2.1 Introduction:

The filters are to be considered as frequency selective networks that passes or suppresses a group of signals from mixture. The advent of integrated circuit technology has profoundly influenced the interest in the field of biquadratic RC section. So for, not much effort has been put into the search for all classes of biquadratic sections. The number of circuits by various workers narrowed down to the solutions having interest features of limited interest [1-10]. The active-R filters design techniques are based on single pole model of op-amp [2].

In this present chapter we have represented new biquadratic active-R filter whose transfer function has two quadratic terms one in numerator and another in denominator. The circuit is suitable for high pass band gain with higher value of Q having feedback at non-inverting input. The designed filter provides a satisfactory response for all three filter functions LP, BP, HP. The circuit is studied with variation in Q for fixed center frequency $F_0$.

2.2 Circuit Configuration:

The second order active-R filter circuit with multiple outputs are developed as shown in fig. (2.1) The circuit configuration shows that there are two op-amps having identical gain bandwidth product and three resistances as an active element. The two op-amps are coupled such as
output of first op-amp is connected to non-inverting input of second op-amp. The resistance $R_3$ is connected in between input source and inverting input of first op-amp. The resistance $R_1$ is connected in between inverting input of first op-amp and output of second op-amp. The resistance $R_2$ is connected in between inverting input of first op-amp and coupling of op-amp. Also complete feedback is provided by connecting non-inverting input of first op-amp to output of second op-amp. The inverting input of second op-amp is grounded thus the resonant frequency, $Q$ of poles and the location of zeros can be controlled over wide range by feedback and feedforward circuit. The proposed filter circuit is studied for different circuit merit factor $Q$ ($Q=0.02, 0.04, 0.06, 0.1, 0.5, 1, 5, 10$) with constant center frequency $F_0=10$ kHz. The circuit gives three filter functions low pass, high pass and band pass.

2.3 The Circuit Analysis and Design Equation:–

The high frequency roll-off in frequency response of an operational amplifier leads to a single-pole integrator [2,11-15].

The single-pole models leads complex gain and transfer function is given by:

$$A(S) = \frac{A_0 \omega_0}{S + \omega_0} \tag{1}$$

where

$A_0$= Open dc gain

$\omega_0$=Open loop 3 dB bandwidth

$GB= A_0 \omega_0$=Gain bandwidth product of op-amp

For frequencies $\omega >> \omega_0$ i.e. $S >> \omega_0$
\[ A(S) = \frac{A_0}{S} = \frac{GB}{S} \]  

This shows op-amp works as "integrator" [7].

The analysis of this represented circuit gives the following transfer functions.

The voltage transfer function for low pass filter,

\[ T_{LP}(s) = \frac{-\left(\frac{1}{R_3}\right) + GB_1 \cdot GB_2}{s^2 + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{GB_1}{R_2} + GB_1 \cdot GB_2 \cdot \frac{1}{R_1}} \]  

The voltage transfer function for band pass filter,

\[ T_{BP}(s) = \frac{-\left(\frac{1}{R_3}\right) + GB_1 \cdot s}{s^2 + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{GB_1}{R_2} + GB_1 \cdot GB_2 \cdot \frac{1}{R_1}} \]  

The voltage transfer function for high pass filter,

\[ T_{HP}(s) = \frac{-\left(\frac{1}{R_3}\right) + GB_1 \cdot GB_2 \cdot \left(1 + \frac{s^2}{GB_1 \cdot GB_2}\right)}{s^2 + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{GB_1}{R_2} + GB_1 \cdot GB_2 \cdot \frac{1}{R_1}} \]  

As \( \frac{S^2}{GB_1 \cdot GB_2} \rightarrow 1 \)

\[ T_{HP}(s) = \frac{S^2}{s^2 + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{GB_1}{R_2} + GB_1 \cdot GB_2 \cdot \frac{1}{R_1}} \]  

The circuit was designed for various Q values by comparing the transfer function with the general second order transfer function i.e. coefficient matching technique [3, 9, 10 and 16-21].
The general second order transfer function is given by

\[ T(S) = \frac{a_2 S^2 + a_1 S + a_0}{S^2 + \frac{\omega_0^2}{Q} S + \omega_0^2} \]  

(7)

Comparing equations (3), (4) and (6) with this equation, we get three design equations:

\[ \frac{\omega_0}{Q} = \frac{GB_1}{R_2} \]  

(8)

\[ \omega_0^2 = \frac{GB_1 \cdot GB_2}{R_1} \]  

(9)

\[ 1 = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \]  

(10)

From these three equations, one can get values \( R_1 \), \( R_2 \) and \( R_3 \). For practical implementation, values of all resistances are impedance scaled up by 100. Both op-amps gain bandwidth product are identical. The gain bandwidth product value was taken as \( 5.6 \times 2 \pi \times 10^5 \) rad/sec.

For realization of value of \( R_1 \), \( R_2 \) and \( R_3 \) must be positive. The value of resistances is shown in table no. 2.1 Hence there is lower limit of \( Q \) of this circuit i.e. \( Q \geq 0.015 \) which does not limit input signal frequency.

2.4 Experimental Observations:

This second order active-R filter circuit was constructed by using two identical op-amps and three resistances. The resistances used for different configuration are of 1% tolerance. The most commonly available op-amp \( \mu A 741 \) was used for designing circuit. Two op-amp IC's with almost same value of GB were selected. The performance of the circuit is studied for
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Q</th>
<th>Design Value of resistance (Ω)</th>
<th>Experimental Value of resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$R_1$</td>
<td>$R_2$</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
<td>313.600k</td>
<td>112</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>313.600k</td>
<td>224</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>313.600k</td>
<td>335</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>313.600k</td>
<td>559</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>313.600k</td>
<td>2.8k</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>313.600k</td>
<td>5.6k</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>313.600k</td>
<td>28k</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>313.600k</td>
<td>56k</td>
</tr>
</tbody>
</table>

Table No. 2.1 Resistance value: Design value and Experimental value.
different values of \( Q \). The outputs are taken at three distinct terminals; low pass, high pass and band pass filter responses. The responses plotted for voltage gain with frequency shows excellent performance.

2.5 Results and Discussion:-

The proposed circuit was studied for different circuit merit factor \( Q \) using operational amplifier \( \mu A741 \) and resistors. The filter circuit is designed using identical gain-bandwidth product GB of op. amp, and fixed center frequency \( F_0=10 \text{ kHz} \). The general range of these frequency responses for this active-R filter is from 10 Hz to 1 MHz, as operating range of this op. amp. is 10 Hz to 1.2 MHz. Following observation are performed at three different terminals; low pass, high pass, band stop function for different circuit merit factor \( Q(=0.02, 0.04, 0.06, 0.1, 0.5, 1, 5 \text{ and } 10) \) [3].

(a) Low pass response:-

The response is shown in figure (2.2). For higher \( Q \) the gain roll-off is better. The passband gain increases as \( Q \) increases. In this response; overshoot is observed and increased for \( Q \geq 1 \). For \( Q=0.5 \); the gain roll-off is 34.3 dB /decade for decade 10 kHz to 100 kHz and for decade 100 kHz to 1000 kHz, the gain roll-off is 40 dB /decade. For \( Q \geq 1 \), the gain roll-off per decade is almost 40 dB /decade which is matched with design biquad circuits (40 dB). For \( Q \geq 1 \), below 10 kHz response is independent of \( Q \) and above 400 kHz the response merges together. The center frequency is not disturbed for \( Q \geq 1 \).

The graph analysis is shown in Table No. 2.2.
(b) Band pass response:-

The band pass response is shown in figure (2.3). This circuit has better gain roll-off at lower frequencies. It is also reported that as value of $Q$ increases the bandwidth decreases, so the response is peaked without disturbing center frequencies. This circuit can work for narrow bandwidth as well as wide bandwidth. The response shows all curves merged together at below 50 Hz and above 400 kHz.

The graph analysis is shown in Table No. 2.3

(c) High pass response:-

The high pass response is represented in figure (2.4). The center frequency is also good agreement with design value. This circuit shows excellent response with perfect 40 dB/decade gain roll-off for $Q \geq 1$. The response is extended up to 400 Hz at lower frequencies and 1 MHz at high frequencies range. A overshoot is observed for $Q=5$ and 10.

The graph analysis is shown in Table No. 2.4

2.6 Sensitivity:-

A practical solution is to design a network that has low sensitivity to element changes, thus sensitivity must be less than limit [2-4]. The sensitivity for $Q$ and $\omega_0$ for this new active $-R$ biquadratic filter are given below.

\begin{align*}
1. \quad S_{R_1}^{\omega_0} &= -\frac{1}{2} \left[ 1 - \frac{\omega_0^2}{GB_1GB_2} \right] \\
2. \quad S_{R_2}^{\omega_0} &= \frac{\omega_0}{2GB_1Q}
\end{align*}
3. \( S_{R3}^{\omega_0} = \frac{1}{2} \left[ 1 - \frac{\omega_0}{Q} \frac{\omega_0^2}{GB_1GB_2} \right] \)

4. \( S_{GB1}^{\omega_0} = \frac{1}{2} \)

5. \( S_{GB2}^{\omega_0} = \frac{1}{2} \)

6. \( S_{R1}^{Q} = -\frac{1}{2} \left[ 1 + \frac{\omega_0^2}{GB_1GB_2} \right] \)

7. \( S_{R2}^{\omega_0} = \frac{1}{2} \left[ 1 - \frac{\omega_0^2}{2GB_1Q} \right] \)

8. \( S_{R3}^{Q} = -\frac{1}{2} \left[ 1 - \frac{\omega_0}{Q} \frac{\omega_0^2}{GB_1GB_2} \right] \)

9. \( S_{GB1}^{Q} = \frac{1}{2} \)

10. \( S_{GB2}^{\omega_0} = \frac{1}{2} \)

thus the passive sensitivity are less than unity in magnitude and active sensitivity are half in magnitude.

2.7 Conclusion:

The circuit is suitable for high pass band gain with higher value of \( Q \) having feedback at non-inverting input. For variation in \( Q \), the response shows good results for all three filter functions with perfect gain roll-off of 40 dB/decade with getting overshoot. The high pass response is extended up to 400Hz which is noticeable feature. For high values of \( Q \) [\( Q > 1 \)] overshoot is observed. This filter circuit can work for narrow bandwidth as well as wide
bandwidth and such high frequency band pass filters can be used for channel selection in telephone central offices.
Figure 2.1 Second order active-R filter circuit with multiple feedback for
different circuit merit factor Q.
Figure (2.2) Second order active-R filter low pass response for different Q.
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Q</th>
<th>Max. Pass Band Gain (dB)</th>
<th>$F_{0L}$ (Hz)</th>
<th>$F_{OL}$ - $F_{0L}$ (Hz)</th>
<th>% Change $F_{OL}$</th>
<th>Gain Roll-off / Octave/Decade in the stop band</th>
<th>Overshoot in the Passband</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>50.46</td>
<td>200</td>
<td>9.8k</td>
<td>4900</td>
<td>20 dB/decade</td>
<td>1k</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>64.8</td>
<td>500</td>
<td>9.5k</td>
<td>1900</td>
<td>31 dB/decade</td>
<td>100k</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>66.86</td>
<td>600</td>
<td>9.4k</td>
<td>1567</td>
<td>32 dB/decade</td>
<td>100k</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>68.25</td>
<td>1k</td>
<td>9k</td>
<td>900</td>
<td>37 dB/decade</td>
<td>100k</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>69.65</td>
<td>8k</td>
<td>2k</td>
<td>25</td>
<td>34.3 dB/decade</td>
<td>100k</td>
<td>40 dB/decade for 100kHz to 1000kHz</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>71.1</td>
<td>11k</td>
<td>1k</td>
<td>9</td>
<td>40 dB/decade</td>
<td>100k</td>
<td>40 dB/decade for 100kHz to 1000kHz</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>83.89</td>
<td>10.5k</td>
<td>500k</td>
<td>4.7</td>
<td>40 dB/decade</td>
<td>100k</td>
<td>40 dB/decade for 100kHz to 1000kHz</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>89.9</td>
<td>10k</td>
<td>0</td>
<td>40</td>
<td>100k</td>
<td>20</td>
<td>40 dB/decade for 100kHz to 1000kHz</td>
</tr>
</tbody>
</table>

$F_{OL}$: Frequency at which Overshoot occurs  
$F_{0L}$: -3dB Frequency

Table No. 2.2 Data sheet for low pass response.
Figure (2.3) Second order active-R filter band pass response for different Q.
### Gain Roll-Off/Octave in the Stop Band

#### Trailing Part

Octave starting at (Hz) __ __

BW (KHz) __ __ __

Gain Roll-Off/Octave in the Stop Band

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Q</th>
<th>Max pass band gain (dB)</th>
<th>F₀ Band (kHz)</th>
<th>F₀~F₀ (kHz)</th>
<th>% Change in F₀</th>
<th>f₁ (Hz)</th>
<th>f₂ (Hz)</th>
<th>BW (KHz)</th>
<th>X (F₀~f₁ (kHz))</th>
<th>Y (X~Y (kHz))</th>
<th>Z (X~Y (kHz))</th>
<th>% Change in Z</th>
<th>Leading Part</th>
<th>Trailing Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>-18.4</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>500k</td>
<td>499.8</td>
<td>9.8</td>
<td>490</td>
<td>480.2</td>
<td>4802</td>
<td>5.5</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>1.89</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>210k</td>
<td>209.6</td>
<td>9.6</td>
<td>200</td>
<td>90.4</td>
<td>904</td>
<td>3.98</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>7.4</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>600</td>
<td>160k</td>
<td>159.4</td>
<td>9.4</td>
<td>150</td>
<td>140.6</td>
<td>1406</td>
<td>5</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>13.2</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>1k</td>
<td>100k</td>
<td>99</td>
<td>9</td>
<td>90</td>
<td>81</td>
<td>810</td>
<td>5.5</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>28.68</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>4k</td>
<td>25k</td>
<td>21</td>
<td>6</td>
<td>15</td>
<td>9</td>
<td>90</td>
<td>5</td>
<td>2k</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>34.87</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>6k</td>
<td>16k</td>
<td>10</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>20</td>
<td>6.5</td>
<td>2k</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>48.93</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>9k</td>
<td>11k</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>13.25</td>
<td>4k</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>54.95</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>9k</td>
<td>11k</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>13.3</td>
<td>4k</td>
</tr>
</tbody>
</table>

F₀: Frequency at which Peak of the response

BW: -3dB Bandwidth

Table No. 2.3 Data sheet for band pass response.
Figure (2.4) Second order active-R filter high pass response for different $Q$. 
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Q</th>
<th>$F_{OH}$ (kHz)</th>
<th>$F_{OH}$ (kHz)</th>
<th>%Change in $F_{OH}$</th>
<th>Gain roll-off in the stop band</th>
<th>Gain Stabilization</th>
<th>$P$</th>
<th>$M$</th>
<th>$F_{OSH}$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>700</td>
<td>690</td>
<td>98.57</td>
<td>19.83</td>
<td>-20.5</td>
<td>800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>270</td>
<td>260</td>
<td>96.29</td>
<td>20.28</td>
<td>-5.5</td>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>300</td>
<td>290</td>
<td>96.66</td>
<td>27.5</td>
<td>-3.3</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>100</td>
<td>90</td>
<td>90</td>
<td>22.5</td>
<td>-1.7</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>15</td>
<td>5</td>
<td>33.33</td>
<td>34.06/40</td>
<td>1/100Hz</td>
<td>-0.3</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>8</td>
<td>2</td>
<td>25</td>
<td>13/40</td>
<td>2/100Hz</td>
<td>0.01</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>6.5</td>
<td>3.5</td>
<td>53.84</td>
<td>14/40</td>
<td>2/100Hz</td>
<td>0.09</td>
<td>80</td>
<td>13.97 13.97 10</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6.5</td>
<td>3.5</td>
<td>53.84</td>
<td>13/40</td>
<td>2/100Hz</td>
<td>0.012</td>
<td>90</td>
<td>19.99 19.99 10</td>
</tr>
</tbody>
</table>

$F_{OSH}$: Frequency at which Overshoot occurs  $F_{OH}$: -3dB Frequency  $P$: Peak gain of overshoot  $F_{S}$: Frequency at Which gain is stabilized

Table No. 2.4 Data sheet for High pass response.
References:


14) Active Filter design Techniques Chapter -16 Literature Number SLOAO88, TEXAS INSTRUMENTATION, and P. No. 16-2.


