CHAPTER 5

CURRENT CONVEYOR BASED ACTIVE FILTER

In this chapter two circuit configurations are proposed for realizing all five filters with minimum number of current conveyors and passive components. The first circuit employs two balanced current conveyors and six passive components. This circuit has high input impedances and realizes filters with orthogonality in between quality factor and cutoff/central frequency and low sensitivities to parameter variation. The second circuit realizes a multifunction filter using two current conveyors, one OTA and six passive components.

The basic circuit configuration of current conveyor and its working are discussed in the following section. The subsequent sections present the current conveyor based existing filter circuits, the proposed filter circuits, main results and conclusion.

5.1 CURRENT CONVEYOR (CC)

In 1954 Tellegen introduced the concept of an Ideal amplifier as a general building block for the implementation of linear and non-linear analogue systems [2]. This lead device is a two port network with four associated variables $V_1$, $I_1$, $V_2$ and $I_2$. Further, Tellegen also discussed the properties of a set of 4 ideal amplifiers as controlled sources each with well defined input and output impedances ($R_{\text{in}}$ and $R_{\text{out}}$) as follows:

- Voltage amplifiers referred as Voltage Controlled Voltage Source (VCVS) with $R_{\text{in}} = \infty$ and $R_{\text{out}} = 0$

- Current amplifiers referred as Current Controlled Current Source (CCCS) with $R_{\text{in}} = 0$ and $R_{\text{out}} = \infty$

- Trans-resistance amplifiers referred as Current Controlled Voltage Source (CCVS) with $R_{\text{in}} = R_{\text{out}} = 0$
• Transconductance amplifier referred as Voltage Controlled Current Source (VCCS) with
  \[ R_{\text{in}} = R_{\text{out}} = \infty \]

These controlled sources have infinite gain and output voltage or current which are directly proportional to input voltage or current and are independent of any loading effects. Historically, the first controlled source (VCVS), employing discrete thermo-ionic valves emerged dominantly which could be easily cascaded to provide voltage controlled output with high gain. Subsequently, with the advent of integrated circuit technology the voltage op-amp architecture was implemented in the silicon. The differential amplifiers input stage voltage op-amp has a special feature of rejecting common mode signals. Further, the implementation of single terminal output of the op-amp is very easy as compared to balanced output. The single terminal output may be employed to provide negative feedback and to drive the load conveniently. The architecture of voltage op-amp suffers from the limitation in its performance and versatility. The performance is limited by gain-bandwidth product and slew rate, whose maximum value is determined by the input stage bias current. Further, the device with the single output terminal cannot be easily configured in controlled current mode in the closed loop configurations.

The fixed gain-bandwidth product of voltage op amp limits the frequency performance of the device in situation where high closed loop gain is required. The solution is to employ current feedback amplifiers. It is the combination of current controlled voltage source (CCVS) with an additional voltage follower (VF) as shown in Figure 5.1. The current feedback op-amp may be configured as same as conventional voltage controlled op-amp as shown in Figure 5.2.

![Operating principle of current feedback amplifier (CFA)](image_url)
The feedback is applied to low impedance input terminal. The resulting bandwidth is decided by the feedback resistance $R_f$, keeping $R_1$ free to decide the voltage gain. It does not have fixed gain bandwidth product. It has higher slew rate capability than the conventional op-amp.

Compared to voltage mode, current mode signals could be easily processed to minimize the total power consumption with low impedance levels and low output voltage swing. These circuits are well suited for capacitive load as compared to voltage mode. In 1968, Sedra [114] had shown that signal processing in current mode is much faster than in voltage mode. This was justified by him by proposing a circuit, called current conveyor. The current conveyor circuit, basically being an inner part of the op-amp, works in the open loop mode, so as to provide higher frequency range of operation than the conventional operational amplifier and high input output impedance for cascading of the circuits. The current conveyors are very popular among the analog circuit designers for the realization of controlled sources, impedance converters, impedance inverters, gyrators, filters, oscillators and the wave form generator circuits. Basically current conveyor is a three terminal device as shown in Figure 5.3.
Based on the terminal relations the current conveyors may be classified in three categories, which are discussed in the following subsections.

5.1.1 FIRST GENERATION CURRENT CONVEYOR (CCI)

The port relation of the 3-port first generation current conveyor, presented by Smith and Sedra [114] in 1968, may be represented by equation (5.1).

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

(5.1)

This basic current conveyor circuit employed 3 NPN and 2 PNP bipolar junction transistors as shown in Fig 5.4.
The transistor $Q_1$ acts as current source, which is realized with a voltage source connected in series with a resistance. The transistor $Q_1$ and $Q_2$ constitute a current mirror with the emitter terminal of $Q_2$ connected to ground and therefore same current owing through the emitter terminals of $Q_2$ and $Q_1$. Remaining three matched NPN-transistors $Q_3$, $Q_4$ and $Q_5$ also form current mirrors. Since the output current is taken from the collector terminal of $Q_5$, the circuit offers high output impedance. If the emitter terminal of $Q_2$ is connected to supply voltage $V_y$ in place of ground, the voltage at emitter terminal of $Q_1$ will become $V_y$ irrespective of any current owing through it. Thus virtual short circuit appears at $X$ and $Y$ terminals. As a result, the currents $i_y$ and $i_z$ flowing through collector terminals of the transistors $Q_1$ and $Q_5$ are equal to $i_x$ flowing through collector terminal of $Q_2$. The proposed circuit is therefore called current conveyor and is referred as first generation current conveyor (CCI).

The major problem associated with the CCI shown in Figure 5.4 arises in the fabrication of high quality matched pnp transistors. With the availability of complementary devices in CMOS technology, Temes and Ki [117] have reported a CMOS current amplifier/ buffer design for instrumentation process with gain accuracy dependent on the choice of mirror complexity. The circuit proposed by them is basically a CMOS version of CCI as shown in Figure 5.5.

Due to low input impedance CCI can be used as a current amplifier. It is used as wideband current measuring device [129, 133]. It may also be used as a negative impedance converter by
connecting a resistance between $Y$ terminal and ground \[132\]. The transconductance of MOSFET may be controlled and manipulated by incorporating CCI.

### 5.1.2 SECOND GENERATION CURRENT CONVEYOR (CCII)

The first generation current conveyor circuit has low input impedance, which is not desirable in many applications. To increase the veracities of the current conveyor, second generation current conveyor (CCII) having three terminals, was introduced by Sedra and Smith \[115\] in 1970. The symbolic representation of CCII is similar to CCI as shown in Figure 5.3. The port relation of CCII is given by equation (5.2).

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

This current conveyor differs from the first generation in terms of terminal impedances. It offers low input impedance at terminal $X$ and high input impedance at $Y$ terminal as compared to two low input impedances of CCI. Whereas, input voltage can be introduced at $Y$ terminal, $X$ terminal can be used for both current input and voltage output. CCII can be used in both voltage and current mode operations. Further, the current conveyor may be classified as positive current conveyor and negative current conveyor. In the positive current conveyor the direction of the current through $X$ and $Z$ terminals are same. While the direction of currents through the $X$ and $Z$ terminals are opposite to each other in the negative current conveyor. In both the positive and negative CCII, there exists a voltage follower between the $Y$ and $X$ terminals and current follower between $X$ and $Z$ terminals as shown in Fig 5.6.

![Figure 5.6: Principle of second generation current conveyor (CCII)](image)
The second generation current conveyor can be realized using MOS transistors. Figure 5.7 shows Class-A MOS implementation of second generation current conveyor, which has low output impedance.

![Image]

**Figure 5.7:** Class-A realization of second generation current conveyor

An improvement in the output impedance of the Figure 5.7 is achieved by employing push-pull output stage as shown in Figure 5.8. It also provides a larger operating range as compared to Class-A implementation of Figure 5.7. However, larger output current is obtained at the cost of increased nonlinearity.
CCII is widely used for current mode and voltage mode circuits. It can be employed for realization of various filter circuits and oscillators. Although CCII does not employ negative feedback, its bandwidth is very high, ideally infinite. The bandwidth is practically limited by the internal MOS capacitances. The device has following limitations:

- Current conveyor can be used as voltage amplifier but the gain of the circuit is lesser than that available with the operational amplifier.

- Accuracy of the current conveyor is affected by the gain of the voltage and current follower operations.
5.1.3 THIRD GENERATION CURRENT CONVEYOR (CCIII)

Another current conveyor similar to the first generation current conveyor was introduced in 1995 by Fabre et al [125]. It is referred as CCIII and differs from the first generation current conveyor with the direction of current in Y terminal being opposite to the direction of current in X terminal. The terminal relation of CCIII is expressed by the equation (5.3).

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

(5.3)

The CMOS realization of the CCIII is shown in Figure 5.9.

![Figure 5.9: CMOS realization of third generation current conveyor (CCIII)](image)

Like CCI, the impedances at X and Y terminals of the CCIII are low. CCIII is very useful in many applications as it provides the current in the floating terminal. The main features of CCIII are low gain errors, high linearity and wide frequency response. In addition, the cascading of CCIII with other circuits is easier owing to high output impedance at Z-terminal, without need of additional active element. It may also be used as the input cell of probes and current measuring devices.
5.2 EXISTING REALIZATIONS OF FILTERS USING CURRENT CONVEYOR

In 1997 Higahimura et al. [127] proposed a universal voltage-mode filter that can realize low-pass, high-pass, band-pass, all-pass and notch filters using seven current conveyors, two capacitors and eight resistors shown in fig 5.10.

The voltage mode transfer function of the circuit is given by equation (5.4):

$$\frac{V_o}{V_{in}} = s^2 \frac{C_1 C_2 R_3 R_5}{R_3} - s \frac{C_1 R_4}{R_3} + \frac{1}{R_3}$$  \hspace{1cm} (5.4)$$

The angular frequency $\omega_0$ and quality factor $Q$ of the filters may be expressed as follows:
As evident from equations (5.5) and (5.6), the quality factor \( Q \) is independent of cutoff frequency \( \omega_0 \) and may be controlled independently by changing resistance \( R' \). The various filter responses can be obtained by proper selection of resistance as shown below:

- **Lowpass Filter**: \( R_3 = R_2 = \infty \)
- **Bandpass Filter**: \( R_1 = R_3 = \infty \)
- **Highpass Filter**: \( R_2 = R_1 = \infty \)
- **Notch Filter**: \( R_2 = \infty \)
- **Allpass Filter**: \( R_3 / R'_3 = R_2 / R'_2 = R_1 / R'_1 \)

The sensitivities of \( \omega_0 \) and \( Q \) to passive components are very small and are expressed as follows:

\[
S_{C_1, C_2, R_k, R'_k, R'_k}^{\omega_0} = -\frac{1}{2}
\]

\[
S_{R_k}^{\omega_0} = \frac{1}{2}
\]

\[
S_{R_k}^{Q} = 1
\]

\[
S_{C_1, C_2, R_k, R'_k, R'_k}^{Q} = -\frac{1}{2}
\]

\[
S_{C_1}^{Q} = \frac{1}{2}
\]
The voltage gain of the filter response is also independent of the cutoff frequency. The major disadvantage of the proposed circuit is that several filter responses are obtained by various combinations of passive components, which limits the realization of the filter in the form of a monolithic circuit.

Ozoguz et al. [131] realized high-pass, low-pass and band-pass filter using three positive current conveyor and five passive components as shown in Figure 5.11.

The circuit has one input and three output terminals and realizes LP, BP and HP response at nodes $I_{O1}$, $I_{O2}$ and $I_{O3}$ respectively. All the output nodes offer high impedances. The transfer function of these filter circuits having same cutoff/center frequency and quality factor are given by equation:

$$\omega_0 = \frac{1}{\sqrt{R_1 R_3 C_2 C_4}}$$  \hspace{1cm} (5.8)

$$Q = \frac{R_3 C_4}{R_1 C_2}$$  \hspace{1cm} (5.9)

In 1999 Chang and Lee [129] proposed voltage mode low-pass, band-pass and high-pass filter realization with single input and three outputs employing only current conveyors, two grounded capacitors and three resistors as shown in Figure 5.12.
Toker et al. [133] realized high output impedance trans-admittance type continuous-time multifunction filter (low-pass, high-pass and band-pass) employing three positive type current conveyor and five passive components.
Their circuit offers high output impedance. Most of these circuits which appeared in the literature realize three basic filter responses low pass, high pass and band pass only. Notch and all pass filters can not be realized by these configurations.

5.3 PROPOSED FILTER CIRCUIT

The proposed filter realization employs two balanced output second generation current conveyors (CCII). A balanced output CCII is a four terminal device [135], which is obtained with the combination of CCII+ and CCII-. This balanced output current conveyor, represented symbolically by Figure 5.14, may be described by the following terminal characteristics

Figure 5.14: Balanced Output Current Conveyer

\[
\begin{bmatrix}
V_x \\
I_y \\
I_{z^+} \\
I_{z^-}
\end{bmatrix} =
\begin{bmatrix}
0 & B & 0 & 0 \\
0 & 0 & 0 & 0 \\
K & 0 & 0 & 0 \\
-K & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
I_x \\
V_y \\
V_{z^+} \\
V_{z^-}
\end{bmatrix}
\] (5.10)

where the parameters B and K are frequency dependent and ideally B=1 and K=1. All the basic filters (low pass, high pass, band pass and notch filter) may be realized by selecting appropriate input terminals of the circuit.

The proposed voltage mode multifunction filter circuit employs two balanced output second generation current conveyors (CCII), four resistors and two grounded capacitors as shown in Figure 5.15. The circuit has one output terminal and four input terminals. The analysis and simulation results of the realized filter are given in the following subsections.
5.3.1 ANALYSIS USING IDEAL CURRENT CONVEYOR

The transfer function of the circuit is

\[
V_{out} = \frac{s^2 C_2 C_5}{D(s)} \left[ \frac{R_1 R_6}{s^2 C_2 C_5} V_1 + \frac{R_1 R_3 R_6}{s C_2} V_2 + \frac{R_1 R_3 R_6}{s^2 C_2 C_5} V_3 + \frac{R_1 R_3}{s^2 C_2 C_5} V_4 \right]
\]  

(5.11)

where \(D(s) = s^2 C_2 C_3 R_4 R_5 R_6 + s C_2 R_4 R_5 R_6 + (R_1 R_3 + R_1 R_6)\)

Thus by using equation (5.11) all five filters responses low-pass, high-pass, band-pass notch and all-pass can be realized at the single output terminal by selecting the proper input terminals as shown in Table 5.1.
Table 5.1: Various filter responses using current conveyor based multifunction filter

<table>
<thead>
<tr>
<th>Filter/Input</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-pass</td>
<td>Vᵢₙ</td>
<td>0</td>
<td>0</td>
<td>Vᵢₙ</td>
</tr>
<tr>
<td>High-pass</td>
<td>0</td>
<td>Vᵢₙ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Band-pass</td>
<td>0</td>
<td>0</td>
<td>Vᵢₙ</td>
<td>0</td>
</tr>
<tr>
<td>Notch</td>
<td>Vᵢₙ</td>
<td>Vᵢₙ</td>
<td>0</td>
<td>Vᵢₙ</td>
</tr>
<tr>
<td>All-pass</td>
<td>Vᵢₙ</td>
<td>Vᵢₙ</td>
<td>- Vᵢₙ</td>
<td>Vᵢₙ</td>
</tr>
</tbody>
</table>

Since all the filter transfer functions have same characteristics equations, the cutoff/central frequency, bandwidth and the quality factor of all the filters are same, and are respectively given by equation 5.12- 5.14.

\[
\alpha_0 = \sqrt{\frac{R_1 + R_t}{R_1 R_4 R_6 C_2 C_5}} \tag{5.12}
\]

\[
\frac{\alpha_0}{Q} = \frac{1}{R_2 C_3} \tag{5.13}
\]

\[
Q = R_5 \sqrt{\frac{C_2 (R_1 + R_t)}{R_1 R_4 R_6 C_5}} \tag{5.14}
\]

From the perusal of above equation it is clear that using resistance \( R_3 \) the quality factor of the filter can be changed without affecting the cutoff/central frequency. The sensitivity analysis of the proposed circuit in terms of cutoff/central frequency and the quality factor is as follows:

\[
S_{C_2, C_5, R_3}^{α₀} = -\frac{1}{2} \tag{5.15}
\]

\[
S_{R_5}^{α₀} = -\frac{R_6}{2(R_1 + R_t)} \tag{5.16}
\]
\[ S_{R_{S}}^{\alpha_{0}} = -\frac{R_{i}}{2(R_{i} + R_{o})} \]  
(5.17)

\[ S_{R_{S}}^{O} = 1 \]  
(5.18)

\[ S_{C_{2}}^{O} = \frac{1}{2} \]  
(5.19)

\[ S_{R_{i}, C_{3}}^{O} = -\frac{1}{2} \]  
(5.20)

\[ S_{R_{i}}^{O} = -\frac{R_{a1}}{2(R_{i} + R_{o})} \]  
(5.21)

\[ S_{R_{o}}^{O} = -\frac{R_{i}}{2(R_{i} + R_{o})} \]  
(5.22)

As per these equations the sensitivity of \( Q \) and \( \omega_{0} \) with respect to passive components parameter variation is \( \pm \frac{1}{2} \) except \( S_{R_{i}}^{O} = 1 \).

**5.3.2 NON-IDEAL ANALYSIS OF THE PROPOSED CIRCUIT**

Practically the parameters \( B \) and \( K \) are frequency dependent. The parameter \( B_{1}, K_{1} \) and \( B_{2} \) and \( K_{2} \) represent the corresponding gain of the two dual output current conveyors and their values are real and close to unity. The behavior of the circuit at the output terminal may therefore be expressed as:

\[ V_{out} = \frac{s^{2}C_{1}C_{3}}{D(s)} \left[ \frac{R_{i}R_{o}}{s^{2}C_{2}C_{3}}V_{1} + K_{1}K_{2}B_{2}R_{i}R_{o}R_{4}R_{6}V_{2} + \frac{K_{1}K_{2}B_{2}R_{i}R_{o}R_{4}R_{6}}{sC_{2}}V_{3} + \frac{R_{i}R_{o}}{s^{2}C_{2}C_{3}}V_{4} \right] \]  
(5.23)

where \( D(s) = K_{1}K_{2}B_{1}B_{2}(s^{2}C_{2}C_{3}R_{i}R_{4}R_{6} + sC_{5}R_{i}R_{4}R_{6}) + (R_{i}R_{3} + R_{3}R_{6}) \).

The cutoff/central frequency, bandwidth and the quality factor of the filters with non-ideal parameters are therefore given by the following equations:
It is observed that bandwidth of the filter does not depend on the non-ideal parameters and the effect on the cutoff/central frequency and the quality factor is negligible. The sensitivity analysis of the cutoff/central frequency and the quality factor is obtained in terms of following equations:

\[ \omega_0 = \sqrt{\frac{R_1 + R_6}{K_1 K_2 B_1 B_2 R_1 R_3 R_4 C_2 C_5}} \]  
\[ \frac{\omega_0}{Q} = \frac{1}{C_2 R_3} \]  
\[ Q = R_3 \sqrt{\frac{C_3 (R_1 + R_6)}{K_1 K_2 B_1 B_2 R_1 R_4 R_6 C_5}} \]

So it is observed that sensitivity of Q and \( \omega_0 \) are ±1/2 except \( S_{R_6}^Q = 1 \).

### 5.3.3 SIMULATION RESULT

The balanced current conveyor in the proposed circuit is realized by the commercially available AD844 and the operational transconductance amplifier LM13700. AD844 in open-loop mode it acts as CCII+. For the realization of CCII-, the output of the AD844 is fed to LM13700. The bias current of the LM13700 and load impedance at the input terminal of OTA is adjusted such
that output current of OTA is in out of phase with the output current of the AD844. Figure 5.16 displays the simulation result for the proposed filter which matches with the designed specifications. The circuit is designed for $f_0 = 22.5$ kHz and $Q=14.14$ by considering $R_1 = R_4 = R_6 = 10k\Omega$, $C_2 = C_5 = 1$ nF and $R_3 = 100k\Omega$. The theoretical results are verified to match with simulation result.

![Figure 5.16 (a): Proposed low pass filter magnitude response using balanced current conveyor](image1)

![Figure 5.16 (b): Proposed low pass filter phase response using balanced current conveyor](image2)
Figure 5.16 (c): Proposed high pass filter phase response using balanced current conveyor

Figure 5.16 (d): Proposed high pass filter phase response using balanced current conveyor
Figure 5.16 (e): Proposed band pass filter magnitude response using balanced current conveyor

Figure 5.16 (f): Proposed band pass filter phase response using balanced current conveyor
Active filters with current/voltage controllable frequency have a wide range of applications in the signal processing and instrumentation area. Tsividis et al. [54] employed the realization of on chip MOSFET as voltage controlled resistor. Their contributions and several other research papers may be considered to be motivation for the VLSI industry to make on chip tunable filters [137-139]. These realizations have small range of variation in the frequency. The OTA-C structure is highly suitable for realizing electronically tunable continuous time filters. A number of voltage mode/current mode OTA-C biquad have been reported in the literature. In 1996, Fidler and Sun [140] proposed realization of current mode filter with multiple inputs and two outputs at different nodes using four dual output OTA’s and two grounded capacitors. Later, Chang [128] proposed multifunctional biquadratic filters, using three operational transconductance amplifiers and two grounded capacitors. In 2003, Tsukutani et al. [55] proposed current mode biquad with single input and three multiple outputs using three OTAs and current follower (CF).

In the recent years there has been emphasis on implementation of the voltage /current mode active filters using second generation current conveyors (CCIIs) which provide simple realization with higher bandwidth, greater linearity and larger dynamic range. In 2001 Wang and Lee [141] implemented insensitive current mode universal biquad MIMO realization using three balanced output current conveyors and two grounded capacitors. In 2004 Minaei and Tuikoz [142] proposed electronically tunable current mode filters employing five current controlled current conveyors and grounded capacitors. A tunable current mode multifunction filter was reported in 2008 using five universal current conveyors and eight passive components [136]. No optimal circuit design using current conveyor II with on chip tenability appears to have been reported in the literature. In the following sub section tunable multifunction filter circuit is presented.
5.4.1 PROPOSED TUNABLE MULTIFUNCTION CIRCUIT

The proposed multifunction filter circuit employs using two current conveyors, one OTA, four resistors and two capacitors as shown in Fig 5.17.

The transfer function of the above circuit using nodal analysis is as follows:

\[
V_{\text{out}} = \frac{1}{D(s)} \left( s^2 C_2 C_5 R_4 R_6 g_m V_2 + s C_5 g_m R_4 R_5 V_3 + R_3 V_1 \right)
\]

(5.31)

where

\[
D(s) = s^2 C_2 C_5 g_m R_4 R_6 + s C_5 g_m R_4 R_5 + R_3
\]

(5.32)

Low pass, band pass, high pass, notch and all pass filter responses may be realized using (5.31) at the single output terminal by applying proper inputs at different nodes as shown in Table 5.2.
### Table 5.2: Various filter responses using tunable multifunction filter

<table>
<thead>
<tr>
<th></th>
<th>$V_1$</th>
<th>$V_2$</th>
<th>$V_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low pass</td>
<td>$V_{in}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>High pass</td>
<td>0</td>
<td>$V_{in}$</td>
<td>0</td>
</tr>
<tr>
<td>Band pass</td>
<td>0</td>
<td>0</td>
<td>$V_{in}$</td>
</tr>
<tr>
<td>Notch</td>
<td>$V_{in}$</td>
<td>$V_{in}$</td>
<td>0</td>
</tr>
<tr>
<td>All pass</td>
<td>$V_{in}$</td>
<td>$-V_{in}$</td>
<td>$V_{in}$</td>
</tr>
</tbody>
</table>

Since the denominators for all the filter responses are same, the filtering parameters: cutoff/central frequency ($\omega_0$), bandwidth ($\omega_0/Q$) and quality factor ($Q$) are given by:

$$\omega_0 = \frac{1}{\sqrt{R_1 R_4 R_6 C_2 C_3 g_m}}$$  \hspace{1cm} (5.33)

$$\frac{\omega_0}{Q} = \frac{1}{R_3 C_2}$$  \hspace{1cm} (5.34)

$$Q = R_3 \frac{C_2}{g_m R_1 R_4 R_6 C_5}$$  \hspace{1cm} (5.35)

It can be seen from equation (5.33) - (5.35), the quality factor may be tuned independently by $R_3$ without changing the cutoff/central frequency. The cutoff/central frequency of the filter can be tuned by varying the $g_m$. The transconductance of the OTA ($g_m$) is tunable from the bias current of the OTA.

$$g_m = \frac{I_{bias}}{2V_T}$$  \hspace{1cm} (5.36)

where $V_T$ is the thermal voltage.
The sensitivity analysis of the circuit in terms of sensitivity of the cutoff/central frequency and quality factor with respect to the variation in active and passive components are as follows:

$$S_{C_2,C_3,R_1,R_4,R_6,g_m}^{\omega_0} = -\frac{1}{2}$$

(5.37)

$$S_{R_1}^Q = 1$$

(5.38)

$$S_{g_m,R_1,R_4,R_6,C_3}^Q = -\frac{1}{2}$$

(5.39)

$$S_{C_2}^Q = \frac{1}{2}$$

(5.40)

As per above mentioned equations both $$\omega_0$$ and $$Q$$ sensitivities are low. The frequency response of the filter is shown in Figure 5.17, which matches with designed specifications. Figure 5.18 shows the variation of frequency of the filter with bias current of OTA. The frequency variation depends on the amount of output current and bias current of the OTA. Though the observed graph is nonlinear, the linearity between bias current and frequency is observed, when OTA bias current is much higher than output current.

5.4.2 SIMULATION RESULT

The proposed filter shown in Figure 5.17 is realized on the bread board. The circuit is designed for $$f_0 = 3.22$$ kHz and $$Q = 1.13$$ by considering $$R_1 = R_4 = R_6 = 10$$ k$$\Omega$$, $$C_2 = 1$$nF, $$C_5 = 1$$nF, $$R_3 = 100$$ k$$\Omega$$ and $$g_m = 2.44$$ mS. Higher $$Q$$ can be realized by changing the $$C_2$$, $$C_5$$ and $$R_3$$. The power supply employed in the circuit is ±5V. The theoretical results have been verified to match with the practical results as shown in Figure 5.18. Figure 5.19 shows the cutoff/center frequency of the filter with respect to the changes in bias current of the OTA. The linear response is available when the bias current is higher than the output current of the OTA.
Figure 5.18(a): Low pass filter magnitude response of tunable multifunction filter

Figure 5.18(b): Low pass filter phase response of tunable multifunction filter
Figure 5.18(c): High pass filter magnitude response of tunable multifunction filter

Figure 5.18(d): High pass filter phase response of tunable multifunction filter
**Figure 5.18(e):** Band pass filter magnitude response of tunable multifunction filter

**Figure 5.18(f):** Band pass filter phase response of tunable multifunction filter
5.5 CONCLUSION

This chapter proposed two new universal filter (low-pass, high-pass, band-pass and notch filters) realization using current conveyor by employing minimum active and passive components. The first proposed circuit is realized by using two current conveyors, four resistors and two grounded capacitors while second circuit realized using two current conveyors, one OTA, four resistors and two capacitors. The second circuit is a modified version of the first circuit. The second circuit is on chip tunable for more than a decade range. The circuit provides more number of filter realizations at the single output terminal and does not have any matching constraint/cancellation conditions. Further, it is suitable for IC fabrication as it employs grounded capacitor. The realization is orthogonally tunable between the cutoff frequency and the bandwidth. It can be tuned linearly when the bias current of the OTA is higher than the output current. The sensitivity figures of the circuit for active and passive components are low.