CHAPTER - 5

MULTIPLE-INPUT SINGLE-OUTPUT (MISO) FILTERS

The results of the following papers have been reported in this Chapter:


It is well known that the system transfer function remains unchanged by lifting elements off ground or connecting additional components to virtual ground nodes [1]. So, a variety of responses can be obtained at a single output node/branch by injecting input signal selectively to multiple nodes of the filter section. This chapter addresses the filter configurations based on this methodology and are called multiple-input single-output (MISO) filters. The MISO filters may require less number of both active and passive components than single-input single-output (SISO) and single-input multiple-output (SIMO) universal filters, add versatility and simplicity to the design and bring cost reduction to integrated circuit manufacturer. A generic configuration that can serve as a reference for realizing MISO current mode biquad is introduced and then a voltage mode universal filter has been presented. Mixed mode filter is an important analog filter due to its ability to provide various modes (current mode, voltage mode, transimpedance mode, transadmittance mode) of filter responses from the same structure depending upon the excitation. A new MISO mixed mode filter structure has been also presented.

5.1 CURRENT MODE MISO FILTER

During the last one decade and recent past a number of multiple-input single-output (MISO) current mode filters [83] - [90] structures have been reported in the literature. A critical investigation of MISO current mode circuits exhibits the following important features:

(i) use of three to six active components [83] – [89],

(ii) two CFOAs/CCs required to realize a low pass (LP) response [90],

(iii) use of excessive (six to eight) number of resistors [83], [85], [87], [89],
(iv) pole $\omega_0$ and pole $Q_0$ are independently adjustable in structures [83], [85], [86], [87], [89] in contrast to refs. [84], [88], [90],

(v) need to satisfy complex matching constraints of passive components to realize filter functions [90],

(vi) use of floating resistor [85] and floating capacitor [90].

Hence, no single and even two current conveyor (CC)/CFOA-based CM universal filter has yet been reported in the literature which can provide explicit CM output with all the following features:

(i) independent adjustability of $\omega_0$ and $Q_0$,

(ii) no or simple matching constraints of passive elements,

(iii) use of all grounded and canonie in number count of passive components.

In this section a configuration that is capable of realizing eight (8) three-input single-output (TISO) current mode universal filter with features discussed above is introduced. The configuration is based on dual output second generation current conveyors (DOCCIIs) and uses five passive components. All the passive components are grounded for most of the topologies which is beneficial from integrated circuit implementation point of view. The structure realizes all the basic filter functions i.e. LP, BP, HP, notch and AP responses at high output impedance which makes it ideal candidate for cascading in current mode operation and requires simple passive component matching. The filter has low passive and active sensitivities, and also most of the generated structures enjoy the attractive feature of orthogonal control of the filter parameters via grounded resistor.
5.1.1 CIRCUIT DESCRIPTION

The proposed MISO filter is constructed with two DOCCIIIs and four admittances \((y_1 \text{ to } y_4)\) as shown in Fig. 5.1. The DOCCII can be described by the following port relationships

\[ v_x = v_y, \quad i_{z^+} = i_x, \quad i_{z^-} = -i_x \quad \text{and} \quad i_y = 0 \]

where `+' and `-' signs in \(i_{z^+}\) and \(i_{z^-}\) denote positive and negative current conveyance from \(z^+\) and \(z^-\) ports.

![Diagram of MISO biquad circuit](image)

Fig. 5.1 Proposed current mode MISO biquad.

Circuit analysis of the network yields the output current as

\[
I_{out} = \frac{y_1y_3I_1 - y_1y_4I_2 + y_2y_4I_1}{y_1y_3 + y_2y_4} \quad (5.1.1)
\]

A number of MISO filter circuits can be obtained by appropriate selection of admittances \((y_1 \text{ to } y_4)\). Eight circuits are derived by using five passive components. Table 5.1 contains the selection of admittances for eight circuits, the specialization in the numerator of (5.1.1) and matching condition, if any, to be satisfied for universal filter
realization. The resonant frequency \( (\omega_0) \), band width \( (\omega_0/Q_0) \) and quality factor \( (Q_0) \) for the circuits are as follows:

Circuit 1:
\[
\omega_0 = \left( \frac{G_2G_4}{C_1C_3} \right)^{1/2}; \quad \omega_0 = \frac{G_3}{C_3}, \text{ and } Q_0 = \frac{1}{G_3} \left( \frac{G_2G_4C_3}{C_1} \right)^{1/2}
\]  
(5.1.2)

Circuit 2:
\[
\omega_0 = \left( \frac{G_1G_3}{C_2C_4} \right)^{1/2}; \quad \omega_0 = \frac{G_4}{C_4}, \text{ and } Q_0 = \frac{1}{G_4} \left( \frac{G_1G_3C_4}{C_2} \right)^{1/2}
\]  
(5.1.3)

Circuit 3:
\[
\omega_0 = \left( \frac{G_2G_4}{C_1C_3} \right)^{1/2}; \quad \omega_0 = \frac{G_1}{C_1}, \text{ and } Q_0 = \frac{1}{G_1} \left( \frac{G_2G_4C_1}{C_3} \right)^{1/2}
\]  
(5.1.4)

Circuit 4:
\[
\omega_0 = \left( \frac{G_2G_4}{C_2C_4} \right)^{1/2}; \quad \omega_0 = \frac{G_2}{C_2}, \text{ and } Q_0 = \frac{1}{G_2} \left( \frac{G_2G_4C_2}{C_4} \right)^{1/2}
\]  
(5.1.5)

Circuit 5:
\[
\omega_0 = \left( \frac{G_2G_4}{C_1C_3} \right)^{1/2}; \quad \omega_0 = \frac{G_2G_4}{G_4C_1}, \text{ and } Q_0 = G_3 \left( \frac{C_1}{G_2G_4C_2} \right)^{1/2}
\]  
(5.1.6)

Circuit 6:
\[
\omega_0 = \left( \frac{G_2G_4}{C_1C_3} \right)^{1/2}; \quad \omega_0 = \frac{G_2G_4}{G_4C_3}, \text{ and } Q_0 = G_1 \left( \frac{C_3}{G_2G_4C_1} \right)^{1/2}
\]  
(5.1.7)

Circuit 7:
\[
\omega_0 = \left( \frac{G_2G_4}{C_2C_4} \right)^{1/2}; \quad \omega_0 = \frac{G_3}{G_4C_2}, \text{ and } Q_0 = G_4 \left( \frac{C_2}{G_2G_4C_1} \right)^{1/2}
\]  
(5.1.8)
Circuit 8:

\[ \omega_0 = \left( \frac{G_1G_3}{C_2C_4} \right)^{1/2}; \quad \frac{\omega_0}{Q_0} = \frac{G_1G_3}{G_2C_4}, \text{ and } Q_0 = G_2 \left( \frac{C_4}{G_1G_3C_2} \right)^{1/2} \]

(5.1.9)

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Admittances</th>
<th>LP</th>
<th>BP</th>
<th>HP</th>
<th>Notch</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( y_1=sC_1 ), ( y_2=G_2 ), ( y_3=G_3 + sC_3 ), ( y_4=G_4 )</td>
<td>( I_1=I_2=0 )</td>
<td>( I_3=I_1=0 )</td>
<td>( I_3=0 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
</tr>
<tr>
<td>2</td>
<td>( y_1=G_1 ), ( y_2=sC_2 ), ( y_3=G_3 ), ( y_4=G_4 + sC_4 )</td>
<td>( I_2=I_3=0 )</td>
<td>( I_3=I_1=I_n )</td>
<td>( I_3=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( G_4 = 2G_3 )</td>
</tr>
<tr>
<td>3</td>
<td>( y_1=G_1 + sC_1 ), ( y_2=G_2 ), ( y_3=sC_3 ), ( y_4=G_4 )</td>
<td>( I_3=I_2=0 )</td>
<td>( I_1=I_n )</td>
<td>( I_3=I_1=I_n ) ( G_1 = G_2 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
</tr>
<tr>
<td>4</td>
<td>( y_1=G_1 ), ( y_2=G_2 + sC_2 ), ( y_3=G_3 ), ( y_4=sC_4 )</td>
<td>( I_2=I_3=I_n )</td>
<td>( I_1=I_n )</td>
<td>( I_2=I_3=I_n ) ( G_1 = G_2 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( G_1 = G_2 )</td>
</tr>
<tr>
<td>5</td>
<td>( y_1=sC_1 ), ( y_2=G_2 ), ( y_3=C_2G_3/(C_3+sC_3) ), ( y_4=G_4 )</td>
<td>( I_2=I_3=0 ) ( G_1 = G_2 )</td>
<td>( I_2=I_3=I_n ) ( G_2 = G_4 )</td>
<td>( G_1 = C_3 )</td>
<td>( G_4 = G_1 = G_2 )</td>
<td>( G_1 = G_2 )</td>
</tr>
<tr>
<td>6</td>
<td>( y_1=sC_1G_1/(C_1+sC_1) ), ( y_2=G_2 ), ( y_3=C_3 ), ( y_4=G_4 )</td>
<td>( I_3=I_2=I_n )</td>
<td>( I_3=I_2=0 ) ( G_1 = G_2 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( G_1 = G_2 )</td>
</tr>
<tr>
<td>7</td>
<td>( y_1=G_1 ), ( y_2=sC_2 ), ( y_3=G_3 ), ( y_4=C_2G_3/(C_4+sC_4) )</td>
<td>( I_3=I_1=I_n )</td>
<td>( I_3=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_1=I_2=I_3=I_n )</td>
</tr>
<tr>
<td>8</td>
<td>( y_1=G_1 ), ( y_2=sC_2G_1/(G_2+sC_2) ), ( y_3=G_3 ), ( y_4=sC_4 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( I_2=I_3=I_n ) ( C_2 = C_4 )</td>
<td>( I_1=I_3=0 ) ( G_1 = G_2 )</td>
<td>( I_1=I_2=I_3=I_n )</td>
<td>( G_1 = 2G_3 )</td>
</tr>
</tbody>
</table>

Table 5.1

Admittances, the specializations in numerator and matching conditions

for the eight circuits.
It can be seen from (5.1.2) to (5.1.9) and Table 5.1 that for circuit 1, the parameters $\omega_0$ and $\omega_0/Q_0$ are orthogonally tunable for all the filter functions with grounded resistor $R_2 (= 1/G_2)$. The parameters $\omega_0$ and $Q_0$ are orthogonally adjustable with grounded resistor $R_3 (= 1/G_3)$ for low pass and band pass, whereas the orthogonality of $\omega_0$ and $Q_0$ is achievable in the case of high pass and notch filter if the grounded resistors $R_3$, $R_4$ and $R_2$ are simultaneously adjusted i.e. $R_2 = R_3 = R_4 = R$. If these resistors are replaced by equal valued MOSFET-based voltage control resistances (VCRs), such as the one proposed by Banu and Tsividis [126], and are driven by a common control voltage $V_c$, then electronic tunability of $\omega_0$ is achievable without disturbing $Q_0$. The orthogonal adjustability of all pass filter parameters is obtained through proper selection of $R_3$, $R_4$ and $R_2$. Above discussion is also true for circuits 4, 6 and 7 (Table 5.1) with different combination of resistors.

The input impedance of the circuits may differ; this however will not be a problem from cascadability point of view since output impedance is high. Furthermore, electronic tunability for all the filter parameters or a part of the parameters can be added to the filter characteristics of circuits 1, 3, 5, 6 and 8 (Table 5.1) by replacing DOCCII and series resistance at port x by DOCCCII (dual output current controlled conveyor). It may also be noted that gain of band pass filter can be made more than unity.

5.1.2 EFFECT OF NONIDEALITIES

The frequency performance of the filter circuit may deviate from the ideal one due to nonidealities of CCIIs. The non ideal effects may be categorized in two groups. The first comes from frequency dependence of internal current and voltage transfers that
is $\alpha(s)$ and $\beta(s)$ of CCII which can be approximated by first order low pass transfer function (section 2.2) and can be ignored if operating frequency range is chosen well below the poles of current and voltage transfers.

The second effect comes from parasitics of CCII comprising of resistances and capacitances connected between terminals y and z (i.e. $R_y$, $C_y$, $R_z$ and $C_z$) and a series resistance ($R_x$) at terminal x (section 2.2). The effects of these parasitics on filter response depend strongly on circuit topology. In the proposed topologies 1, 3, 5 and 6 (Table 5.1) parasitic resistances of the DOCCIIIs at x terminals are in series with external resistors and parasitic capacitances are in parallel with external capacitors. Thus, for these topologies the loading effects of the parasitics of DOCCII can be compensated by pre-distorting the values of these external passive components, whereas the effects of parasitics will have dominance in remaining topologies.

Considering the nonidealities of current and voltage transfers of current conveyor as outlined in section 2.2, the output current for circuit 1 (Table 5.1) is modified as

$$I_{out} = \frac{sC_1(G_3 + sC_3)I_3 - sG_4C_1\beta_2I_2 + G_2G_4\alpha_i\beta_4I_4}{s^2C_1C_3 + sG_4C_1 + \alpha_i\alpha_2\beta_4G_2G_4}$$  \hspace{1cm} (5.1.10)

The transfer function (5.1.10) is characterized by the following parameters:

$$\alpha_0 = \left(\frac{\alpha_i\alpha_2\beta_2G_2G_4}{C_1C_3}\right)^{1/2}, \quad \omega_0 = \frac{G_3}{C_3}, \text{ and}$$

$$Q_0 = \frac{1}{G_3}\left(\frac{\alpha_i\alpha_2\beta_2G_2G_4C_3}{C_1}\right)^{1/2}$$  \hspace{1cm} (5.1.11)
It can be observed from (5.1.11) that the values of pole $\omega_0$ and pole $Q_0$ may be altered slightly by the non unity voltage and current transfers of CCII. The bandwidth, however, remains unaltered. The active and passive sensitivity analysis of pole $\omega_0$ and pole $Q_0$ gives us

\[ S^a_{\alpha_1} = S^a_{\beta_1} = S^a_{\beta_2} = \frac{1}{2}, \quad S^a_{R_1} = S^a_{R_2} = S^a_{C_1} = S^a_{C_2} = -\frac{1}{2}, \quad S^a_{R_3} = 0 \]

\[ S^\phi_{\alpha_1} = S^\phi_{\beta_1} = S^\phi_{\beta_2} = \frac{1}{2}, \quad S^\phi_{R_1} = S^\phi_{R_2} = S^\phi_{C_1} = S^\phi_{C_2} = -S^\phi_{C_3} = -\frac{1}{2}, \quad S^\phi_{R_3} = 1 \]

All the sensitivities are small and lie within unity in magnitude, so the proposed structure can be classified as insensitive [127]. Similar calculations for remaining structures also show low sensitivity performance.

### 5.1.3 RESULTS

To validate the theoretical results, circuit 1 (Table 5.1) is simulated with PSPICE using translinear current conveyor. The DOCCII is simulated using circuits as given in section 2.2.2 [65] with DC supply voltage of ±10V. The circuit has been simulated using typical parameters of bipolar transistors PR100N (NPN) and NR100N (NPN) [112] of bipolar ALA arrays. The simulated and ideal responses for the low pass, band pass and high pass filters are shown in Fig. 5.2 for the component values $R_2 = R_3 = R_4 = 1$ kΩ, $C_1 = 20$ nF, $C_3 = 10$ nF. The responses of the notch filter are shown in Fig. 5.3 for the component values $R_2 = R_3 = R_4 = 1$ kΩ, $C_1 = 10$ nF, $C_3 = 10$ nF. To illustrate orthogonal tunability, a band pass filter is designed at a center frequency of 127 kHz by selecting $R_2 = R_4 = 1$ kΩ, $C_1 = 20$ nF, $C_3 = 10$ nF. Figure 5.4 shows the responses of the band pass filter for three values of $Q_0$ obtained for the values of grounded resistor $R_3$ values as
1 kΩ, 2 kΩ and 5 kΩ. There is a close agreement between the simulated and theoretical values.

![Graph](image)

**Fig. 5.2** Low pass, Band pass and High pass responses for circuit 1 (Table 5.1).

--- Simulated ---- Theoretical

![Graph](image)

**Fig. 5.3** Gain and phase responses of the notch filter for circuit 1 (Table 5.1).

--- Simulated ---- Theoretical

The circuit of Fig. 5.1 is also tested for dynamic range i.e. up to what level of input current the output is within the permitted distortion level. Figure 5.5 shows the
total harmonic distortion (THD) variations with the input signal amplitude. It is clear that THD is within acceptable limits of the order of THD=5% [60] for large range of input signal level.

![Graph showing orthogonal tunability of band pass response.](image)

Fig. 5.4 Orthogonal tunability of band pass response.

![Graph showing dependence of total harmonic distortion (%THD) on input signal.](image)

Fig. 5.5 Dependence of total harmonic distortion (%THD) on input signal.

The dependence of output current and output voltage on load resistor $R_L$ is simulated for input signal level $I_{in} = 20 \mu A$, and frequency 127 kHz. The results are tabulated in Table 5.2. It can be seen that output current level remains approximately constant till load value of 20 kΩ and can be considered independent of load. The output voltage increases linearly with increasing load resistance showing that DOCCI operates in linear region. However, for resistance beyond 20 kΩ output current starts deviating which can be
attributed to parasitic resistance at port z which is 220 kΩ for the chosen topology. The output resistance can be increased by replacing simple current mirror with cascode current mirror and thus this limitation may be ruled out.

Table 5.2

<table>
<thead>
<tr>
<th>Resistance(R_L)(kΩ)</th>
<th>Current(µA)</th>
<th>Voltage (mV)</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>24.0</td>
<td>0.240</td>
<td>0.06</td>
</tr>
<tr>
<td>0.10</td>
<td>24.0</td>
<td>2.40</td>
<td>0.07</td>
</tr>
<tr>
<td>1</td>
<td>24.0</td>
<td>24</td>
<td>0.08</td>
</tr>
<tr>
<td>10</td>
<td>22.0</td>
<td>220</td>
<td>0.08</td>
</tr>
<tr>
<td>20</td>
<td>16.9</td>
<td>342</td>
<td>0.1</td>
</tr>
<tr>
<td>50</td>
<td>12.0</td>
<td>600</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>8.33</td>
<td>833</td>
<td>0.3</td>
</tr>
<tr>
<td>200</td>
<td>5.0</td>
<td>1000</td>
<td>0.47</td>
</tr>
</tbody>
</table>

5.1.4 CONCLUSION

In this section eight current mode universal three-input single-output filter circuits have been presented. The salient features of the proposed circuits are as follows:

(i) These employ only two DOCCIIs and five passive components.

(ii) All the circuits use grounded capacitors and four out of eight circuits use all grounded resistors which is advantageous from integration point of view.

(iii) The proposed filter circuits have low sensitivity performance.

(iv) The pole ω₀ and band width ω₀/Q₀ are orthogonally adjustable for all filter functions for circuits 1, 4, 6, and 7 (Table 5.1). Ref [90] lacks this property except for LP and BP.
(v) The pole $\omega_0$ and quality factor $Q_0$ can be adjusted independently for all filter functions for circuits 1, 4, 6, and 7 (Table 5.1). Refs. [84], [89] and [90] lack this property.

(vi) The electronic tunability can be added to filter parameters like $\omega_0$, $\omega_0/Q_0$, $Q_0$ etc. for circuits 1, 3, 5, 6, and 8 (Table 5.1) by replacing first DOCCII and series resistance at port x by DOCCII.

(vii) The output current is available at high output impedance which makes them ideal candidates for cascading in CM operations.

(viii) When compared with previously reported circuits using same number of passive elements [90], some of the proposed circuits enjoy simpler matching constraints and use grounded capacitors making them more adaptable in integrated circuit implementation environment.

(ix) Total hardware requirement is minimum compared to reported MISO current mode universal filter having features discussed above till date.

Thus the proposed configuration is most efficient in terms of integrated circuit performance parameters such as area requirement and power dissipation.

5.2 VOLTAGE MODE MISO FILTER

Recently a number of MISO voltage mode configurations have been reported in the literature [91] - [99]. A critical investigation exhibits the following:

(i) Use of excessive number of current conveyors [91], [92], [94], [98],

(ii) Use of both types (plus and minus) of current conveyors (CCII) [91- [93], [95], [96].
(iii) Although the use of only CCII+ simplifies the circuit configuration but uses complex matching constraints [97],

(iv) Requires both normal and inverting type of voltage input signals to realize all pass function [91], [93], [96], [98], hence would require one more active device (CC or op amp etc.),

(v) Not completely extendible from CCII to current controlled conveyor (CCCII) based structure [91], [92], [94], [98] and thus not suitable for electronic adjustability of filter parameters without including any passive resistor,

(vi) Electronic adjustability is possible in ref. [99] only if resistances $R_1$ and $R_2$ are replaced by some active device such as JFET, CC (current conveyor) etc.

In applications where power consumption and adaptation in integrated circuit environment are important, the number of active elements employed will be of prime concern. Since the use of only plus type CCII simplifies the circuit configuration [97], there is a drive to design filter structures that requires minimum number of only plus type CCIIIs. Keeping this trend in mind, a circuit employing only two plus type CCIIIs, two resistors and two capacitors is presented in this section. The structure realizes all the standard functions of universal filter i.e. low pass, band pass, high pass, notch and all pass and requires a very simple matching constraint.

The structures possessing the electronic tunability of filter parameters are more adaptable for signal processing in integrated circuit (IC) environment as they allow change in filter parameters without disturbing passive component values. Some of the
CCII based filter circuits may have the flexibility to extend to second generation current controlled conveyor (CCCII) based circuit to avail electronic adjustability of filter functions. The replacement of each CCII+ together with a resistor at terminal x by CCCII+ results in the configuration that needs only two CCCII+s and two grounded capacitors. The performance of these circuits is studied with both experiment and PSPICE simulations.

5.2.1 CIRCUIT DESCRIPTION

The proposed CCII+ based network is shown in Fig. 5.6. Port relations of CCII+ using standard notations can be represented as

\[ v_x = v_y, \quad i_z = i_x, \quad \text{and} \quad i_y = 0 \]

![CCII+ based voltage mode MISO filter](image)

Fig. 5.6 CCII+ based voltage mode MISO filter.

Circuit analysis yields the output voltage as

\[ V_{out}(s) = \frac{s^2 C_1 C_2 R_1 R_2 V_{in3} + s V_{in2} R_1 C_1 - s V_{in1} R_2 C_1 + V_{in2}}{D(s)} \]  

(5.2.1)

where

\[ D(s) = s^2 R_1 R_2 C_1 C_2 + s R_1 C_1 + 1 \]  

(5.2.2)

The specializations in the numerator of (5.2.1) results in the following filter responses:
(i) High pass response: \( V_{in2} = V_{in1} = 0 \) and \( V_{in3} = V_{in} \)

(ii) Band pass response: \( V_{in3} = V_{in2} = 0 \) and \( V_{in1} = V_{in} \)

(iii) Low pass response: \( V_{in3} = 0 \) and \( V_{in1} = V_{in2} = V_{in} \) and \( R_1 = R_2 \)

(iv) Notch response: \( V_{in3} = V_{in2} = V_{in1} = V_{in} \) and \( R_1 = R_2 \)

(v) All pass response: \( V_{in3} = V_{in2} = V_{in1} = V_{in} \) and \( 2R_1 = R_2 \)

Thus the proposed structure can be viewed as three-input single-output (TISO) voltage mode universal filter. It may be noted that very simple component matching constraint is required. The filters are characterized by the following parameters:

\[
\alpha_0 = \left( \frac{1}{R_1 R_2 C_1 C_2} \right)^{1/2}; \quad \frac{\alpha_0}{Q_0} = \frac{1}{R_2 C_2} \quad \text{and} \quad Q_0 = \left( \frac{R_2 C_2}{R_1 C_1} \right)^{1/2} \quad (5.2.3)
\]

The filter of Fig. 5.6 can also be realized using CCCII+s [13]. The properties of CCCII+ are similar to the second generation current conveyor (CCII+) but CCCII+ has a finite input resistance \( R_x \) at terminal x which is controllable by bias current \( I_0 \) and is expressed as \( R_x = V_T/2I_0 \), where \( V_T \) is the thermal voltage. Using standard notations the port relations of an ideal CCCII+ (section 2.1) can be characterized by

\[
v_x = v_y + i_x R_x (I_0), \quad i_z = i_x, \quad \text{and} \quad i_y = 0
\]

The CCCII+ based TISO filter is shown in Fig. 5.7. It is obtained by replacing CCII+ and resistor at terminal x in Fig. 5.6 by a CCCII+. Equations (5.2.1) to (5.2.3) remain same except that \( R_1 \) and \( R_2 \) are replaced respectively by \( R_{x1} \) and \( R_{x2} \).
5.2.2 **EFFECT OF NONIDEALITIES**

Considering the nonidealities outlined in section 2.2, the denominator for CCCII based MISO filter may be written as

\[
D_n(s) = s^2 R_{x_1} R_{x_2} C_1 C_2 + s R_{x_1} C_1 + \alpha_1 \alpha_2 \beta_1
\]  

(5.2.4)

The transfer function is now characterized by the following filter parameters:

\[
\omega_0|_n = \left( \frac{\alpha_1 \alpha_2 \beta_1}{R_{x_1} R_{x_2} C_1 C_2} \right)^{1/2}, \quad \omega_0|_n = \frac{1}{R_{x_2} C_2}, \quad \text{and} \quad Q_0|_n = \left( \frac{\alpha_1 \alpha_2 \beta_1 R_{x_2} C_2}{R_{x_1} C_1} \right)^{1/2}
\]  

(5.2.5)

It can be observed from (5.2.5) that the value of bandwidth remains unchanged in the presence of nonidealities whereas the values of pole \(\omega_0\) and pole \(Q_0\) change slightly. The effect can be accommodated via external bias currents (\(I_{01}\) and \(I_{02}\)) adjustment. The results of active and passive sensitivity analysis of various parameters are given as

\[
S_{a_1}^a = S_{a_2}^a = S_{a_1}^b = S_{a_2}^b = \frac{1}{2}, \quad S_{b_1}^a = S_{b_2}^b = 0, \quad S_{R_1}^a = S_{R_2}^a = S_{C_1}^a = S_{C_2}^a = -\frac{1}{2},
\]

\[
S_{a_1}^{a/Q_0} = S_{a_2}^{a/Q_0} = S_{b_1}^{a/Q_0} = S_{b_2}^{a/Q_0} = 0, \quad S_{R_1}^{a/Q_0} = S_{C_1}^{a/Q_0} = 0, \quad S_{R_2}^{a/Q_0} = S_{C_2}^{a/Q_0} = -1,
\]

\[
S_{a_1}^{b/Q_0} = S_{a_2}^{b/Q_0} = \frac{1}{2}, \quad S_{b_1}^{b/Q_0} = S_{b_2}^{b/Q_0} = 0, \quad S_{R_1}^{b/Q_0} = -S_{R_2}^{b/Q_0} = S_{C_1}^{b/Q_0} = -S_{C_2}^{b/Q_0} = -\frac{1}{2}.
\]
All active and passive sensitivities of pole $\omega_0$, band width $\omega_0/Q_0$ and quality factor $Q_0$ are low and within unity in magnitude. Thus the proposed structure can be classified as insensitive. Equation (5.2.3) reveals that $\omega_0$ can be adjusted by varying $R_1$ (Fig. 5.6) or bias current $I_{01}$ (Fig. 5.7) without disturbing $\omega_0/Q_0$. Orthogonal control of $\omega_0$ and $Q_0$ can be achieved with the simultaneous adjustment of $R_1$ (or $I_{01}$) and $R_2$ (or $I_{02}$). Equation (5.2.3) also indicates that high values of Q-factor can be obtained from moderate values of ratios of passive components [123]. These ratios can be chosen as $(R_2/R_1) = (C_2/C_1) = Q_0$. Hence the spread of the component values becomes of the order of $\sqrt{Q_0}$. This feature of the filter related to the component spread allows the realization of high $Q_0$ values more accurately as compared to the topologies where the spread of passive components becomes $Q_0$ or $Q_0^2$ [123].

5.2.3 COMPARISON

The present work has been found to be closely comparable with the works of [95], [97] and [99]. It is seen that

(i) Although the passive component matching constraints are little simpler, the circuit of [95] has the following short comings compared to the proposed work:

   (i) uses one resistor more than the present work.

   (ii) uses both types (plus and minus) of CCIIs.

   (iii) to get electronic adjustment (by bias current or voltage) of $\omega_0$ and $Q_0$, the grounded resistor $R_1$ of ref. [95] needs to be replaced by an active device (JFET or CC or op amp).
On the other hand, in the present work, the replacement of CCII+ of Fig. 5.6 by CCCII+s (Fig. 5.7) enables the circuit to have the property of bias current \( (I_{01}, I_{02}) \) controlled adjustment of \( \omega_0 \) and \( Q_0 \).

(2) In comparison with [97], the proposed circuit,

(i) uses simpler matching constraints.

(ii) needs one passive component less in count.

(iii) is more convenient for the orthogonal control of \( \omega_0 \) and \( Q_0 \).

(3) The circuit in [99] does not require any matching constraint, hence is suitable for IC implementation for constant filter parameters \( (\omega_0, Q_0, \text{ gain etc.}) \). However, for the applications which demand change (electronic control) of filter parameters, the resistors in the circuit have to be replaced by some active device such as JFETs or CCs or op amps. The proposed circuits, on the other hand do not require any active device to achieve electronic control of filter parameters, rather eliminates the existing two resistors (Fig. 5.7). Although the present work needs simple matching constraints, it does not put any hindrance in possessing all the functional properties as that of [99].

5.2.4 RESULTS

The performance of the proposed configuration has been confirmed by experiments and PSPICE simulation. The circuit of Fig. 5.6 is constructed with passive component values \( R_1 = R_2 = 4.65 \, \text{k}\Omega \) and \( C_1 = C_2 = 1 \, \text{nF} \). The active elements used to construct plus type CCII are commercially available IC AD844s with supply voltages of \( \pm 12 \, \text{V} \). Figures 5.8(a) and (b) show the simulated and experimental results for low pass,
high pass, band pass and notch filters based on CCII+. The experimental and simulation results agree quite well.

Fig. 5.8 Simulated and Experimental frequency responses for CCII+ based filter

(a) low pass and high pass  (b) band pass and notch.

The CCCII+ based structure of Fig. 5.7 is simulated using typical parameters of bipolar transistors PR100N (PNP) and NR100N (NPN) [112] with supply voltage of ±2.5 volts. Figure 5.9 shows the simulation results for control of $Q_0$ while keeping $\omega_0$ fixed for $C_1 = C_2 = 1 \text{ nF}$ and $I_{01} = 50 \mu \text{A}$, $I_{02} = 50 \mu \text{A}$ ($Q_0 = 1$); $I_{01} = 100 \mu \text{A}$ and $I_{02} = 25 \mu \text{A}$ ($Q_0 = 2$); $I_{01} = 200 \mu \text{A}$ and $I_{02} = 12.5 \mu \text{A}$ ($Q_0 = 4$) respectively.

Fig. 5.9 Variation of $Q_0$ keeping $\omega_0$ constant (= 636.94 kHz) for band pass output.
Figure 5.10 shows the simulation results for control of $\omega_0$ while keeping $Q_0$ fixed for $C_1 = C_2 = 1$ nF and $I_{01} = I_{02} = 5$ $\mu$A; $I_{01} = I_{02} = 25$ $\mu$A; and $I_{01} = I_{02} = 50$ $\mu$A respectively.

![Graph](image)

Fig. 5.10 Variation of $\omega_0$ keeping $Q_0$ constant (=1.0) for band pass output. $\omega_{01} = 63.69$ kHz ($\Theta$), $\omega_{02} = 318.47$ kHz ($\varphi$), $\omega_{03} = 636.94$ kHz ($+$).

5.2.5 CONCLUSION

A new three-input single-output voltage mode filter using only CCII+s has been presented and extended the same for introducing electronic tunability using CCCII+s. Both the circuits use two grounded capacitors for their realization. The experimental and simulation results agree with the theoretical results. The salient features of the proposed circuit are as follows:

(i) It employs only two plus type CCCII+s and two capacitors or two plus type CCII+s and four passive components.

(ii) The proposed circuit has low sensitivity performance.

(iii) Both $\omega_0$ and $\omega_0/Q_0$; and $\omega_0$ and $Q_0$ are orthogonally tunable.

(iv) The $\omega_0$, $Q_0$ and $\omega_0/Q_0$ are electronically tunable with bias currents of CCCII+s (Fig. 5.7).
(v) Low output impedance.

(vi) No requirement of inverting type voltage input signal.

(vii) Low component spread for high Q application.

(viii) The comparison in section 5.2.3 reveals that the proposed work has a number of advantages over the work reported till date.

5.3. MIXED MODE MISO FILTER

The mixed mode operations are useful in the special filtering applications where interconnection is required between voltage and current mode circuits [103], [128]. It may also eliminate the need of voltage to current or current to voltage converter and thus reduces the overall hardware cost. Limited work has been done in the domain of mixed mode universal filters [26], [103] – [106], [128], [129]. The structures [103], [128] are operated only in transadmittance mode whereas [104], [129] are operated in transimpedance mode. Generalized mixed mode structures i.e. single structure which can realize voltage mode (i.e. both input and output as voltages), current mode (i.e. both input and output as currents), transadmittance mode (i.e. input as voltage and output as current) and transimpedance (i.e. input as current and output as voltage) are limited [26], [105], [106]. The structure [105] employs four current controlled conveyors (CCCIIs) and two grounded capacitors, and realizes low pass, band pass, high pass and notch filter functions. The structures [26], [106] can realize all the generic functions of universal filter i.e. LP, BP, HP, notch and AP. The structure [106] uses seven current conveyors (CIIIs), eight resistors and two capacitors whereas the structure [26] uses four CFOAs, nine resistors, two capacitors and a switch. Applications where power consumption and
adaptation in integrated circuit environment is important, the number of active and passive components employed is of prime concern.

In this section, a current conveyor (CCII) based multiple-input single-output mixed mode universal filter structure has been proposed that employs three single-output current conveyors (CCIIs), four resistors, two capacitors and two switches, which is lesser in number count of CCIIs/CFOAs and resistances compared to those used in [26], [106]. The structure realizes all five generic filter functions (i.e. LP, BP, HP, notch, and AP) and requires a very simple matching constraint. The filter, under all operations, exhibits low active and passive sensitivities. The workability of the proposed structure has been confirmed by PSPICE simulation and experiment.

5.3.1 CIRCUIT DESCRIPTION

The proposed network is shown in Fig. 5.11 and is based on employing only plus type current conveyors. It has high impedance y terminal i.e. $i_Y = 0$. Port relations using standard notations can be represented as $v_X = v_Y$ and $i_Z = i_X$.

![Circuit Diagram](image)

Fig. 5.11 MISO mixed mode filter configuration based on plus type current conveyors.
The output current and voltage of the circuit shown in Fig. 5.11 can be expressed as

\[ I_{out} = -\frac{1}{R_3} \frac{N_v(s) + N_i(s)}{D(s)} \quad \text{with switch } K_2 \text{ OFF} \quad \text{(5.3.1)} \]

\[ V_{out} = R_4 I_{out} \quad \text{with switch } K_2 \text{ ON} \quad \text{(5.3.2)} \]

where

\[ N_v(s) = V_{in3} D(s) - s(1 + K_1)C_2 R_1 V_{in2} - V_{in1} \quad \text{(5.3.3)} \]

\[ N_i(s) = R_4 I_{in3} D(s) - (1 + s(1 + K_1)C_2 R_2)R_1 I_{in1} + R_1 I_{in2} \quad \text{(5.3.4)} \]

\[ D(s) = R_1 R_2 C_1 (1 + K_1)C_2 s^2 + sR_1 C_1 + 1 \quad \text{(5.3.5)} \]

\( V_{in1}, V_{in2}, V_{in3} = \) input voltages, \( V_{out} = \) output voltage,

\( I_{in1}, I_{in2}, I_{in3} = \) input currents, \( I_{out} = \) output current and \( K_1, K_2 = \) switches.

From (5.3.1) to (5.3.5) we can see that specializations in the numerator results in the following filter responses:

Case I. With \( I_{in1} = I_{in2} = I_{in3} = 0 \), we obtain voltage mode (VM) response with \( K_2 \) ON and transadmittance mode response with \( K_2 \) OFF under the conditions as shown in Table 5.3.

Case II. With \( V_{in1} = V_{in2} = V_{in3} = K_1 = 0 \), we obtain current mode (CM) response with \( K_2 \) OFF and transimpedance mode response with \( K_2 \) ON under the conditions as shown in Table 5.3.
Table 5.3
Details of filter responses for mixed mode filter of Fig. 5.11.

<table>
<thead>
<tr>
<th>Function Type</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case I (VM and Transadmittance mode)</td>
</tr>
<tr>
<td>Low pass</td>
<td>$V_{in2}=V_{in3}=0$, $V_{in1}=V_{in}$, $K_1=0$</td>
</tr>
<tr>
<td>Band pass</td>
<td>$V_{in1}=V_{in3}=0$, $V_{in2}=V_{in}$, $K_1=0$</td>
</tr>
<tr>
<td>High pass</td>
<td>$V_{in1}=V_{in2}=V_{in3}=V_{in}$, $C_1=C_2$, $K_1=0$</td>
</tr>
<tr>
<td>Notch</td>
<td>$V_{in1}=0$, $V_{in2}=V_{in3}=V_{in}$, $C_1=C_2$, $K_1=0$</td>
</tr>
<tr>
<td>All pass</td>
<td>$V_{in1}=0$, $V_{in2}=V_{in3}=V_{in}$, $C_1=C_2$, $K_1=1$</td>
</tr>
</tbody>
</table>

Thus the proposed structure can be viewed as generalized MISO mixed mode universal filter. It can be noted that very simple component matching constraint is required. Further, the coefficient of $s$ in (5.3.5) cannot be equal to zero; hence the circuit is always stable.

The transfer functions are characterized by

$$\omega_0 = \left(\frac{1}{(1+K_1)R_1R_2C_1C_2}\right)^{1/2}; \quad \frac{\omega_0}{Q_0} = \frac{1}{((1+K_1)R_2C_2)}, \quad \text{and}$$

$$Q_0 = \left(\frac{(1+K_1)R_2C_2}{R_1C_1}\right)^{1/2} \quad (5.3.6)$$

It may be noted that in voltage mode and transadmittance mode for all the five filters (LP, HP, BP, Notch and AP), the parameters $\omega_0$ and band width ($\omega_0/Q_0$) can be orthogonally adjusted by resistor $R_1$ while the orthogonal tuning of $\omega_0$ and $Q_0$ can be
achieved by simultaneous adjustment of $R_1$ and $R_2$ such that $R_1 = R_2$. Similarly in the case of current mode and transimpedance mode, the orthogonal tunability of $\omega_0$ and bandwidth are obtained by adjusting $R_2$, whereas that of $\omega_0$ and $Q_0$ is obtained by simultaneous adjustment of $R_1$ and $R_2$ with $R_1 = R_2 = R_3$ for low pass, band pass, high pass, notch, and $R_1 = R_2 = 2R_3$ for all pass filter.

The electronic tunability for all the filter parameters i.e. $\omega_0$, $\omega_0/Q_0$ and $Q_0$ or part of the parameters can be obtained by simply replacing first and second CCII and series resistance at port x by CCCII (current controlled conveyor). It may further be noted that the third CCII can also be replaced by CCCII for voltage and transadmittance mode filter.

### 5.3.2 EFFECT OF NONIDEALITIES

Considering the nonidealities of CCIIIs as outlined in section 2.2.1, the output current and voltage expressions given in (5.3.1) modify to

$$I_{\text{out}} \big|_n = -\frac{1}{R_3} \frac{N_{\text{in}}(s) + N_{\text{in}}(s)}{D_n(s)} \quad \text{with switch K}_2 \text{ OFF}$$  \hspace{1cm} (5.3.7)

$$V_{\text{out}} \big|_n = R_4 I_{\text{out}} \big|_n \quad \text{with switch K}_2 \text{ ON}$$ \hspace{1cm} (5.3.8)

where

$$N_{\text{in}}(s) = \alpha_3 (V_{\text{in}_3} D_n(s) - \alpha_2 \beta_3 s (1 + K_1) C_2 R_4 V_{\text{in}_2} - \alpha_4 \alpha_2 \beta_3 V_{\text{in}_1})$$ \hspace{1cm} (5.3.9)

$$N_{\text{in}}(s) = \alpha_3 (R_3 I_{\text{in}_3} D_n(s) - \beta_3 (1 + s(1 + K_1) C_2 R_2) R_4 I_{\text{in}_1} + \alpha_2 \beta_3 R_3 I_{\text{in}_2})$$ \hspace{1cm} (5.3.10)

$$D_n(s) = R_1 R_2 C_1 (1 + K_1) C_2 s^2 + s R_1 C_1 + \alpha_4 \alpha_2 \beta_1$$ \hspace{1cm} (5.3.11)

The transfer functions are characterized by
\[
\alpha_{0|n} = \left( \frac{\alpha_1 \alpha_2 \beta_1}{(1 + K_1) R_1 R_2 C_1 C_2} \right)^{1/2}, \quad \omega_{b|n} = \left( \frac{1}{(1 + K_1) R_2 C_2} \right), \quad \text{and} \\
Q_{0|n} = \left( \frac{\alpha_1 \alpha_2 \beta_1 (1 + K_1) R_2 C_2}{R_1 C_1} \right)^{1/2}
\]

(5.3.12)

The results of active and passive sensitivity analysis of \( \alpha_0 \) and \( Q_0 \) are given as

\[
S_{0|\alpha_1} = S_{0|\alpha_2} = S_{0|\beta_1} = 1/2, \quad S_{0|c_1} = S_{0|\beta_2} = S_{0|\beta_3} = 0,
\]

\[
S_{0|\alpha_3} = S_{0|\beta_4} = S_{0|c_2} = S_{0|c_3} = -1/2, \quad S_{0|\beta_5} = S_{0|\beta_6} = 0,
\]

\[
S_{0|\alpha_4} = S_{0|\alpha_5} = S_{0|\alpha_6} = 1/2, \quad S_{0|\alpha_7} = S_{0|\alpha_8} = S_{0|\alpha_9} = 0,
\]

\[
S_{0|\beta_7} = S_{0|\beta_8} = S_{0|\beta_9} = S_{0|c_4} = -1/2, \quad S_{0|\beta_10} = S_{0|\beta_11} = 0.
\]

All active and passive sensitivities are low and within 1 in magnitude. Thus the circuit can be regarded as insensitive. Equations (5.3.6) and (5.3.12) indicate that high values of \( Q \) factor will be obtained from moderate values of ratios between passive components [123]. These ratios can be chosen as \( (R_2/R_1) \approx (C_2/C_1) = Q_0 \). Hence the spread of the component values becomes of the order of \( \sqrt{Q_0} \). This feature of the filter related to the component spread allows the realization of high \( Q_0 \) values more accurately as compared to the topologies where the spread of passive components becomes \( Q_0 \) or \( Q_0^2 \) [123].

53.3 COMPARISON

Survey of literature till date on universal mixed mode filters reveals that only two topologies for implementing all standard universal filter functions (LP, HP, BP, notch,
AP) in generalized mixed mode are available [26], [106]. Hence, we compare our work with refs. [26], [106].

(i) **Requirement of passive components:**

The total number of passive components used is 10 in ref. [106] and 11 in ref. [26], whereas our implementation needs only six passive components.

(ii) **Requirement of active components (CCII+/ CFOA):**

The number of active components used is 7 in ref. [106] and 4 in ref. [26] whereas the present work uses only three active components.

(iii) **Implementation constraints:**

Ref. [26] needs a number of resistances (r₄, r₅, r₆ and r₇ of Fig 1 of ref [26]) to be opened in the case of current mode/transadmittance mode filter function to be realized. Hence the integrated circuit implementation for ref. [26] needs either (i) a switch in series with each of the resistances (r₄, r₅, r₆ and r₇ Fig 1 of ref. [26]) and of course, more pins to have external control or (ii) more number of pins (to externally short or open the resistances as per requirement). The present work requires only one such switch K₂ in series with R₄ for this purpose. The topology of ref. [26] does not impose any such restriction.

(iv) **Component spread:**

The present work possesses the feature of low component spread [123], an advantage over [26].
Orthogonal control of $\omega_0$, BW and $Q_0$:

The present work possesses the feature of orthogonal control of $\omega_0$, BW and $Q_0$ similar to that in refs. [26], [106].

5.3.4 RESULTS

The workability of the proposed configuration has been confirmed by experiments and PSPICE simulation. The circuit of Fig. 5.11 is constructed with passive components value of $R_1 = R_2 = R_3 = R_4 = 1$ k$\Omega$ and $C_1 = C_2 = 1$ nF. The active elements used to construct plus type CCII are commercially available IC AD844s with supply voltages of $\pm 12$ V. Figure 5.12 shows the simulated and experimental results for current mode low pass, high pass, band pass, notch and all pass filters. The experimental and simulation results agree quite well.

5.3.5 CONCLUSION

A new generalized MISO mixed mode universal filter has been presented. The filter has the following attractive features (i) the proposed filter uses three CCII+, four resistances, two grounded capacitors and two switches which is the lowest in number count of CCII's/ CFOAs and resistances as reported in literature till date, (ii) use of only grounded capacitors makes the structure less sensitive to parasitic and easier to integrate, (iii) low active and passive sensitivities, (iv) independent control of $\omega_0$ without disturbing BW, (v) orthogonal control of $\omega_0$ and $Q_0$, (vi) realization of all standard functions of universal filter with simple matching constraints and (vii) allows high Q with low component spread. It is interesting to note that the switch $K_2$ may be eliminated if
the third CCII+ is replaced by a double output CCII (DO-CCII) whose one output will be used for $I_{\text{out}}$ and another output for $V_{\text{out}}$. Comparison reveals that the proposed mixed mode structure has a number of advantages over the work reported in the literature till date.

Fig. 5.12 Experimental and Simulated frequency response for

(a) low pass and high pass (b) band pass and notch (c) all pass filters.