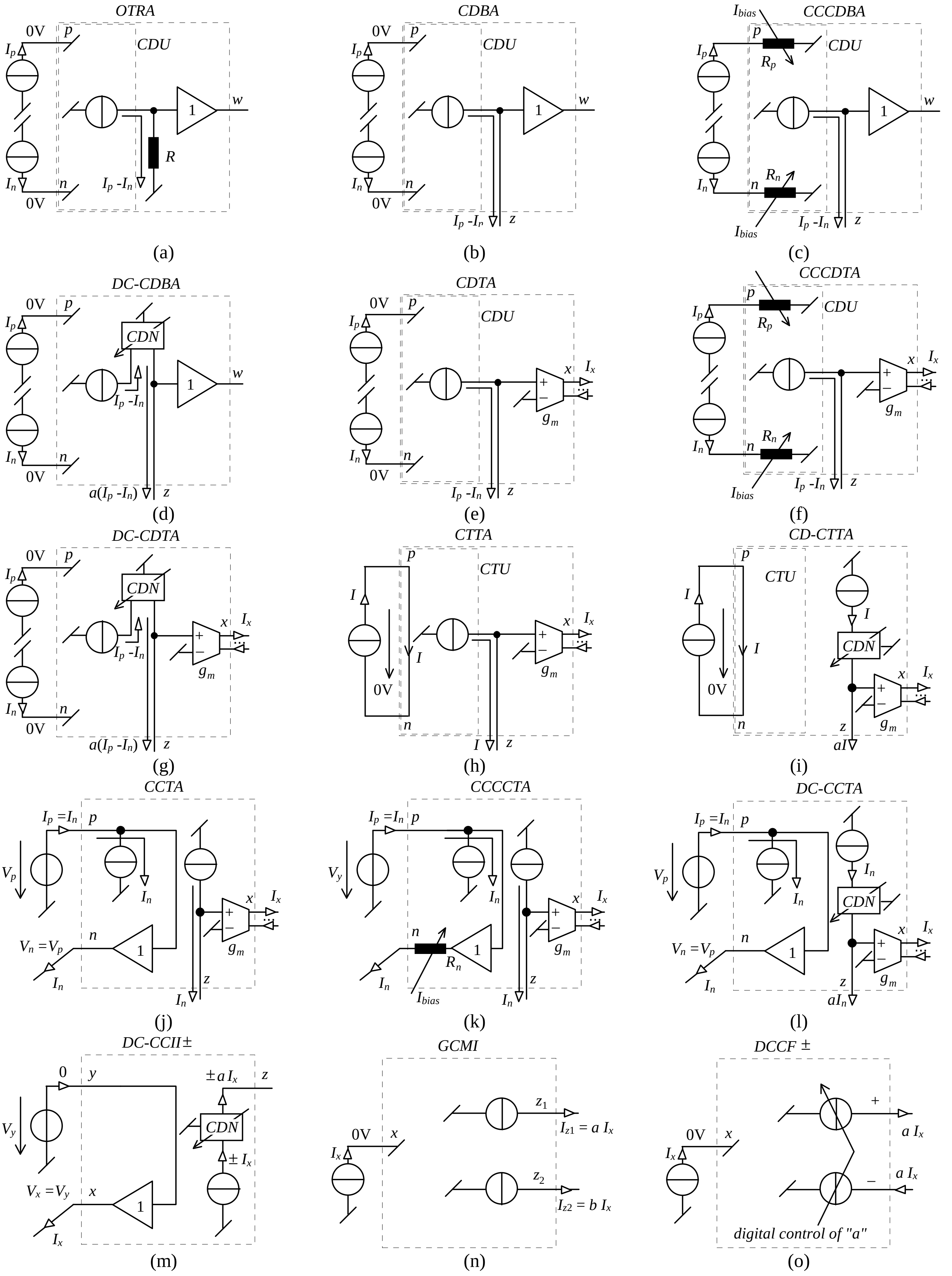

Fig. 3. Other active elements.

required, the VFAs (Voltage Feedback Amplifiers) can be preferably employed.

Requests for the electronic control of conventional OpAmp parameters enforced designing the CC-CFA (Current-Controlled CFA) [60]. The parasitic *x*-terminal resistance of the current conveyor, which forms the input part of the CFA, is controlled electronically via the bias current. Some interesting variants of CFAs have also been proposed such as Differential Voltage CFA (DVCFA) [61] and its further generalized form, namely the Differential Difference Complementary Current Feedback Amplifier (DDCCFA), as in [62]. Note that DVCFA and DDCCFA are DVCC+ and DDCCC elements, complemented by unity-gain voltage buffers.

A special OpAmp type, which is not commercially available, is the so-called TCOA (True Current Operational Amplifier) [63, 64]. It works analogously to the conventional voltage-feedback amplifier but with currents, not voltages. It consists of two low-impedance inputs, + and -, and an arbitrary number of high-impedance current outputs. The output currents, which can be of both polarities, have identical values, which are given by the formula $I_{out} = A\,(I_+ - I_-)$. For ideal TCOA, the current gain A is infinite. Due to the negative feedback, the input difference current is adjusted to zero analogously to the difference input voltage of VFA. The TCOA can be easily obtained, e.g. from the CDTA element (see Section 2.3) with open *z* terminal.

Note that the TCOA concept was published already in the eighties of the last century. Details are given in [65] by Bruun. In addition, the difference-input double-output current amplifier is described here, consisting of a current differencing unit and of a high-g_m OTA. Thus the amplifier structure corresponds to the CDTA element (see Section 2.3).

A systematic OpAmp classification according to the types of signal at their input and output gates (voltages, currents, voltage and current) is proposed in [34]. Nine types of OpAmps are assigned to nine existing combinations. Eight of them are represented by concrete, already defined types of active element. A special type of operational amplifier, called CFB OTA (Current-Feedback Operational Transconductance Amplifier) [66], is assigned to the combination of hybrid input (voltage and current) and current output. In fact, this OpAmp is a second-generation current conveyor with double current output *z*+ and *z*-, thus DO-CCII.

The fact that the advantages of the current conveyor consist in the speed, caused by a simple circuit architecture, whereas the strong point of the conventional OpAmp is the accuracy, which is caused by the effect of negative feedback, is utilized in the circuit element called OC (Operational Conveyor) [23], [67], [68], which is compounded of one OpAmp and one CCII. The OpAmp feedback is fed from its output through the *y*-*x* gate of the CCII to the inverting OpAmp input. As a result, the influence of the nonzero resistance of *x* terminal is suppressed. In reality, this effect works only within the OpAmp bandwidth. In order to minimize the problems with stability, the OpAmp should be of the voltage-feedback type. The advantages of such an integration of two different circuit principles are demonstrated in several papers for circuits in the small-signal linear regime such as instrumentation amplifiers and filters [67-69], and also for nonlinear applications, namely rectifiers [70].

2.3 Other Active Circuit Elements

Models of active elements described in this Section are shown in Fig. 3.

In 1992 and 1999, two papers were published which introduced new circuit elements OTRA (Operational Transresistance Amplifier) [71] and CDBA (Current Differencing Buffered Amplifier) [72]. The latter is also known as DCVC (Differential Current Voltage Conveyor) [73]. CDBA, a generalization of OTRA, is a universal element for filter design, primarily for voltage-mode operation. Numerous papers were published about CDBA applications [74-80]. Some of the applications profit from the basic CDBA feature, i.e. the non-problematic implementation of both noninverting and inverting integrator as a building block of filters of arbitrary order.

CDBA contains the so-called CDU (Current Differencing Unit) and the voltage unity-gain buffer. Basically, CDU is a current conveyor of the MDCC type: It has two low-impedance terminals, *p* and *n*. The difference of currents I_p and I_n flows out of the *z* terminal and the corresponding voltage drop on the external impedance is copied by the buffer to the *w* output. That is why the additional impedances are necessary for implementing the feedbacks from the voltage output to the current inputs. It is inconvenient from the point of view of simplicity and low power consumption. Another drawback is the impossibility of direct electronic control of circuit parameters such as that for the OTA-based applications. This problem is solved via two different approaches. The CC-CDBA (Current Controlled CDBA) is described in [81]. The non-zero parasitic resistances of *p* and *n* terminals of the CDU are controlled electronically via bias currents. The *p* and *n* terminals thus act as voltage input terminals. These voltages are then transformed into currents, whose values are electronically controlled. In fact, this approach represents a transition to a “pure” voltage mode. Another solution is described in [82] from 2008 in the form of a new circuit element called DC-CDBA (Digitally Controlled CDBA). The output current of the current differencing unit is modified in the CDN (Current Division Network), whose current output is connected to the *z* terminal of the voltage buffer input. The CDN block works as a current attenuator with digitally controlled attenuation. Such a concept of controlling the parameters seems to be optimal, because –

in contrast to the analog control – a greater accuracy of the parameter race of more active elements in the application can be guaranteed.

In the paper [83] from 2003, the CDTA (Current Differencing Transconductance Amplifier) active element was described for the first time. The input part of the CDTA is formed – much like for the CDBA – by the current differencing unit (CDU). It is followed by the multiple-output OTA. The difference of currents I_p and I_n flows out of the z terminal, causing a voltage drop on the external impedance. This voltage is then transformed via the internal OTA back into the current I_x. From the point of view of currents I_p, I_n, and I_x, the circuit operates as a current-mode amplifier. Its gain is given by the product of external impedance and internal transconductance. When the z-terminal voltage is maintained within relatively low levels, then the circuit operation approaches the ideal current mode. In principle, CDTA applications do not require the use of external resistors, which are substituted by internal transconductors. Analogously to the well-known "g_mC" applications, the "CDTA-C" circuits are formed by CDTA elements and grounded capacitors. Such structures are well-suited for on-chip implementation.

In the last decade, lots of papers about the CDTA and its applications have been published in international journals and at conferences [84-97]. Within the frame of EUROPRACTICE, the very first CDTA chip in CMOS technology has been fabricated [98].

The authors of papers [99-101] performed a generalization of the CDTA element. Their modification is called CCCDTA (Current Controlled CDTA). It is an analogy to CCCDBA, where the electronic control is based on the dependence of parasitic input resistances of the CDU on the bias current. The above mentioned drawback consists in moving the circuit operation to the voltage mode.

Note that the CDU, which is an important component of the above elements, is a special case of DCCII with the y terminal grounded, i.e. MDCC with z_2 terminal omitted.

GCMI (Generalized Current Mirror and Inverter) [102] is an element which is – in a certain sense – a dual element to the CDU. GMCI has x, z_1, and z_2 terminals and its equations are as follows: $I_{z1} = aI_x$, $I_{z2} = bI_{z2}$. Usually a=1, b=-1. Then GMCI is reduced to current mirror and current inverter, jointly excited from the low-impedance x terminal. This element has been published formerly under the name DOCF (Double Output Current Follower) [103].

A novel circuit element, CTTA (Current-Through Transconductance Amplifier), is described in [104]. In contrast to the CDTA, its input block is the so-called CTU (Current Through Unit). The pair of input terminals serves as a voltage short circuit. The terminal current is copied to the output terminal. The CTU is designed as an ideal current sensor because it converts a current flowing through an arbitrary branch to its copy, which flows to an independent load for subsequent processing.

The CTU can be theoretically synthesized from the FTFN after connecting its input and output gates in parallel. However, among other things, the parasitic gate impedances as well as impedances of the individual terminals can cause a serious realization problem, because a part of the current sensed can leak through them out of the CTU.

In respect of the difficulty of practical implementation of the CTTA, a simplified version called CCTA (Current-Conveyor Transconductance Amplifier) has been described in [105]. Instead of the CTU, the well-known CCIII (Current Conveyor of the third generation) is used here, enabling also the current sensing. In [106], a generalization to the so-called CCCCTA (Current Controlled CCTA) is given, where the above principle of electronic tuning of the parasitic resistance of the x terminal is utilized.

3. Several Application Problems

Exploiting modern active elements in concrete applications can bring several problems. Below, three problems will be noted which occur in varying degrees in linear frequency filters: The problem of the so-called parameter racing, the problem of output currents into working impedances, and the problem of the so-called impedance effect of current mirrors.

3.1 Problem of Parameter Racing

This problem appears in the course of electronic control of filter parameters. The control can be performed, for example, by modifying the OTA transconductance or the x-resistance of current conveyor via the bias current. Typical representatives of active elements which enable such analog control are OTA, CDTA, CCCII, CCCDTA, CCCCBA, and CCCCTA. The quality of the control of filter parameters such as ω_0 and Q of a biquad depends on the accuracy of the agreement of the characteristics of controlling elements, e.g. the g_m versus the bias current etc. Analog control methods often lead to unacceptable inaccuracies.

An implementation of digitally controlled elements on the chip or an implementation of such a method directly into the active element seems to be a good solution. A typical example is the DC-CDBA, in which the CDN (Current Division Network) [82] is used for the gain control. We can analogously define, for instance, the DC-CDTA element with digitally controlled current of the z terminal. Similarly, the DC-CTTA, DC-CCTA, or DC-CCII elements can be defined (see Fig. 3 (g), (i), (l), (m)).

The above mentioned DCCF [30] in Fig. 3 (o) appears to be a perspective independent active element with digitally controlled parameters.

3.2 Problem of Output Currents Into Working Impedances

This problem will be illustrated on examples of two universal 2nd-order filters with OTAs and CDTAs.

A universal g_mC current-mode biquad, based on two integrators in the feedback loop, can be made up of two OTAs [55]. Fig. 4 shows the flow graph which corresponds to the well-known KHN (Kerwin, Huelsman, Newcomb) filter structure. The appropriate implementation is in Fig. 5 (a). It is obvious that the node, to which the non-inverting input of the first OTA is connected, serves as the summing node for adding up the currents according to the formula

$$I_{HP} = I_{in} - I_{BP} - I_{LP}. \tag{1}$$

The problem consists in that when currents I_{BP} and I_{LP} can flow from the OTA outputs directly into independent loads without affecting the filter parameters, the current I_{HP} flows through the working capacitor C_1 into the ground and thus it cannot be directly sensed for additional utilization without disturbing the circuit parameters.

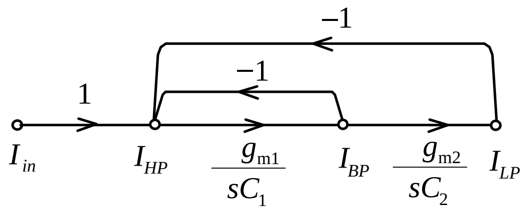

Fig. 4. Flow graph of KHN structure.

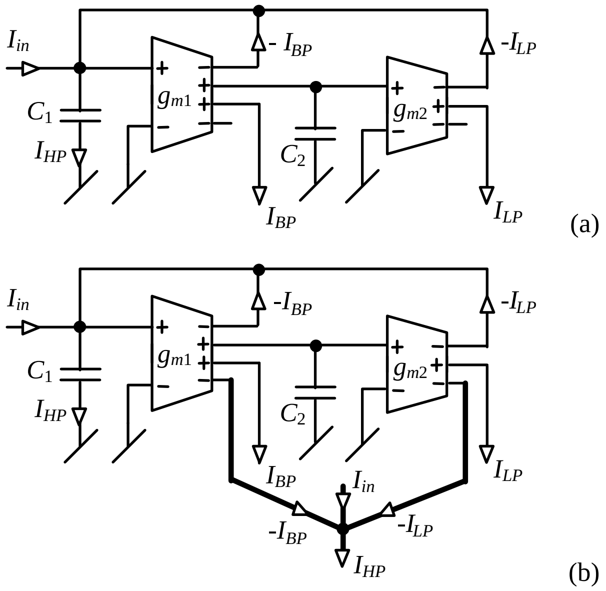

Fig. 5. (a) OTA biquad designed from the flow graph in Fig. 4, (b) method of providing HP output.

Such a problem is commonly solved by an auxiliary circuit which reconstructs the I_{HP} current according to Eq. (1). The solution is in Fig. 5 (b). However, it has two drawbacks: 1) A copy of the input current I_{in} must be produced. 2) The I_{HP} current is reconstructed with an error which depends on the concordance rate of the output currents of each of the multiple-output OTAs, as well as on the error of the copy of the input current. As a consequence of the first drawback, the circuit must be extended with an auxiliary circuitry for making the copy of I_{in} current, and thus the original feature of only a two-element configuration is lost. The second factor results in parasitic transfer zeros appearing in the HP transfer function and thus in frequency response degradation in the low-frequency region [57].

Note that the I_{HP} current into an independent load can be obtained after augmenting the circuit in Fig. 5 (a) by one more OTA, which will serve for summing the currents according to (1) [56].

The next circuit in Fig. 6 (a) is a modification of the two-CDTA biquad from [96]. A problematic availability of the output current I_{HP} is again the case. The I_{BP} current flows also through the working capacitor, but it can be sensed and conveyed into an independent load from the additional $x+$ output of CDTA No. 1.

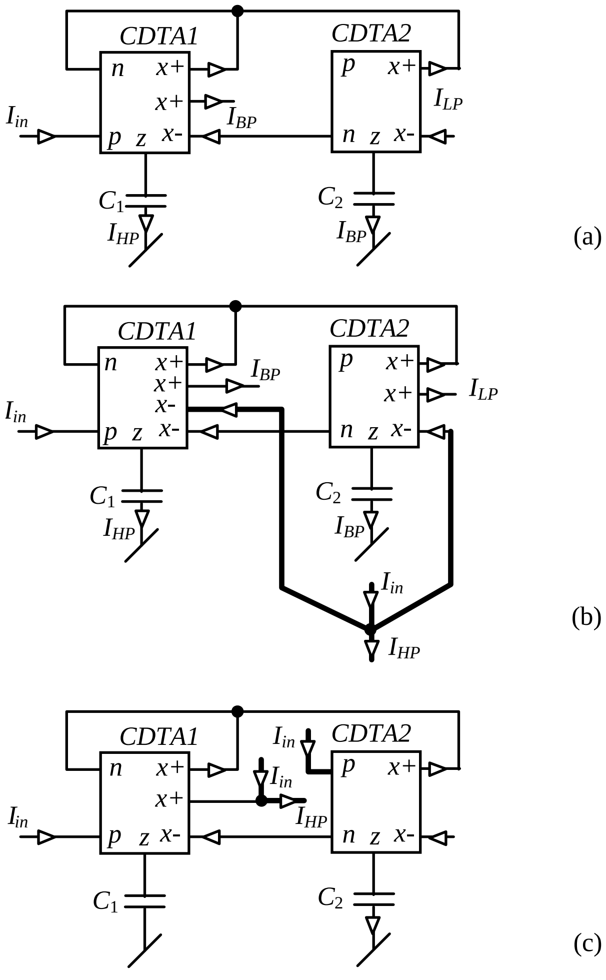

Fig. 6. (a) CDTA-based biquad [96], (b), (c) two methods of providing HP output.

A solution, consisting in the reconstruction of I_{HP} current according to (1), is shown in Fig. 6 (b). Except that it is sensitive to the accuracy of acquired copies of currents I_{BP}, I_{LP}, and I_{in}, it calls for the utilization of another, already the fourth current output of the CDTA1.

Another method of obtaining I_{HP} current for supplying an independent load, described in [89], is given in Fig. 6 (c). Now, however, two copies of input current are required. The circuit analysis also confirms large transfer function sensitivity to the matching errors of these copies.

It seems that a more advantageous method could be making a copy of the *z*-current directly on the chip within the CDTA. This option is discussed in Section 4.

Note that the “*z*-current copy” technique cannot be used for circuits with OTAs. Obtaining the currents for the independent loads can be implemented via increasing the number of active elements in the feedback loop. However, this is accompanied – among other things – by adding undesirable parasitic poles to the transfer function and by a deterioration of the dynamic properties of the entire filter. In this case, a possible solution can be high-impedance sensing of voltage across the working impedance and the following reconstruction of the current flowing through another impedance by means of an auxiliary circuit [107].

3.3 Problem of Impedance Effect of Current Mirrors

This effect appears when current mirrors deliver multiple copies of current to different parts of the circuit. Current outputs of MO-OTA or CDTA or the above copies of the *z* terminal are typical examples.

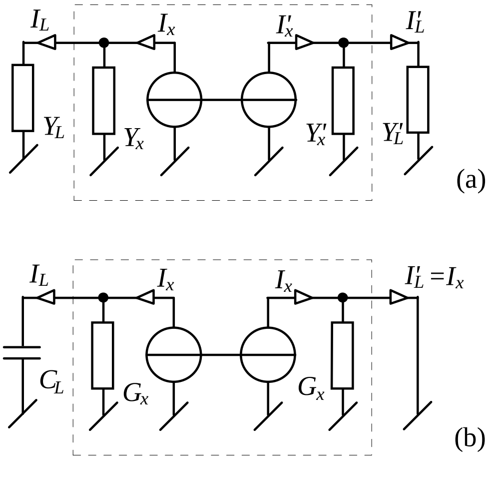

Fig. 7. Problem of impedance effect of current mirrors.

A simplified small-signal model of a pair of simultaneously controlled sources is shown in Fig. 7 (a). In the ideal case, both sources have identical values of internal currents $I_x = I_x'$ and internal admittances $Y_x = Y_x'$. In a concrete application, these sources generally work into different load admittances Y_L and Y_L'. Currents through these loads will thus be different. The resulting error is now determined not only by the tracking errors of current mirror, but also by the different character of the loads of individual current outputs. The frequency dependence of such an error is evident.

Analyses of OTA and CDTA filters in Fig. 5 (a) and 6 (a) lead to the conclusion that multiple current outputs of a concrete element work partly into a pure capacitive load, partly into low-impedance *p* and *n* inputs of the CDTA or into an unspecified independent load which is usually of low-impedance in the current mode. The case of a pair of identical current sources working into the capacitive load and into the short circuit is illustrated in Fig. 7 (b). It is obvious that currents into both loads will be virtually identical only at frequencies above the cutoff frequency $f_m = G_x/(2\pi C_L)$. For frequencies approaching zero in the filter in Fig. 6 (a), the attenuation of current through C_1 will increase indefinitely (the high-pass filter), but a copy of this current, which would be performed via the conventional current mirror, will exhibit finite attenuation below the parasitic cutoff frequency.

The above effect of low-frequency parasitic transfers to HP and BP outputs can be inferred from the simulation results in a number of papers dealing with universal biquads. Let us mention [108] at least. This effect is rather hidden in frequency plots with linear vertical axis. More evident modifications can be observed in phase responses [109].

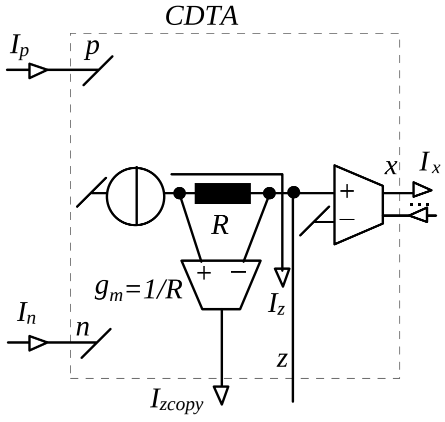

Fig. 8. Alternative method of providing the copy of *z*-terminal current.

For g_mC filters, the impedance effect of current mirrors can be reduced only by means of careful design of current mirrors with extremely high output resistances. Outstanding results can however, be achieved in filters employing CDBAs or CDTAs, utilizing the principle in Fig. 8. The current I_z is flowing through an auxiliary resistor *R*, and the corresponding voltage drop is transformed into a current via an OTA. Resistance *R* should be sufficiently small. Otherwise, its voltage drop would decrease the voltage dynamic range of the active element. The current copy now is tracking the original current because it is directly derived from it. More implementation problems, associated with the voltage and current offsets of the auxiliary OTA, with the influence of the common-mode parasitics, and with providing the equality $g_m = 1/R$ need to be solved.

4. Searching for Novel Circuit Elements

Why search for other circuit elements? Currently there are at least five different rational motivation factors:

- Efforts to increase the universality of a circuit element while preserving the simplicity of its topology.
- Elimination of parasitic effects, some of which were discussed in Section 3.
- Need for analog or digital control of element parameters.
- Efforts to design elements, enabling applications with a minimum number of these elements and with a minimum number of other additional elements.
- Efforts to have a trade-off between required speed and accuracy.

Fig. 9 summarizes several suggested principles of novel circuit elements which reflect the above motivation factors.

The ZC-CDBA and ZC-CDTA (Z Copy CDBA and Z Copy CDTA) elements reflect the demand for higher universality of the conventional CDBAs and CDTAs. Now a copy of the current through the *z* terminal is available at the *zc* terminal. This copy can be implemented either by a current mirror with high-impedance *zc* terminal or by the technique from Fig. 8. An example of the utilization of ZC-CDTA is in Fig. 10. Thanks to the I_z current copy, the problem of the output current of high-pass section of the universal biquad from Fig. 6 (a) is easily resolved.

The CDeTA (Current Differencing external Transconductance Amplifier) is based on the CDTA, but now the transconductance of the internal OTA is defined by an external two-terminal circuit. The CdeTA is inspired by commercial OTA MAX435 [110], which works on a similar principle. Considering the external two-pole impedance Z_e and the impedance Z_z, connected between the *z* terminal and the ground, the circuit current gain will be given by the ratio Z_z/Z_e. CdeTA can be used, for example, for the synthesis of generalized immitance converters or atypical filters, when the two-pole Z_e can be a SMD-type coil, X-tal, etc. Replacing Z_e by short connection and Z_z by open connection yields the TCOA (True-Current Operational Amplifier).

The CDCC (Current Differencing Current Conveyor) is proposed as a generalization of the CDeTA. The basic idea starts from the observation that OTA can be implemented by the 2nd-generation current conveyor and one resistor. The admittance of a two-pole connected between the *x* terminal of the CCII and the ground serves as the generalized transconductance. In this case, the operations of the CDCC and the CdeTA are similar. However, CDCC is more universal because of its "*i*" terminal, which can be used as an additional current input.

Comparing the CDBA and the CDTA, both containing a CDU, from the point of view of the universality of the input/output configurations, we can conclude that the difference inputs are a necessity for the CDBA while for the CDTA they only improve its universality: For the CDBA, which has only a single-polarity output, the CDU is the only instrument for the choice of the sign of transfer function and of the feedback type (positive, negative). The CDTA has a difference input and also a two-polarity outputs, such that the *p* and *n* inputs need not be used simultaneously in a number of applications: the negative feedback from the *x*+ output to the *n* terminal can be substituted by connecting the *x*- and *p* terminals. Then the CDTA structure can be simplified, replacing the CDU by a simple current follower or inverter. For most applications, a pragmatic requirement of such a simplification is a sufficient number of current outputs *x*+, *x*-, because some of them are necessary for implementing the feedback connections. The appropriate simplified circuit elements are called MO-CFTA (Multiple-Output Current Follower Transconductance Amplifier) and MO-CITA (Multiple-Output Current Inverter Transconductance Amplifier). The general notation of these elements, MO-CCTA (Multiple-Output Current Copy Transconductance Amplifier), which comes into consideration when it is not specified whether the *z*-current is a copy or the inversion of the input current, is in collision with the formerly introduced notation "Current Conveyor Transconductance Amplifier" [105] with the same abbreviation. For example, one can show a simple implementation of a quadrature oscillator based on first-order all-pass filter with only one MO-CFTA, one resistor, and one grounded capacitor. It is well known that a similar implementation with CDTA or CDBA requires a floating capacitor [95].

The universality of these elements can be increased by means of the above described methods: completion of the I_z copy, the g_m control by an external two-pole, and OTA replacement by the CCII. The last option is shown in Figs 9 (g), (h) in the form of MO-CFCC and MO-CICC (Multiple-Output Current Follower/Inverter Current Conveyor).

The methodology described, which uses the CDU or CF or CI as the input unit, and the following simple blocks such as voltage buffer, OTA, and CCII, represents an open system: Let us continue with the variation that the input unit will now implement voltage and not current differences. The differential-input OTA is a simple element for realizing the voltage difference. Simultaneously, it can provide the

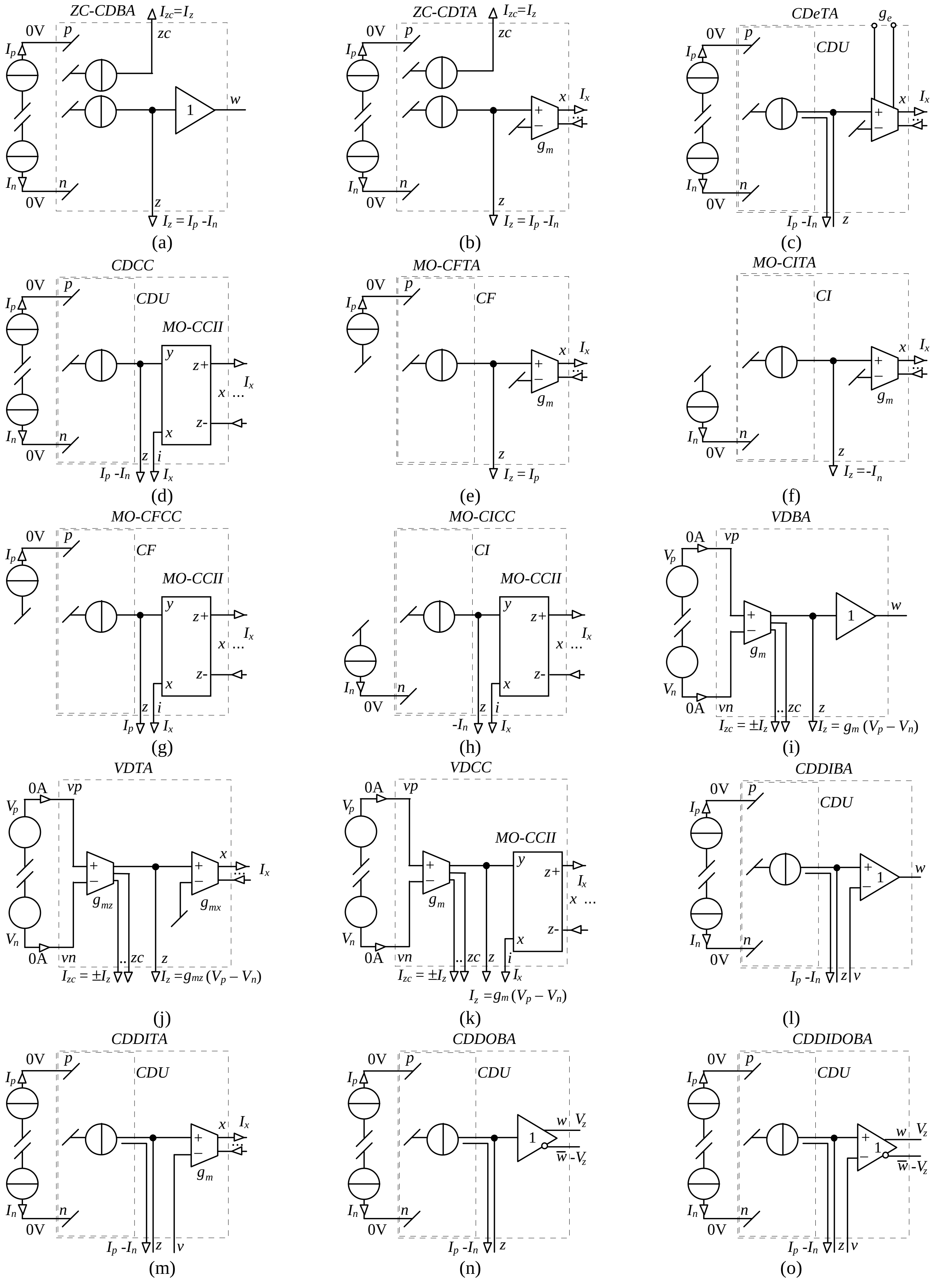

Fig. 9 (a)-(o). Proposed novel circuit elements (continued on the next page).

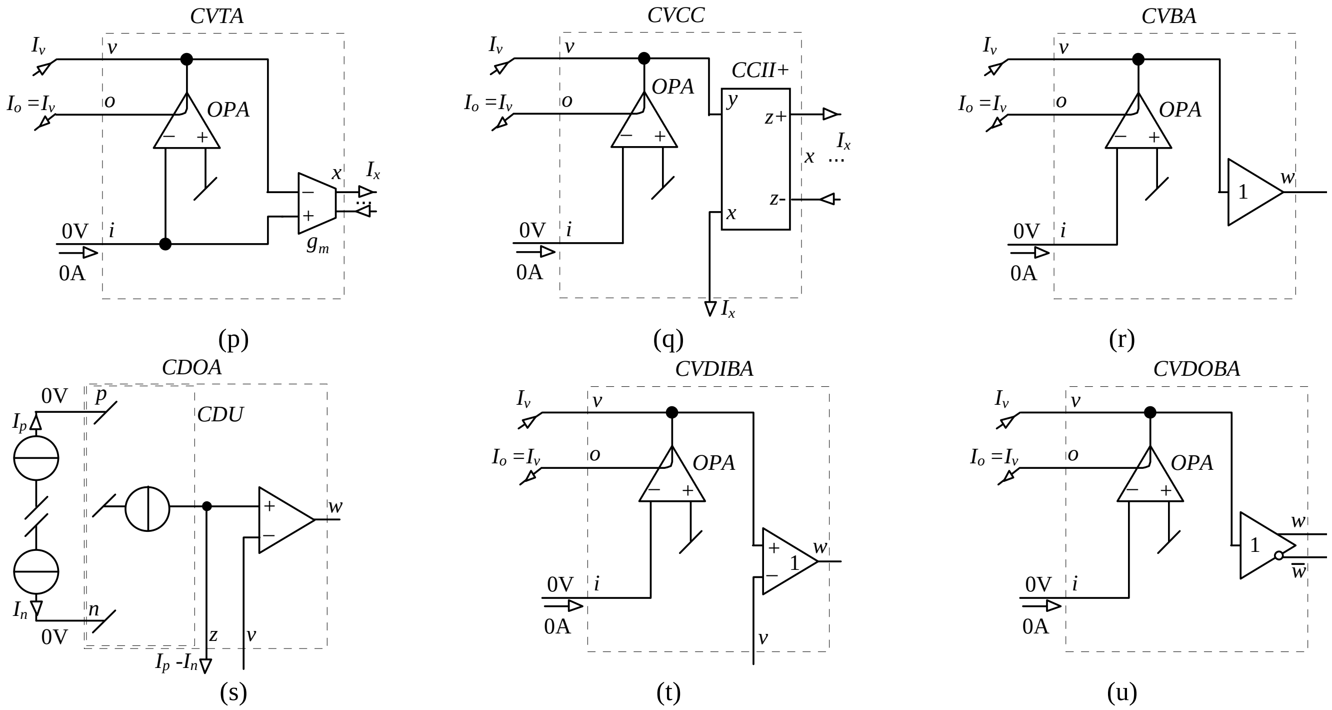

Fig. 9 (p)-(u). Proposed novel circuit elements (continued from the previous page).

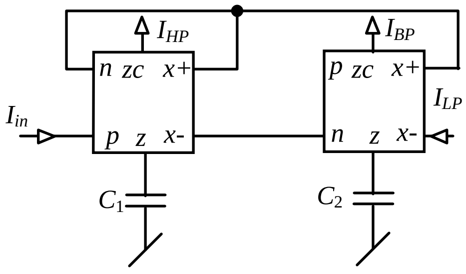

Fig. 10. Universal biquad employing ZC-CDTA elements.

possibility of electronic control. The behavioral models of the suggested elements VDBA (Voltage Differencing Buffered Amplifier), VDTA (Voltage Differencing Transconductance Amplifier), and VDCC (Voltage Differencing Current Conveyor) are shown in Figs 9 (i), (j), and (k) . Multiple copies of I_z currents are indicated here in order to increase the universality of these elements. Thus, according to the proposed methodology, the above elements should have the “ZC“ (Z Copy) attribute. Some of them have an interesting application potential: for example, the floating loss-less inductor can be simulated only by one VDTA and one grounded capacitor.

The universality of the above elements, which utilize OTAs or voltage buffers as output devices, can be increased by using the availability of differential input or output. Examples are given in Fig. 9 (l)-(o). CDDIBA (Current Differencing Differential Input Buffered Amplifier) is an extension of CDBA obtained by adding the negative high-impedance input of buffered amplifier. Similarly, CDDITA (Current Differencing Differential Input Transconductance Amplifier) uses a differential-input OTA instead of a single-input OTA employed in the conventional CDTA. CDDOBA (Current Differencing Differential Output Buffered Amplifier) provides differential output voltages whereas CDDIDOBA (Current Differencing Differential Input Differential Output Buffered Amplifier) is a combination of the CDDIBA and CDDOBA elements. Note that this methodology can also be applied to other circuit elements such as CFA, OTRA, CTTA, CCTA, CFTA, CITA, VDBA, VDTA, etc.

The last four circuit principles, indicated in Figs 9 (p), (q), (r), (s), represent attempts to find a trade-off between speed and accuracy. That is why they combine the fast and accurate elements, namely OTA, CCII, and CDU, with the conventional OpAmp in order to achieve their optimal interaction. The CVTA (Current Voltage Transconductance Amplifier) is primarily designed for current excitation into the *i* input. Connecting *v* and *i* terminals via a two-pole and thus closing the negative feedback loop will maintain the zero potential of the *i* terminal. If a capacitor serves as such a two-pole, the circuit will operate, regarding the I_x outputs, as a current integrator with electronically controlled time constant. The user can also utilize a copy of the input current via the current sensing technique. A voltage equivalent of the output current is available at the low-impedance *v* terminal.

CVCC (Current Voltage Current Conveyor) increases the application range of the CVTA, replacing the OTA by the multiple-output CCII. In the CVBA (Current Voltage Buffered Amplifier), the voltage at the *v* terminal is only buffered and its copy appears at the *w* terminal. There is a difference between connecting the load to terminals *w* and *v*: The current, sensed from the *o* terminal, is not/is affected by the load in the first/second case.

The last principle, denoted CDOA (Current Differencing Operational Amplifier), combines the input Current Differencing Unit and the conventional OpAmp. For example, loading the *z* terminal by grounded impedance Z_1 and applying the second impedance Z_2 between the *w* and *n* terminals, the voltage at the *z* terminal is transferred to the *w* output with gain $–Z_1/Z_2$ and current I_p with transfer Z_2. Figs. 9 (t) and (u) show some of the possible generalizations of CVBA, applying the concept of differential input and output.

Note that the proposed methodology generates more circuit principles than those in Fig. 9. In addition to the basic variants, we can include the “ZC“ method, i.e. the copies of I_z current (which can be of the follower, “ZF“ or of the inverter, “ZI“ types), the method of analog or digital control, thus “CC“ or „DC“ types, the method of external control of the transconductance, i.e. “e” for the OTA subblock, and the approach of differential inputs and outputs. Future research will examine which of the suggested principles can find wider practical application.

5. Conclusion

The summary of current active elements for analog signal processing, given in the introductory Sections, shows the comprehensiveness and the variety of the circuit principles used today. The reason consists in the variety of specific requirements, imposed on the analog subsystems working in various operating modes and under their interaction with digital circuits: high dynamic range, noise immunity, low supply voltage and power consumption, high linearity and high bandwidth, low nonlinear distortion, specific impedance levels, etc. The development of new circuit elements over the last ten years, for example CDBA, CDTA, ICCII, FDCCII, MCCIII, CCOA, DDOFA, FBFTFN, CFA-OTA, CC-CFA, CCTA, CCCDTA, CCCCTA, CTTA, CCCDBA, DC-CDBA, CMI, DCCF, etc. shows that the procedure of finding new circuit elements is up-to-date. The paper suggests a methodology for prospective continuation of this process, which is based on the concurrence of simple building blocks such as CDU, CF, CI, OTA, voltage buffer and OpAmp.

Acknowledgements

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