CHAPTER-2
CHAPTER 2

DIFFERENT CURRENT MODE DEVICES

2.1 INTRODUCTION

Since the beginning of electronics, the need of new active devices has always been very important. It has driven to the birth of transistors which have been used in amplifiers, oscillators, impedance converters, filters, etc. As the demand of amplifiers in analog signal processing field increased, the voltage operational amplifier (Op-Amp) has rapidly become the main analog block and has dominated the market since the advent of the first analog integrated circuits. Nowadays, the situation is changing because there is a new impulse towards current mode circuits, which are able to overcome the limitation of a constant gain-bandwidth product and trade-off between speed and bandwidth of Op-Amps. Therefore the performance of the circuits are improved in terms of low-voltage characteristics, slew-rate and bandwidth.

The current-conveyor, published in 1968 [1], represent the first building block intended for current signal processing. In 1970 appeared the enhanced version of the current-conveyor: the second-generation current-conveyor (CC II) [2]. In second-generation current-conveyor, high quality PNP-NPN transistors of a like polarity and match with each other is used. The difference in current gain of the transistors, due to the base current error, reduced the circuit accuracy. The current conveyor is intended as a general building block as with the Operational Amplifier (Op – Amp). But neither the first generation Current Conveyor (CC-I) nor the second generation Current Conveyor (CC-II) became popular as a consequence of introduction of integrated op-amp at the time. Because of op-amp concept has been widely used since late 1940’s, it is difficult to get any other similar concept accepted. Additionally, integrated current conveyors were difficult to realize due to lack of high performance integration technologies. During 1980’s, research societies started to notice that the voltage Operational Amplifier (Op-Amp) is not necessarily the best solution to all analog circuit design problems. Voltage Op-Amp does not perform well in applications where a current output signal is needed and consequently there is
an application field for current conveyors [3-5].

2.2 BASIC CURRENT CONVEYOR

A Current Conveyor is a three or more port \((X, Y, Z)\) network, whose input-output relationship is given by:

\[
\begin{bmatrix}
I_y \\
V_x \\
I_z
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 \\
B & R_x & 0 \\
0 & C & 0
\end{bmatrix}
\begin{bmatrix}
V_y \\
I_x \\
V_z
\end{bmatrix}
\] (2.1)

Where \(A, B, C\) assume a value either 1, 0 or -1 and \(R_x\) is the intrinsic resistance offered by the port \(X\) to the input currents. For an ideal CC, \(V_x = V_y\) and the input resistance \((R_x)\) at port \(X\) is zero.

The commonly used block representation of a Current Conveyor is shown in Figure 2.1, where \(X\) and \(Y\) are the input terminals and \(Z\) is the output terminal.

\[\text{Figure 2.1: General Current Conveyor Symbol}\]

2.3 CLASSIFICATION OF CURRENT CONVEYORS

There are several schemes for classification of Current Conveyors (CC). Most common techniques among them are based on the characteristics of its ports \(X, Y\) and \(Z\).

2.3.1 PORT Y BASED CLASSIFICATION

Port \(Y\) of the Current Conveyor 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 current from the input voltage source. So, when port \(Y\) draws a current equal to the current injected at port \(X\) \((A = 1)\), the configuration is termed as
current equal to the current injected at port \( X \) \((A = 1)\), the configuration is termed as first generation current conveyor (CC-I). When port \( Y \) draws zero current \((A = 0)\), it is second generation Current Conveyor (CC-II). Similarly, when this current is equal to the current injected at port \( X \) but of opposite polarity \((A = -1)\), the configuration is known as third generation Current Conveyor (CC-III) [6-9].

**FIRST GENERATION CURRENT-CONVEYOR (CCI)**

The first generation Current Conveyor (CC-I) forces both the currents and the voltages in ports \( X \) and \( Y \) to be equal and a replica of the current is mirrored (or conveyed) to the output port \( Z \).

![Diagram of CCI nullator-norator model](image)

Figure 2.2: (a) CCI nullator-norator model, (b) block diagram (c) Simple MOS implementation of the first generation current-conveyor CCI
In this configuration, port Y draws a current equal to the current injected at port X i.e. \((A = 1)\).

The CC-I device exhibits a virtual short-circuit input characteristics at port X and dual virtual open-circuit input characteristic at port Y. This functionality can be described by following hybrid equation:

\[
\begin{bmatrix}
I_y \\
V_x \\
I_z
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
1 & 0 & 0 \\
0 & \pm 1 & 0
\end{bmatrix}
\begin{bmatrix}
V_y \\
I_x \\
V_z
\end{bmatrix}
\]

Figure 2.2 presents nullator-norator model, block diagram and simple MOS implementation of the first generation Current-Conveyor (CC-I). Macromodels of conveyors is shown in Figure 2.2 (a). Macromodels consist from basic ideal elements nullator, norator, ideal current- and voltage-sources. Figure 2.2 (b) shows the symbol of current conveyor and Figure 2.2 (c) shows the internal structure of current conveyor. In this circuit, the NMOS transistors \(M_1\) and \(M_2\) form a current mirror that forces the drain currents of the PMOS transistors \(M_3\) and \(M_4\) to be equal and hence the voltages at the terminals X and Y are forced to be identical.

Because of low impedance at the input terminal X, CC-I 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 therefore input voltage-to-current conversion is easier. It can also be used as a negative impedance converter (NIC) [10].

SECOND GENERATION CURRENT CONVEYOR (CC-II)

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.

Table 2.1: Basic elements

<table>
<thead>
<tr>
<th>Type</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
</table>
| Nullator        | ![Nullator Symbol](nullator.png) | $V_1 = V_2$  
$I_1 = I_2 = 0$ |
| Norator         | ![Norator Symbol](norator.png) | $I_1 = -I_2$  
$V_1, V_2$ are arbitrary |
| Voltage mirror  | ![Voltage Mirror Symbol](voltage_mirror.png) | $V_1 = -V_2$  
$I_1 = I_2 = 0$ |
| Current mirror  | ![Current Mirror Symbol](current_mirror.png) | $I_1 = I_2$  
$V_1, V_2$ are arbitrary |

Second generation Current-conveyor has one high and one low impedance input rather than the two low impedance inputs as in CC-I. Current Conveyor II (CC-II) can be described by following matrix:

\[
\begin{bmatrix}
I_y \\
V_x \\
I_z
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & \pm 1 & 0
\end{bmatrix} \begin{bmatrix}
V_y \\
I_x \\
V_z
\end{bmatrix}
\]  

Equation (2.3), shows that terminal Y exhibits infinite input impedance. The voltage at
X terminal follows the Y potential. Terminal X exhibits zero input impedance, and the

(a) The positive conveyor $\text{CCII}^+$, $i_z = i_x$.
(b) The negative conveyor $\text{CCII}^-$, $i_z = -i_x$.
(c) $\text{CCI}$ nullator-norator model
(d) Low power high bandwidth current conveyor II

Figure 2.3: The principle of the second generation current-conveyors.
current flows through X port is again conveyed to the high impedance current output Z. The 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 CC-I [11].

This current-conveyor differs from the first generation current conveyor in that the terminal Y is a high impedance port, i.e. there is no current flows into Y terminal \( (A = 0) \). 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: positive current-conveyor CC-II+ and negative current-conveyor CC-II-. In the positive current-conveyor (CC-II+), the currents \( i_x \) and \( i_z \) have the same direction as in a current-mirror and in the negative current-conveyor (CC-II-) the currents \( i_x \) and \( i_z \) 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. The negative second-generation current-conveyor CCII- can also be considered an idealized MOS-transistor, where the currents \( i_y = i_g = 0 \) and \( i_z = i_d = -i_x = -i_s \) and the voltages \( v_x = v_s = v_y \). An ideal MOS transistor is one that has a zero threshold voltage \( V_t \) and zero channel length modulation parameter \( \lambda \) and operates in the saturation region regardless of the drain-source voltage (positive or negative). It's very suitable building block for design of the active- RC filters or number of special imittance (admittance) converters. Nowadays, number of high-speed and wide-bandwidth op-amps based on second generation current conveyor structure is commercially available. The Op-Amps based on second generation current conveyor structure can also be designed to operate at low voltage.

Because of the separate voltage and current inputs, both voltage and current amplifiers can easily be realized with the second-generation current conveyors and the gain can be
Because of the separate voltage and current inputs, both voltage and current amplifiers can easily be realized with the second-generation current conveyors and the gain can be set by resistor ratios as in operational amplifier circuits. Signal processing in current-conveyor circuits is based on voltage-to-current and current-to-voltage conversions and on signal buffering by voltage and current buffers. Because there is typically no feedback in current-conveyor circuits, wide bandwidth operation without any slewing at large signal amplitudes is achieved. The conventional applications of CCs include amplifiers, oscillators, filters, wave shaping circuits, analog computers etc. Low-voltage and low-power architectures of CCs are particularly suitable in the design of voltage and power starved systems.

**THIRD GENERATION CURRENT-CONVEYOR (CC-III)**

Third generation Current-conveyor (CC-III) was proposed in 1995 [7]. The operation of the third generation current-conveyor CC-III is similar to that of the first order current-conveyor CC-I, 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 CC-III 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.

\[
\begin{bmatrix}
I_y \\
V_x \\
I_z
\end{bmatrix} =
\begin{bmatrix}
0 & -1 & 0 \\
1 & 0 & 0 \\
0 & \pm1 & 0
\end{bmatrix}
\begin{bmatrix}
V_y \\
I_x \\
V_z
\end{bmatrix}
\]

(2.4)

![Diagram of CCIII nullator-norator model and simple implementation based on CCIIIs](image-url)
Figure 2.5: The circuit configuration of the CCIII-

Figure 2.6: The circuit configuration of the proposed CCIII+

2.3.2 PORT X BASED CLASSIFICATION

For voltage signals, port Y serves as input port and the port X serves as output port. The output voltage at port X can either have same polarity as that of the input voltage ($V_Y$) or that of opposite polarity. CCs in which the polarity of the output voltage is
opposite to that of the voltage applied at port Y, are termed as inverting CCs \( B = -1 \), but when the polarity at port X remains same as that of input voltage, Current Conveyor is called non-inverting Current Conveyor and \( B = 1 \).

### 2.3.3 PORT Z BASED CLASSIFICATION

Port Z is the current output port and usually, the magnitude of the output current at port Z equals to the magnitude of the current injected into port X. In some cases, however, this amplitude may be scaled version (generally up scaled) of the input current and also the direction of the current may be same or opposite to that of the current in port X. A Current Conveyor with positive current output is termed as positive Current Conveyor (CC+) and with negative output currents as negative Current Conveyor (CC−). A Current Conveyor can have two or more output ports, which can independently sink or source currents. Such a CC is known as multi port Current Conveyor. A multiport CC with both types of output ports (positive as well as negative), is known as composite port Current Conveyor.

### OTHER CC CONFIGURATIONS

Other CC configurations of Current Conveyor are Electronically Controlled Current Conveyor (ECC-II), Differential Voltage Current Conveyor (DVCC), Differential Difference Current Conveyor (DDCC), Fully Differential Current Conveyor (FDCC) and Operational Floating Conveyor (OFC). There are some other variations in the above structure. A various other introduced CC structure are Current Feedback Operational Amplifier (CFO), Composite Current Conveyors (CCC), Fully Differential Current Conveyor (FDCC), Operational Floating Current Conveyor (OFCC), Operational Transconductance Amplifier (OTA), Current Differencing Transconductance Amplifier (CDTA), Dual Output CDTA, Current Controlled CDTA (CCCDTA), Dual-Output Current Controlled CDTA (DOCDTA) etc.

### 2.4 CURRENT-FEEDBACK OPERATIONAL AMPLIFIER (CFOA)

The Current-Feedback Operational Amplifier commonly known as Current Feedback Amplifier (CFA) is positive second generation Current-Conveyor (CC-II+) with an
additional voltage buffer at the Conveyor Current output [12]. 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's Z-output. Therefore, in the literature, the Current-Feedback Operational Amplifier is also referred to as a transimpendance amplifier.

The most commercial current-feedback operational amplifier is AD844 [13], 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.

![Diagram of CFA](image)

**Figure 2.7:** The operating principle of the current-feedback operational amplifier.

### 2.5 OPERATIONAL FLOATING CONVEYOR

The operational floating conveyor 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 [14]. The matrix representation of the operational floating conveyor is:

\[
\begin{bmatrix}
V_x \\
I_y \\
V_w \\
I_z
\end{bmatrix}
= 
\begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
Z_i & 0 & 0 & 0 \\
0 & 0 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
i_x \\
v_y \\
i_w \\
v_z
\end{bmatrix}
\]

(2.5)

Where

\( Z_i \) is the transimpedance of the internal current-feedback operational amplifier.

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-

![Diagram](image)

**Figure 2.8: The operational floating conveyor constructed of two second generation current-conveyors.**

conveyors. With this circuit, it is possible to realize all four types of amplifiers: voltage, current, transconductance, and transimpedance amplifiers, as presented in Figure 2.9. The voltage amplifier operates identically to the current-feedback operational amplifier realization of the noninverting voltage amplifier. The four amplifier types can also be
realized with second generation current-conveyors as open loop amplifiers. However, when operational floating conveyor realizations 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) Voltage amplifier (b) Current amplifier
(c) Transconductance (d) Transresistance

Figure 2.9: Basic amplifier types realized with operational floating conveyor.

2.6 COMPOSITE CONVEYORS
The operational floating conveyor can also be configured to form a high performance second generation current-conveyor as presented in Figure 2.10. This is a useful technique for designing CMOS current-conveyors: with two simple CMOS positive second generation conveyors as shown in Figure 2.10 (a) and (b) and with one positive conveyor, one negative current conveyor with enhanced X-terminal impedance $Z_x$ as shown in Figure 2.10 (c). In the case of simple CMOS conveyors even the resistor $R_f$ can generally be omitted as the X-terminal is high enough to prevent any stability and settling problems. 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

$$Z_{x, \text{composite}} = Z_{x_1} + A_{i_2} Z_{x_2} \approx Z_{x_1} - Z_{x_2}$$

(a) A composite CCII+ with enhanced $Z_x$ resembling an operational floating conveyor.
(b) A composite CCII- with a different technique to lower $Z_x$.
(c) A composite CCII+ with enhanced $Y_x$.

Figure 2.10: Different composite conveyors.

2.7 FULLY DIFFERENTIAL CURRENT CONVEYOR (FDCC- II)

An active element called the FDCC-II has been proposed by El-Adawy, to improve the dynamic range in mixed-mode applications where fully differential signal processing is required [16]. The matrix input-output relationship of the eight-terminal FDCCII is:
\[
\begin{bmatrix}
V_{x+} \\
V_{x-} \\
I_{z+} \\
I_{z-}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 1 & -1 & 1 & 0 \\
0 & 0 & -1 & 1 & 0 & 1 \\
-1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
i_{x+} \\
i_{x-} \\
V_{y1} \\
V_{y2} \\
V_{y3} \\
V_{y4}
\end{bmatrix}
\] (2.6)

2.8 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 2.7. The port labeled 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. The transmission properties of the ideal OFCC can be conveniently described as:

\[
\begin{bmatrix}
I_y \\
V_x \\
V_w \\
I_{z+} \\
I_{z-}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & Z_1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 & 0
\end{bmatrix} \begin{bmatrix}
V_y \\
i_x \\
i_w \\
V_{z-} \\
V_{z+}
\end{bmatrix}
\] (2.7)

Where,

\[i_z\] and \[v_z\] are the inward current and voltage at the Y port respectively.
$i_x$ and $v_x$ are the input current and voltage at the X port, respectively.

$i_w$ and $v_w$ are the output current and voltage at W port, respectively.

$i_z$ and $v_z$ are the output current and voltage at Z+ port, respectively.

Similarly,

$i_{Z-}$ and $v_{Z-}$ are the output current and voltage at the Z- port, respectively.

### 2.9 OPERATIONAL TRANSCONDUCTANCE AMPLIFIER (OTA)

An OTA is a voltage controlled current source [17]. It takes the difference of two voltages as the input and produces current. The output current is the product of transconductance $g_m$ (ideally constant) as the proportionality factor and the difference of two input voltages. To summarize, an ideal OTA has two voltage inputs with infinite impedance (i.e. there is no input current). The common mode input range is also infinite, while the differential signal between these two inputs is used to control an ideal current source (i.e. the output current does not depend on the output voltage) that functions as an output.

Since an OTA can be used without feedback, the maximum output current can be adjusted with the transconductance $g_m$. The ideal transfer characteristic is:

$$I_{out} = g_m \left( V_{in+} - V_{in-} \right) \quad (2.8)$$

or, by taking the pre-computed difference as the input,

$$I_{out} = g_m \, V_{in} \quad (2.9)$$

The OTA is popular for implementing voltage controlled oscillators (VCO) and voltage controlled filters (VCF) for analog music synthesizers, because it can act as a two-quadrant multiplier. It is also used to drive low-impedance sinks such as coaxial cable with low distortion at high bandwidth. Many commercial available OTAs such as MAX436, OPA660 and CA3080 are in widespread use.
Figure 2.11: Model of Ideal OTA

The most simple bipolar (or FET) OTA consists of a differential pair to convert the input voltage difference to two currents I+ and I−. These two currents are then mirrored to the output so that their difference becomes the output of the OTA, while the rest of the OTA is made up of bias circuitry. The tail current I₀, which is a necessary part of the biasing, can be used to control the transconductance.

2.10 DIFFERENTIAL DIFFERENCE CURRENT CONVEYOR (DDCC)

DDCC has three voltage input terminals: Y₁, Y₂ and Y₃, which have high input impedance. Terminal X is a low impedance current input terminal [18]. There is a high impedance current output terminal Z. The electrical symbol of DDCC is shown in Fig. 2.12. The input-output characteristics of ideal DDCC is described as:

\[
\begin{bmatrix}
V_y \\
I_{y1} \\
I_{y2} \\
I_{y3} \\
I_x
\end{bmatrix} =
\begin{bmatrix}
1 & -1 & 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{y1} \\
V_{y2} \\
V_{y3} \\
I_x
\end{bmatrix}
\] (2.10)
2.11 CURRENT DIFFERENTIAL BUFFERED AMPLIFIER (CDBA)

The novel active mixed-mode block called current differential buffered amplifier (CDBA) was published in 1999 [19]. CDBA is four-port block having two differential inputs and two voltage outputs. The symbol and implementation of CDBA using CFA (AD-844) is shown in Fig. 2.13. Differential input terminals n and p are low-impedance (current) inputs, terminal z is input output node and terminal w is voltage output terminal. Moreover, it can be proved that using previously introduced reciprocal principle the CDBA is reciprocal block to DVCC+.

Figure 2.13 (a) Symbol of CDBA block (b) Realization CDBA using commercial ICs AD844
CDBA offers the advantageous features such as high slew rate, absence of parasitic capacitance, wide bandwidth. Since CDBA consists of unity gain current differential amplifier and unity gain voltage amplifier, this element is suitable for current mode signal processing applications. The current and voltage characteristics can be described by following matrix:

\[
\begin{bmatrix}
I_z \\
V_w \\
V_y \\
V_x
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 1 & -1 \\
1 & 0 & 0 & 0 \\
Z_t & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
V_z \\
I_w \\
I_y \\
I_x
\end{bmatrix}
\]  

(2.11)

Differential current input (realized by input n and p) is very useful advantage of this block. Current that flows through terminal z resulted from this differential input stage. Voltage drop, which is created due to the current flow in z terminal, is then copied on output terminal w.

This novel group of active building block is very useful in many applications such as filters, converters. It is possible to implement the differential inputs, multiply and complementary outputs to voltage conveyor as in case of current conveyor.

**2.12 CURRENT DIFFERENCE TRANSCONDUCTANCE AMPLIFIER (CDTA)**

Biolek D. introduced an active element with two current inputs and two kinds of current output, named the Current-Differencing Transconductance Amplifier (CDTA). This element is a synthesis of the DCBA (Current-Differencing Buffered Amplifier) and OTA (Operational Transconductance Amplifier) elements to facilitate the realization of current-mode analog filters.

A simple model of ideal CDTA element proposed by Biolek D. is shown in Figure 2.14 [20]. It has difference current inputs p and n. The difference of these currents flows from terminal z into an outside load. The voltage developed across the z terminal is transferred by a transconductance $g_m$ to a current taken out as a current pair to the x terminals. The last element part is transconductance operational amplifier (OTA) in
which the transconductance $g_m$ is controllable electronically through an auxiliary port.

The pair of output currents from the x terminals, shown in Figure 2.14, may have three combinations of directions: 1. Both currents can flow out (CDTA++). 2. The currents have different directions (CDTA+-). 3. Both currents flow inside the CDTA element (CDTA--).

Figure 2.14: Behavioral model of CDTA element (b) Symbol of the CDTA element, (c) Implementation by current conveyors and by OTA with double current output.

The CDTA can be characterized with the following equations:

$$V_p = V_n = 0$$  \hspace{1cm} (2.12)

$$I_z = I_p - I_n$$  \hspace{1cm} (2.13)

$$I_{x+} = g_m V_z$$  \hspace{1cm} (2.14)

$$I_{x-} = -g_m V_z$$  \hspace{1cm} (2.15)

Where $V_z = I_z \cdot Z_z$

and

$Z_z$ is the external impedance connected to z terminal of the CDTA.
In this design, CDTA is considered as combination of a current differencing unit followed by a dual-output operational transconductance amplifier, DO-OTA. Ideally, the OTA is assumed as an ideal voltage-controlled current source and can be described by $I_x = g_m (V+ - V-)$, where $I_x$ is output current, $V+$ and $V-$ denote non-inverting and inverting input voltage of the OTA, respectively. The transconductance $g_m$ is a function of the bias current. When this element is used in CDTA, one of its input terminals is grounded (e.g., $V-$ = 0V). With dual output availability, $I_{x+} = -I_{x-}$ condition is assumed. A possible CMOS-based CDTA circuit realization suitable for the monolithic IC fabrication is displayed in Figure 2.15.

Figure 2.15 (a) Symbol for the CDTA (b) CMOS-based CDTA
2.13 DUAL OUTPUT-CURRENT DIFFERENCE TRANSCONDUCTANCE AMPLIFIER (DO-CDTA)

DO-CDTA properties are similar to the conventional CDTA, except that the DO-CDTA has two x terminals. The relationship of voltages and current of DO-CDTA can be shown by following equation [21].

\[
\begin{bmatrix}
V_p \\
V_n \\
I_z \\
I_{x1} \\
I_{x2}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & g_{m1} & 0 \\
0 & 0 & 0 & g_{m2} & 0
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_n \\
V_{x1} \\
V_{x2} \\
V_z
\end{bmatrix}
\]

(2.16)

Where,

\[
g_{m1} = \frac{I_{B1}}{2V_T}, \quad g_{m2} = \frac{I_{B2}}{2V_T}
\]

$I_b$ and $V_T$ are the input bias current and thermal voltage respectively. The symbol and equivalent circuit of DO-CDTA can be respectively shown in Figure 2.16(a) and (b).

(a) DO - CDTA

(b) equivalent circuit

Figure 2.16: DO-CDTA (a) symbol (b) equivalent circuit
2.14 CURRENT CONTROLLED CDTA (CCCDTA)

The CCCDTA is composed of translinear elements, mixed loops and complementary current mirrors. Generally, CCCDTA properties are similar to the conventional CDTA, except that input voltages of CCCDTA are not zero and the CCCDTA has finite input resistances $R_p$ and $R_n$ at the p and n input terminals, respectively [22]. These parasitic resistances are equal and can be controlled by the bias current $I_{b1}$ and $I_{b2}$ as shown in the following equation.

\[
\begin{bmatrix}
V_p \\
V_n \\
I_x \\
I_z
\end{bmatrix} =
\begin{bmatrix}
R_p & 0 & 0 & 0 \\
0 & R_n & 0 & 0 \\
1 & -1 & 0 & 0 \\
0 & 0 & 0 & \pm g_m
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_n \\
V_x \\
V_z
\end{bmatrix}
\]

(2.17)

\[
R_p = R_n = \frac{V_f}{2I_{b1}},
\]

\[
g_m = \frac{I_{b2}}{2V_f}
\]

Where $g_m$ is the transconductance of the CCCDTA and $V_f$ is the thermal voltage. The symbol and the equivalent circuit of the CCCDTA are illustrated in Figure 2.17(a) and (b), respectively.

![Figure 2.17: CCCDTA (a) Symbol (b) Equivalent circuit](image-url)
2.15 DUAL-OUTPUT CURRENT CONTROLLED CDTA (DO-CCCDTA)

The DO-CCCDTA is composed of translinear elements, mixed loops and complementary current mirrors. Generally, DO-CCCDTA properties are similar to the conventional CDTA, except that input voltages of DO-CCCDTA are not zero and the CCCDTA has finite input resistances $R_p$ and $R_n$ at the p and n input terminals, respectively[23]. These parasitic resistances are equal and can be controlled by the bias current $I_{ib}$ as shown in the following equation:

$$
\begin{bmatrix}
V_p \\
V_n \\
I_z \\
I_{x1} \\
I_{x2}
\end{bmatrix} =
\begin{bmatrix}
R_p & 0 & 0 & 0 & 0 \\
0 & R_n & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & g_{m1} & 0 \\
0 & 0 & 0 & 0 & g_{m2}
\end{bmatrix}
\begin{bmatrix}
I_p \\
I_n \\
V_x \\
V_z \\
V_{x1}
\end{bmatrix}
$$

(2.18)

Where,

$$ R_p = R_n = \frac{V_I}{2I_{ib}}, $$

$$ g_{m1} = \frac{I_{ib}}{2V_I}, $$

$$ g_{m2} = \frac{I_{ib}}{2V_I} $$

![Diagram](a)

![Diagram](b)

Figure 2.18: DO-CCCDTA (a) Symbol (b) Equivalent circuit.
2.16 CURRENT FOLLOWER TRANSCONDUCTANCE AMPLIFIER (CFTA)

The schematic symbol and the ideal behavioral model of the CFTA are shown in Figure 2.19 (a) and (b). It has one low-impedance current input $f$ port. The current flows from port $Z$. In some applications, to utilize the current through $Z$ terminal, an auxiliary $Z_c$ ($Z$-copy) terminal is used [24]. The internal current mirror provides a copy of the current flowing out of the $Z$ terminal to the $Z_c$ terminal. The voltage $V_z$ on $Z$ terminal is transferred into current using transconductance $g_m$, which flows into output terminal $X$. The $g_m$ is tuned by $I_u$. In general, CFTA can contain an arbitrary number of $x$ terminals, providing currents $I_x$ of both directions.

The characteristics of the ideal CFTA are represented by the following hybrid matrix:

$$
\begin{bmatrix}
V_f \\
I_{z,zc} \\
I_x
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 0 & \pm g_m
\end{bmatrix}.
\begin{bmatrix}
I_f \\
V_x \\
V_z
\end{bmatrix}
$$

(2.19)

Figure 2.19: CFTA (a) Symbol (b) Equivalent circuit

2.17 CONVERSION OF VOLTAGE-MODE CIRCUIT TO CURRENT-MODE: ADJOINT PRINCIPLE

Realization of Current mode filter techniques is often complicated and demand a lot of time consuming mathematical calculations. In contrast, by simply using the principle of
network transposition, current-mode filter structures can be obtained from the associated voltage-mode counterparts.

As a wide range of voltage-mode analog circuits already exist, a straightforward method of converting these voltage-mode circuits to current-mode circuits would be very useful. In such a method, a circuit using voltage amplifiers and passive components is converted into one that contains current Amplifiers and passive components. An ideal voltage Amplifier has infinite input impedance and zero output impedance, while an ideal current Amplifier has zero input impedance and infinite output impedance. Consequently, direct replacement of a voltage Amplifier with a current Amplifier 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. According to this principle, a network N 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 2.20. Thus, the resulting transfer functions of these two networks N and Na are identical:

$$H_v(s) = \frac{V_{out}}{V_{in}} = \frac{I_{out}}{I_{in}} = H_i(s)$$  \hspace{1cm} (2.20)

![Interreciprocal networks N and Na](image)

**Figure 2.20: Interreciprocal networks N and Na**

The networks N and Na are thus said to be inter-reciprocal 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 2.2.

**Table 2.2: Some circuit elements with their corresponding adjoint elements**

<table>
<thead>
<tr>
<th>Original</th>
<th>Adjoint</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

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 its adjoint. Converting a voltage-mode bipolar transistor circuit to a current-mode MOS-transistor circuit could be beneficial as it minimizes 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.

![Diagram](image)

(a)

(b)

**Figure 2.21: Sallen-Key active biquad Filter using (a) Op-amp (b) Current conveyor II**

**2.18 CONCLUSION**

In this chapter, review of different Current mode devices has been presented. The concept of modularity has been introduced in analog circuit design through reconfiguring a current conveyor as CFAs and OFCs. We have seen that these Current mode devices perform better than operational amplifier in almost all signal-processing

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applications, because of high slew rate and wide bandwidth. The circuit of current mode devices are now available in custom-built analog ICs. It is possible to explore new type of devices and their applications.
REFERENCES:


[18] Usa Torteanchai, Montree Kumnagern, Kobchai Dejhan, "A CMOS Log-Antilog


