Current Conveyor: Novel Universal Active Block

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ABSTRACT

This paper describes the current conveyors used as a basic building block in a variety of electronic circuit in instrumentation and communication systems. Today these systems are replacing the conventional Op-amp in so many applications such as active filters, analog signal processing, and converters. A detailed study is presented here for its applications.

Keywords : *Current conveyors, communication systems, conventional Op-amp, active filters.*

I. INTRODUCTION

THE current-conveyor, published in 1968 [1], represented the first building block intended for current signal processing. In 1970 appeared the enhanced version of the current-conveyor: the second-generation current-conveyor CCII [2]. They used high quality PNP - NPN transistors of a like polarity and match each other but difference in current gain reduced the circuit accuracy. This is due to the base current error. The other current conveyor was devised in 1984 by G. Wilson [3] where another current-mirror configuration; known as Wilson current mirror was employed. It consists of an operational amplifier and external PNP transistors. A second generation current conveyor (CCII) was presented in 1990 using an operational amplifier and external CMOS transistors [4]. Both circuits were subject to the OP-AMP performance and again to the transistor mismatching. During that time, research societies started to notice that the voltage-mode operational amplifier is not necessarily the best solution to all analogue circuit design problems. New research findings regarding current-mode signal processing using current-conveyors were presented. Furthermore, a commercial product became available: the current-feedback operational amplifier [5, 6]. The high slew rate and wide bandwidth of this amplifier resulted in its popularity in video amplifier applications.

The current conveyor is receiving considerable attention as they offer analog designers some significant advantages over the conventional op-amp. These advantages can be pointed out as follows:

- Improve AC performance with better linearity.
- Wider and nearly constant bandwidth independent of closed loop gain.
- Relatively High slew rate (typically 2000V/?s).
- Flexibility of driving current or voltage signal output at its two separate nodes, hence suitable for current and voltage mode devices.
- Reduced supply voltage of integrated circuits.
- Accurate port transfer ratios equal to unity hence employed in low sensitivity design.
- Requirement of smaller number of passive components to perform a specific function.

In 1988 the principle of a MOS current copier was presented [7], which enabled analogue circuit designers to design different Current Conveyors using only MOS-transistors. Therefore, apart from above advantages following are the driving force behind the development of MOS Current Conveyor:

- Analog VLSI addresses almost all real world problems and finds exciting new information processing applications in variety of areas such as integrated sensors, image processing, speech

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recognition, hand writing recognition etc [5]. The need for low-voltage low-power circuits is immense in portable electronic equipments like laptop computers, pace makers, cell phones etc. Voltage Mode Circuits are rarely used in low-voltage circuits as the minimum bias voltages depend on the threshold voltages of the MOSFETs. However, in current mode circuits (CMCs), the currents decide the circuit operation and enable the design of the systems that can operate over wide dynamic range.

- MOS-transistors in particular are more suitable for processing currents rather than voltages because the output signal is current both in common-source and common-gate amplifier configurations. Common-drain amplifier configuration is almost useless at low supply voltages because of the bulk-effect present in typical CMOS-processes.
- MOS current-mirrors are more accurate and less sensitive to process variation. Therefore, MOS-transistor circuits should be simplified by using current signals in preference to voltage signals. For this reason, integrated current-mode system realizations are closer to the transistor level than the conventional voltage-mode realizations.

When signals are widely distributed as voltages, the parasitic capacitances are charged and discharged with the full voltage swing, which limits the speed and increases the power consumption of voltage-mode circuits. Current-mode circuits cannot avoid nodes with high voltage swing either but these are usually local nodes with less parasitic capacitances. Therefore, it is possible to reach higher speed and lower dynamic power consumption with current-mode circuit techniques. Current-mode interconnection circuits in particular show promising performance.

II. BASIC CURRENT CONVEYOR

A CC is a three or more port (X, Y, Z) network. Whose input-output relationship is given by:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & A & 0 \\ B & R_X & 0 \\ 0 & C & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix}$$

where A, B, C assume a value either 1, 0 or - 1 and RX is the intrinsic resistance offered by the port X to the input currents. For an ideal CC VX = VY and the input resistance (RX) at port X is zero (equation (1)). But in practical CCs, RX is a nonzero positive value.

The commonly used block representation of a CC is shown in Figure 1, where X and Y are the input terminals and Z is the output terminal.

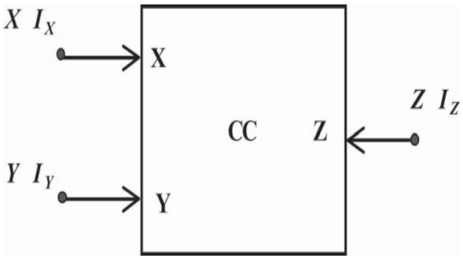


Fig. 1: General Current Conveyor Symbol

A. First Generation Current- Conveyor CCI

The first generation current conveyor CCI forces both the currents and the voltages in ports X and Y to be equal and a replica of the currents is mirrored (or conveyed) to the output port Z. Port Y is used as input for voltage signals and it should not load the input voltage source by drawing current. But, in some applications, it is desirable to draw currents from the input voltage source. When A = 1, port Y draws a current equal to the current injected at port X and the configuration is termed as CCI.

Figure 2 presents a simple MOS implementation of the first generation current-conveyor CCI. In this circuit, the NMOS transistors M1 and M2 form a current mirror that forces the drain currents of the PMOS transistors M3 and M4 to be equal and hence the voltages at the terminals X and Y are forced to be identic

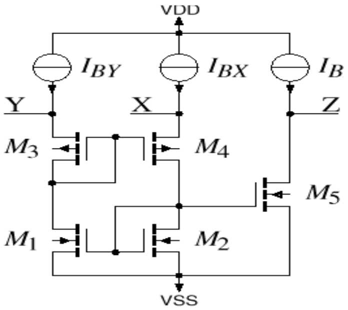


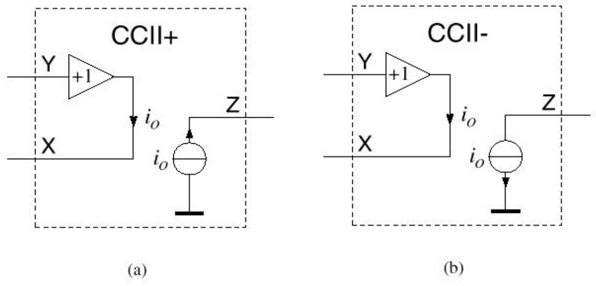
Fig. 2: simple MOS implementation of the first generation current-conveyor CCI

Because of this low impedance at the input terminal CCI circuit can be used as an accurate current amplifier. In addition, the DC-voltage level at the current input X can be easily set to a desired value by the voltage at the Y-terminal and input voltage-to-current conversion is easier .It can also be used as a negative impedance converter (NIC) [12], if the Y-terminal is terminated with a grounded resistance R. The impedance at the terminal X equals.

$$Z_X \Big|_{Z_Y=R} \approx -R.$$

B. Second Generation Current Conveyor CCII

In many applications, only one of the virtual grounds in terminals X and Y of the first generation current-conveyor is used and the unused terminal must be grounded or otherwise connected to a suitable potential. This grounding must be done carefully since a poorly grounded input terminal may cause unwanted negative impedance at the other input terminal. Moreover, for many applications a high impedance input terminal is preferable. For these reasons, the second generation current-conveyor was developed. It has one high and one low impedance input rather than the two low impedance inputs of the CCI [2].



(a)

(b)

Fig. 3: The principle of the second generation current-conveyors.
(a) The positive conveyor CCII+, iz = ix.
(b) The negative conveyor CCII-, iz =- ix.

This current-conveyor differs from the first generation conveyor in that the terminal Y is a high impedance port, i.e. there is no current flowing into Y(A = 0). The Y-terminal of the second generation current-conveyor is a voltage input and the Z-terminal is a current output, the X-terminal can be used both as a voltage output and as a current input. Therefore, this conveyor can easily be used to process both current and voltage signals unlike the first generation current-conveyor or the operational amplifier.

A further enhancement to the second generation current-conveyor is that there are two types of conveyors: in the positive current-conveyor CCII+, the currents ix and iz have the same direction as in a current-mirror and in the negative current-conveyor CCII-the currents ix and iz have opposite direction as in a current buffer. The second-generation current-conveyor is in principle a voltage-follower with a voltage input, Y, and a voltage output, X, and a current-follower (or current-inverter) with a current input X and a current output Z connected together (Figure 3). The negative second-generation current-conveyor CCII- can also be considered an idealised MOS-transistor, where the currents iy =ig =0 and iz =id = -ix = - is and the voltages vx = vs = vy = vg. An ideal MOS transistor is one that has a zero threshold voltage Vt and zero channel length modulation parameter ? and operates in the saturation region regardless of the drain-source voltage (positive or negative).

C. Third Generation Current Conveyor CCIII

Current-conveyor III was proposed in 1995 [9]. The operation of the third generation current-conveyor CCIII is similar to that of the first order current-conveyor CCI, with the exception that the currents in ports X and Y flow in opposite directions (A= -1). As the input current flows into the Y-terminal and out from the X-terminal, the CCIII has high input impedance with common-mode current signals, i.e. identical currents are fed both to Y- and X-terminals. Therefore common-mode currents can push the input terminals out from the proper operation range. Therefore this conveyor is used as current probing.

III. CURRENT-FEEDBACK OPERATIONAL AMPLIFIER

The current-feedback operational amplifier is positive second generation current-conveyor CCII+ with an additional voltage buffer at the conveyor current output (5, 7, 8). The non-inverting port (Y) exhibits high impedance to voltage signals where as the inverting port (X) present low impedance to the input current signals. The current at the inverting input (X) of the current-feedback operational amplifier is transferred to the high impedance current-conveyor output Z, causing a large change in output voltage. The current-feedback operational amplifier has a transresistance equal to the impedance level at the conveyor Z-output. Therefore, in the literature, the current-feedback operational amplifier is also referred to as a transimpedance amplifier.

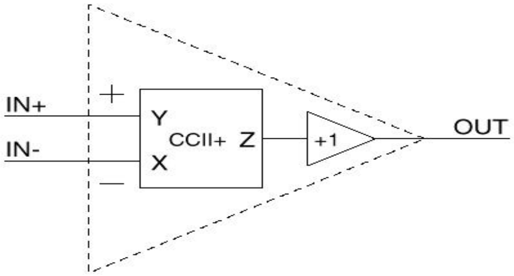


Fig. 4: The operating principle of the current-feedback operational amplifier.

The most commercial current-feedback operational amplifier is AD844 [11], where the user has access to the high impedance node TZ. This amplifier can also be utilised as a second generation current-conveyor and current to-voltage converter. The applications and advantages in realizing active filter transfer function using CFAs have received great attention because the amplifier enjoys the feature of constant feedback independent of closed loop gain and high slew rate besides having low output impedance. Thus it is advantageous to use CFA as a basic building block in the accomplishment of various analog signal-processing tasks.

IV. OPERATIONAL FLOATING CONVEYOR

The operational floating conveyor (Figure 5) is a current-mode building block that combines the transmission properties of a current-conveyor and a current-feedback operational amplifier, and has an additional output current sensing capability [13]. The matrix representation of the operational floating conveyor is

$$\begin{bmatrix} v_x \\ i_y \\ v_w \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ Z_t & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} i_x \\ v_y \\ i_w \\ v_z \end{bmatrix},$$

where Zt is the transimpedance of the internal current-feedback operational amplifier.

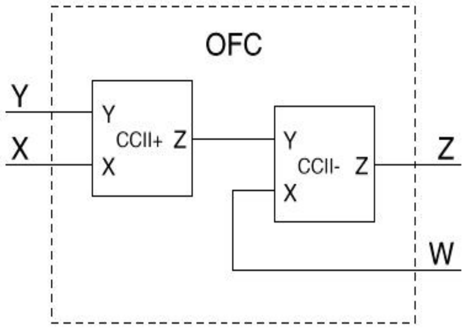


Fig. 5: The operational floating conveyor constructed of two second generation current-conveyors.

If a current-conveyor is a voltage-follower with an additional output current-sensing circuit, the operational floating conveyor is a current-feedback operational amplifier with a similar output current-sensing circuit. Alternatively this conveyor can be constructed of two cascaded current conveyors. With this circuit, it is possible to realise all four types of amplifiers: voltage, current, transconductance, and transimpedance amplifiers, as presented in Figure 6. The voltage amplifier in Figure 6 operates identically to the current-feedback operational amplifier realization of the noninverting voltage amplifier.The four amplifier types can also be realised with second generation current-conveyors as open loop amplifiers. However, when operational floating conveyor realisations are used, the amplifier gain is less sensitive to finite X-terminal impedance. Since the feedback reduces impedance levels at both X- and W-terminals, the band- widths of the amplifiers are less sensitive to parasitic capacitances. Furthermore, the feedback also reduces distortion at low frequencies but still the current signal path from W- to Z-terminal remain outside the feedback loop and thus the nonlinearity remains unchanged in that part.

A. Composite Conveyor

The operational floating conveyor can be also configured to form a high performance second generation current-conveyor as presented in Figure 7a.

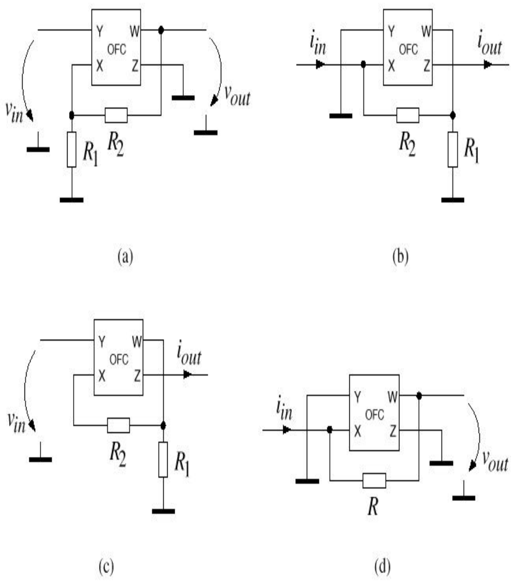
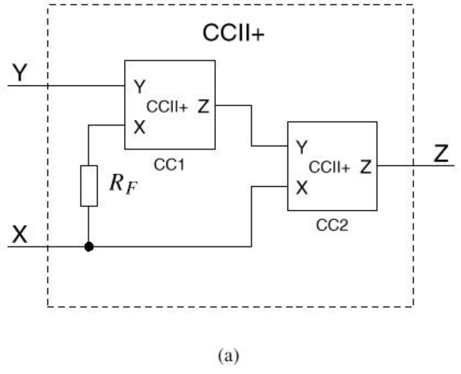


Fig. 6: Basic amplifier types realised with operational floating conveyor.
(a) Voltage amplifier (b) Current amplifier
(c) Transconductance (d) Transresistance

This is a useful technique for designing CMOS current-conveyors: with two poorly operating simple CMOS positive second generation conveyors, one positive conveyor with enhanced X-terminal impedance Zx can be constructed. In the case of simple CMOS conveyors even the resistor RF can generally be omitted as the X-terminal is high enough to prevent any stability and settling problems. There is an alternative way to construct a composite conveyor which lowers the X-terminal impedance. This composite CCII- is presented in Figure 7 b [14]. In this composite conveyor, the lower conveyor CC2 works as a negative impedance conveyor and consequently the X-terminal impedance of the composite CCII- is;

$$Z_{x,composite} = Z_{x1} + A_{i2} Z_{x2} \approx Z_{x1} - Z_{x2}.$$



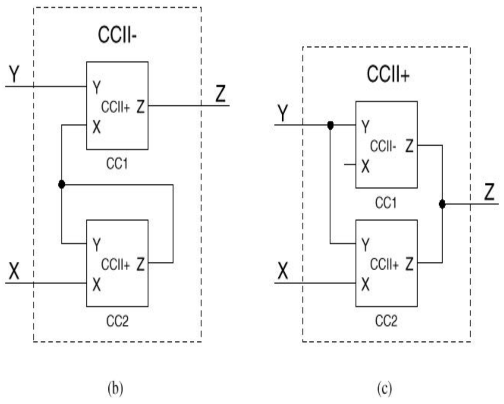


Fig. 7: Different composite conveyors.
(a) A composite CCII+ with enhanced Zx resembling an operational floating conveyor.
(b) A composite CCII- with a different technique to lower Zx.
(c) A composite CCII+ with enhanced Yx.

B. Fully Differential Current Conveyor FDDCII

Recently, a new active element called the FDCCII has been proposed [15] to improve the dynamic range in mixed- mode applications where fully differential signal processing is required. The matrix input-output relationship of the eight-terminal FDCCII is:

$$\begin{bmatrix} V_{X+} \\ V_{X-} \\ I_{-Z+} \\ I_{Z-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 & 1 & 0 \\ 0 & 0 & -1 & 1 & 0 & 1 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_{X+} \\ I_{X-} \\ V_{Y1} \\ V_{Y2} \\ V_{Y3} \\ V_{Y4} \end{bmatrix}$$

C. Operational Floating Current Conveyor OFCC

The OFCC is a five-port network, comprised of two inputs and three output ports, as shown in matrix representation 4.

In this representation, the port labelled X represents a low-impedance current input, port Y is a high-impedance input voltage, W is a low-impedance output voltage, and Z+, and Z- are the high-impedance current outputs with opposite polarities. The OFCC operates where the input current at port X is multiplied by the open loop transimpedance gain to produce an output voltage at port W. The input voltage at port Y appears at port X and, thus, a voltage tracking property exists at the input port. Output current flowing at port W is conveyed in phase to port Z+ and out of phase with that flowing into port Z-, so in this case, a current tracking action exists at the output port. Thus, the transmission properties of the ideal OFCC can be conveniently described as

$$\begin{bmatrix} i_Y \\ v_X \\ v_W \\ i_{Z+} \\ i_{Z-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & Z_t & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_Y \\ i_X \\ i_W \\ v_{Z-} \\ v_{Z-} \end{bmatrix}$$

where iy and vy are the inward current and voltage at the Y port, respectively, as shown in Fig. 4. ix and vx are the input current and voltage at the X port, respectively. iw and vw are the output current and voltage at W port, respectively. iZ and vZ and are the output current and voltage at Z+ port, respectively. Similarly, iZ- and vZ- and are the output current and voltage at the Z- port, respectively.

V. CONVERSION OF VOLTAGE-MODE CIRCUIT TO CURRENT -MODE: ADJOINT PRINCIPLE

As a wide range of voltage-mode analog circuits already exist, a straight forward method of converting these voltage-mode circuits to current-mode circuits would be very useful. In such a method a circuit using voltage ampli?ers and passive components is converted into one that contains current ampli?ers and passive components. An ideal voltage ampli?ers has in?nite input impedance and zero output impedance, while an ideal current ampli?er has zero input impedance and in?nite output impedance. Consequently, direct replacement of a voltage ampli?er with a current ampli?er will lead to different circuit behaviour.

A voltage-mode circuit can be converted into a current-mode circuit by constructing an interreciprocal network by using the adjoint principle [1, 17]. According to this principle, a network is replaced with an adjoint network Na, the voltage excitation is interchanged to a current response, and the voltage response is interchanged to a current excitation, as demonstrated in Figure 8.Thus, the resulting transfer functions of these two networks N and Na are identical:

$$H_v(s) = \frac{v_{out}}{v_{in}} = \frac{i_{out}}{i_{in}} = H_i(s).$$

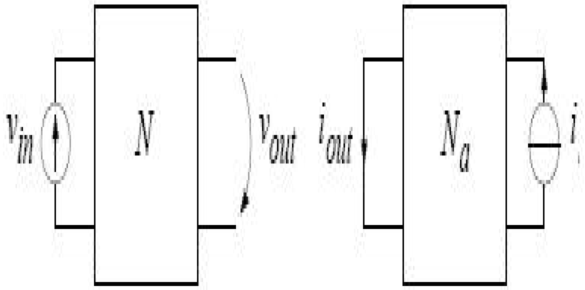


Fig. 8: Interreciprocal networks N and Na.

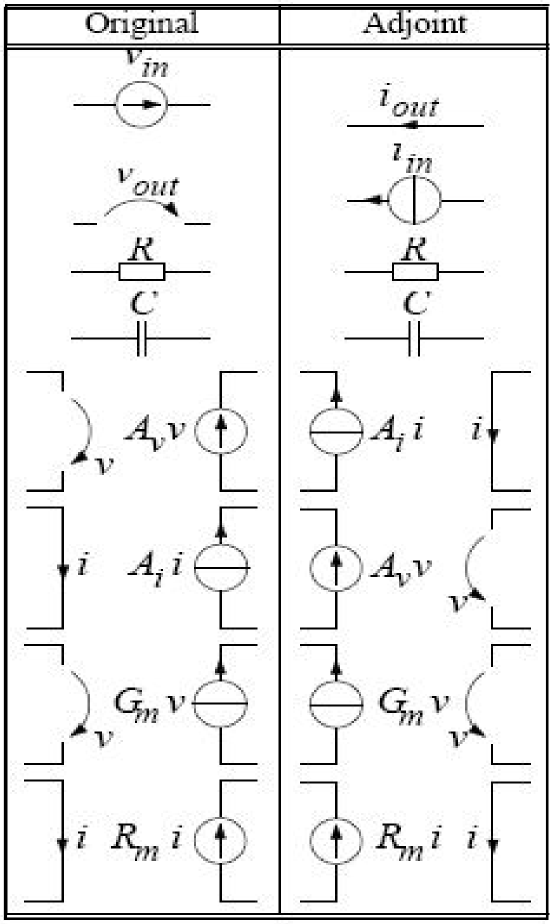
The networks N and Na are thus said to be interreciprocal to one another. When the

networks N and Na are identical, for example in the case of passive networks, the networks are said to be reciprocal. In order to maintain identical transfer functions for both the original network N and the adjoint network Na the impedance levels in the corresponding nodes of both networks should be identical. Therefore, the signal flow is reversed in the adjoint network and a voltage source is converted to a current sensing element as they both behave as short circuits. Similarly, a voltage sensing element is converted to a current source. A list of circuit elements and their adjoint elements are presented in the Table 1.

In addition, controlled sources can be converted with the same principles: the signal flow is reversed and the impedance level is kept the same. In this way, a voltage amplifier is converted to a current amplifier and a current amplifier is converted to a voltage amplifier, respectively. However, since transresistance and transconductance amplifiers are inter-reciprocal, networks containing only transresistance or transconductance amplifiers and passive elements differ only in signal direction and type.

The adjoint principle can also be applied to transistor level circuits. In this case, a bipolar transistor in a common-emitter amplifier configuration is inter-reciprocal to itself and the common-collector amplifier configuration has the common-base configuration as

Table 1: Some circuit elements with their corresponding adjoint elements



its adjoint. Converting a voltage-mode bipolar transistor circuit to a current-mode MOS-transistor circuit could be beneficial as it minimises the use of source-follower stages which have poor low-voltage performance due to the bulk effect. Bipolar transistor circuits are conventionally constructed of common-emitter and common-collector amplifier stages and the resulting MOS-transistor adjoint circuit is constructed of common-source and common-gate amplifier stages.

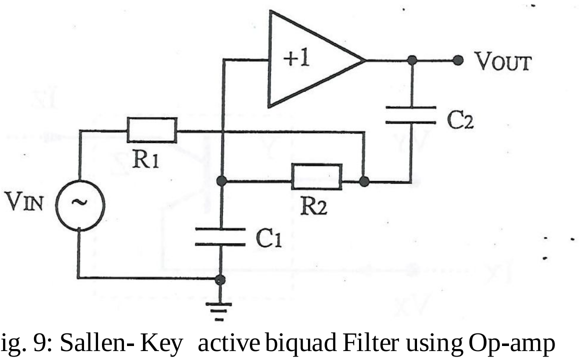


Fig. 9: Sallen- Key active biquad Filter using Op-amp

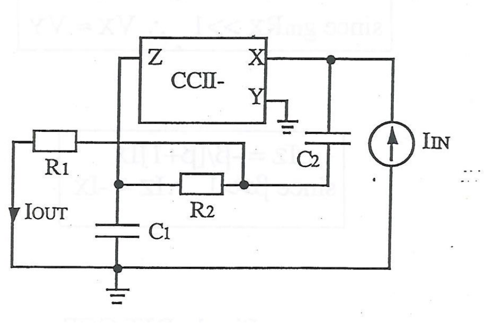
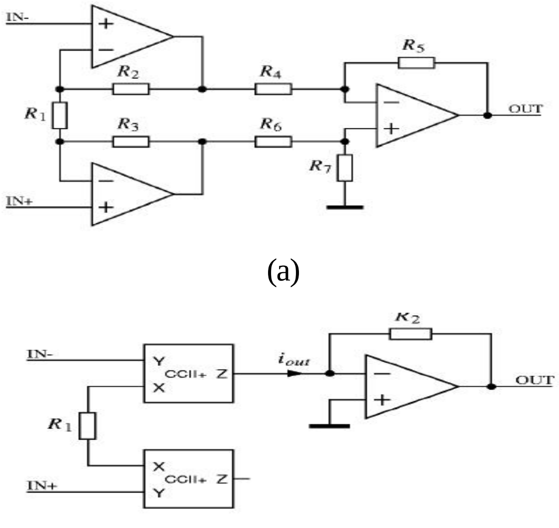


Fig. 10: Sallen-Key active biquad Filter using Current conveyor II

Using the adjoint principle the low-pass Sallen-Key circuit can be replaced with a current conveyor based circuit. The transfer function is the same for both of the circuits

$$T(s)=\frac{V_{out}}{V_{in}}=\frac{I_{out}}{I_{in}}=\frac{4kQ^2/R^2C^2}{s^2+2/RC\left[2Q(1-K)+1\right]s+4Q^2/R^2C^2}$$



(a)

(b)

Fig. 11: Instrumentation amplifiers
(a) using Op-Amp (b) using CCII+

As shown in Figure11, Instrumentation amplifiers implemented with three op-amps. It requires several matched resistors to guarantee high CMRR because of the limited gain-bandwidth product of the high-gain amplifiers the bandwidth of the CMRR is limited. A differential amplifier with high CMRR can be also realised with two current conveyor and two resistors without any matching components.

VI. CONCLUSION

From the above study it is observed that the bandwidth of the current conveyor based amplifier is large with high voltage gains as current conveyors operate in open-loop without the gain-bandwidth product limitation.

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