# CHAPTER – V

# STUDY OF BAND PASS AND BAND REJECT FILTER

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## 5.1 INTRODUCTION :-

A band pass filter is a frequency selector. It allows one to select or pass only one particular band of frequencies of bandwidth B from all other frequencies that may be present in the circuit. This type of filter has a maximum gain at a resonant frequency fo. The quantity of interest in a bandpass filter is the quality factor Q defined by Q = fo/B. Hence a high Q indicates a highly selective filter since the band of frequencies which pass is narrow compared to the center frequency. The gain of the filter (K) is defined as the amplitude of transfer function H (S) at the center frequency. The frequency at which gain falls to 0.707 is called cutoff frequency. There are two cutoff frequencies lower cutoff frequency $f_L$ and higher cutoff frequency $f_H$. The bandpass filter having a ratio of upper cutoff frequency to lower cutoff frequency of 2 or less are classified as narrow-band, while those having a ratio of 2 or more are classified as wide band. Similar designations hold for the notch response. The wide bandpass filters are used in audio transmission, where it is desired to amplify signals within the audio range while blocking out sub audio components (e.g. dc) as well as noise above the audio range. The bandpass filter can be made more selective by moving $f_L$ and $f_H$ closer together.

A band reject filter or notch filter is one which passes all frequencies except a single band. The band of frequencies which is rejected is centered approximately at fo and its width is B. As in the bandpass case the quantity Q is defined by fo/B. Thus a large Q indicates a small wide band. The most common application of notch filter is the removal of unwanted frequency components from the signal of interest with a minimum of degradation to the adjacent components. Familiar examples are the removal of 50 Hz noise from biomedical equipment and the blanking of control tones from telephone lines.

## 5.2 FIRST ORDER BAND PASS FILTER :-

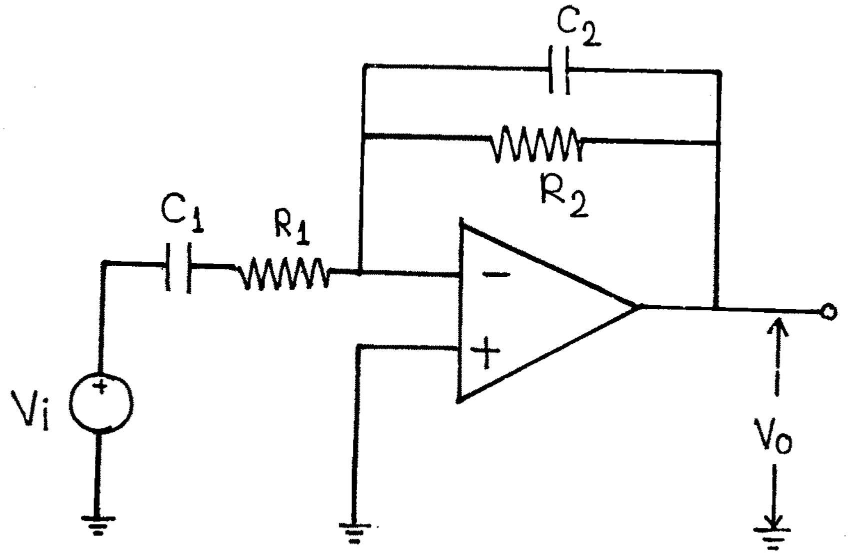

**Fig. 5.1 (First Order Wide Bandpass filter)**

The circuits of first order lowpass and highpass filter can be combined as in Fig. 5.1 to yield a first order bandpass response. The input impedance $Z_1$ is

$$Z_1 = R_1 + \frac{1}{(jwc_1)}$$

$Z_1$ forms a highpass section with cutoff frequency

$$f_L = \frac{1}{2\pi R_1 C_1}$$

The feedback impedance $Z_2$ is

$$Z_2 = R_2 \parallel \left( \frac{1}{(jwc_2)} \right)$$

$Z_2$ forms a lowpass section with cutoff frequency

$$f_H = \frac{1}{2\pi R_2 C_2}$$

If $f_L < f_H$ then input frequencies within the band $f_L \leq f \leq f_H$ will succeed in making it through the circuit while those falling outside will be rejected.

The transfer function $H = -Z_2 / Z_1$

$$H = H_o \frac{J\,(f/f_L)}{[\,1 + j\,(f/f_L)]\ [\,1 + j\,(f/f_H)\,]} \qquad 5.1$$

Where

$$H_o = - \frac{R_2}{R_1} \qquad 5.2$$

$$f_L = \frac{1}{2\pi R_2 C_2} \qquad 5.3$$

$$f_H = \frac{1}{2\pi R_2 C_2} \qquad 5.4$$

The ratio of upper cutoff frequency $f_H$ to lower cutoff frequency $f_L$, of this circuit is less than 2, therefore this filter is especially suited to wide band application.

## 5.3 SECOND ORDER BAND PASS FILTER :-

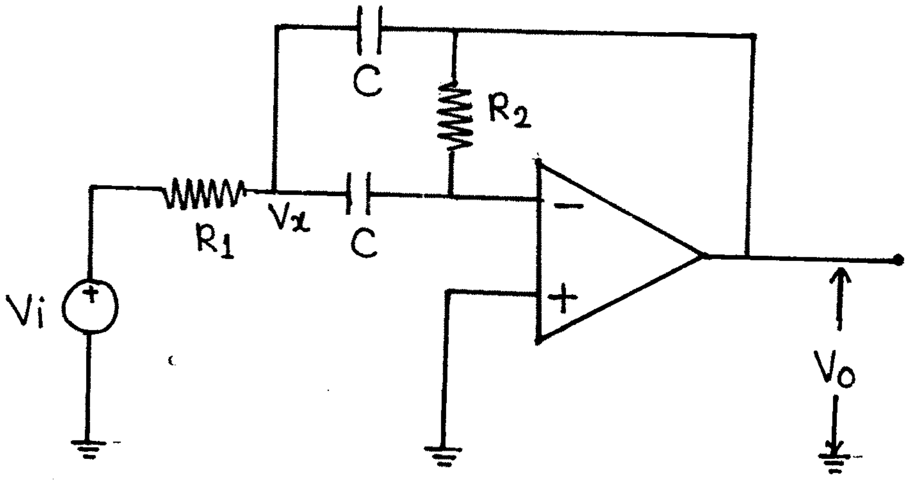

**Fig.5.2 (Second Order Multiple Feedback Band Pass Filter)**

Fig.5.2 shows the most popular single Op. Amp. realization of the second order band pass response. This circuit is referred to as the multiple feedback configuration or Delyiannis Friend circuit. The response of this circuit is more selective than first order wide band pass filter circuit. This circuit is also called narrow band pass filter to obtain the transfer function. The voltage at node $V_x$ is calculated

$$\frac{V_x}{[\ 1/(jwc)]} = -\frac{V_o}{R_2}$$

$$V_o = -\,(jwcR_2)\ V_x \qquad 5.5$$

According to Kirchoffs current law

$$\frac{V_i - V_x}{R_1} = \frac{V_x}{(1/jwc)} + \frac{V_x - V_o}{(1/jwc)} = jwc\ (2V_x - V_o)$$

Eliminating $V_x$, the transfer function H is

$$H = -2\,Q^2 \frac{(j/Q)\ (f/fo)}{1-(f/fo)^2 + (j/Q)\ (f/fo)} \quad - \quad 5.6$$

where center frequency

$$fo = \frac{1}{2\pi\sqrt{(R_1R_2)}\ C} \quad - \quad 5.7$$

$$Q = \frac{1}{2}\left(\frac{R_2}{R_1}\right)^{1/2} \qquad 5.8$$

## 5.4 DESIGN OF SECOND ORDER BAND PASS FILTER :-

To design the multiple feedback second order bandpass filter equations 5.6 to 5.8 are used.

The specification of bandpass filter is given in terms of center frequency fo and quality factor Q.

Then starting out with a reasonable guess for C one compute $R_1$ and $R_2$ using equations

$$R_2 = \frac{Q}{\pi f_o C} \qquad 5.9$$

$$R_1 = \frac{R_2}{4Q^2} \qquad 5.10$$

If resulting resistance values are out of range, scale all components accordingly.

## 5.5 SECOND ORDER MULTIPLE FEEDBACK BAND PASS FILTER WITH INPUT ATTENUATOR :-

In multiple feedback band pass filter the resonant gain increase with Q. Due to increase in resonant gain, the Op. Amp. may easily end up in saturation even for moderate Qs. To avoid the saturation of Op. Amp. the input signal level is kept low. This can be done with an ordinary voltage divider at the input as shown in Fig. 5.3 (a).

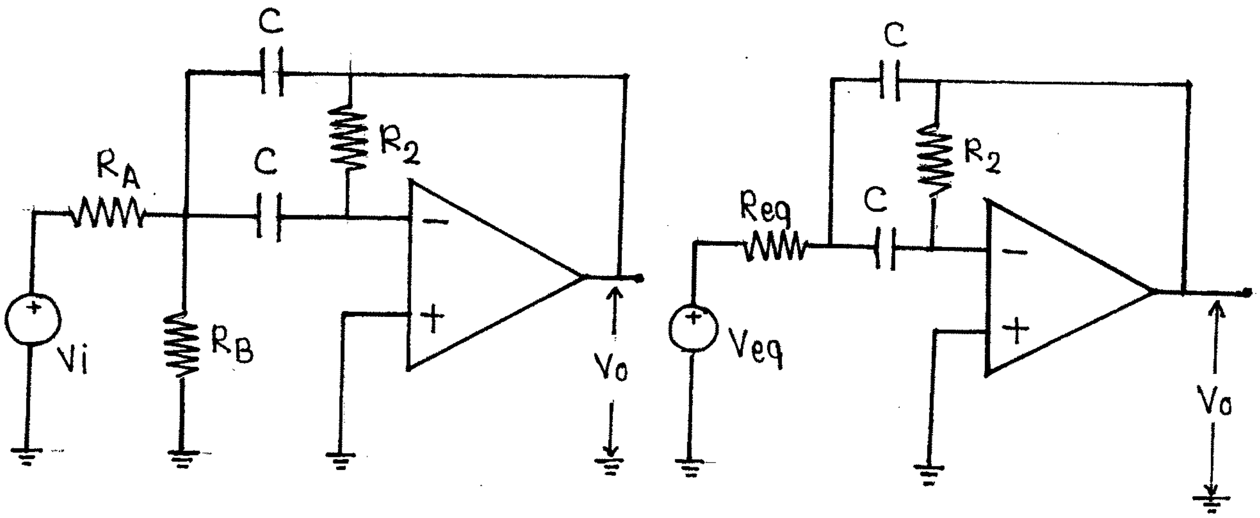

**Fig.5.3 (a)** **(b)**

**(Multiple feedback band pass filter with input attenuator to reduce resonant gain)** **(Thevenin Equivalent Circuit)**

To analyze the circuit, thevenize the input network and obtain the equivalent circuit of Fig. 5.3 (b).

Veq is the voltage across the resistance $R_B$

$$V_{eq} = V_i \frac{R_B}{R_A + R_B}$$

The equivalent resistance $$R_{eq} = \frac{R_A R_B}{R_A + R_B}$$

Then the output voltage Vo according to equation 5.6, with $R_1$ replaced by Req.

$$V_o = -2\,Q^2 \frac{(j/Q)\,(f/fo)}{1-(f/fo)^2+(j/Q)\,(f/fo)}\ \ Veq$$

$$V_o = 2\,Q^2 H_{BP}\ V_i \frac{R_B}{R_A+R_B} \qquad \ldots \qquad 5.11$$

That is

$$H = H_{OBP}\ H_{BP} \qquad \ldots \qquad 5.12$$

Where

$$H_{OBP} = \frac{R_B}{R_A+R_B}\ 2Q^2 \qquad \ldots \qquad 5.13$$

$$fo = \frac{1}{2\pi\sqrt{[Req\ R_2]}\ C} \qquad \ldots \qquad 5.14$$

$$Q = \frac{1}{2}\left(\frac{R_2}{Req}\right)^{1/2} \qquad \ldots \qquad 5.15$$

In the expressions of fo and Q, $R_1$ is replaced by Req. The resonant gain $H_{OBP}$ decreased by the presence of the input attenuator.

## 5.6 STUDY OF BAND PASS FILTER :-

### i) Study of Band pass filter for different Q :-

The band pass filter is frequency selective circuit. The gain of the band pass filter is maximum at resonant frequency fo. The quantity Q is the quality factor which is very important in band pass filter. High Q indicates a highly selective circuit. To study the effect of variation of Q on the frequency response of multiple feedback band pass filter following parameters are selected.

| | |
|---|---|
| Resonant frequency | fo = 5000 Hz |
| | C = 0.01 μf |

The actual component values used to study the effect of q are shown in table 1.

**Table 1**

| RA k. ohm | RB k. ohm | Req k. ohm | $R_2$ k. ohm | C μf | Q |
|---|---|---|---|---|---|
| 39 | 41 | 20 | 50 | 0.001 | 0.79 |
| 20 | 60 | 15 | 68 | 0.001 | 1.06 |
| 25.3 | 16.8 | 10 | 100 | 0.001 | 1.58 |
| 10 | 40 | 8 | 127 | 0.001 | 1.98 |
| 10 | 10 | 5 | 202 | 0.001 | 3.17 |

The frequency response of multiple feedback band pass filter for different Q is shown in Fig. 5.4.

Frequency response shows that with increase of Q the frequency band passed by the filter becomes narrower. With increase of Q circuit becomes more selective. The maximum gain is observed at resonant frequency fo = 5000 Hz. With increase of Q resonant gain of the circuit also increases.

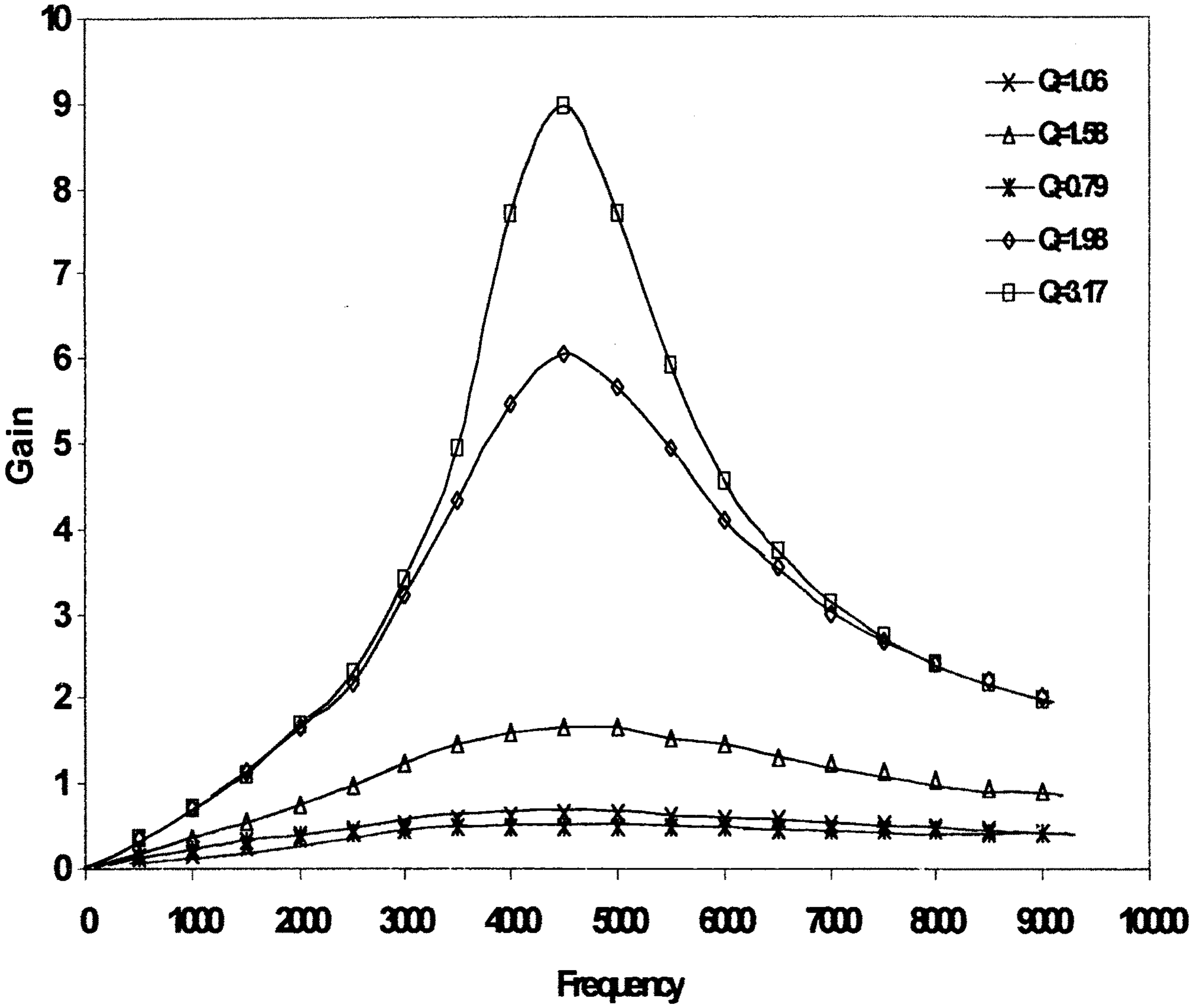

Fig.5.4
Frequency Response of Band Pass Filter for different Q

### ii) Study of band pass filter for different Q using PSpice :-

To study the effect of Q on the frequency response of band pass filter parametric analysis is used. The frequency response is studied in the frequency range from 10 Hz to 100 K Hz. The AC analysis of the circuit is done using .AC statement. The PSpice programme to study the effect of Q on the frequency response is

```
*       Multiple feedback band pass filter
*       For different Q
Vs      1       0       AC      200MV
• PARAM         Q       1
RA      1       2       {20000/Q}
RB      2       0       {(60000 *Q) - 20000/Q}
C1      2       3       0.001 U
C2      2       6       0.001 U
R2      3       6       {60000 * Q}
*       Operational Amplifier
RI      0       3       2MEG
RO      5       6       75
EOP     5       0       3       0       2E+5
* OUTPUT
•  AC           DEC     10      1       100 k
• STEP PARAM Q LIST 0.79   1.06   1.58   1.98   3.17
• PROBE
• END
```

The frequency response observed using PROBE, the graphical post processor of PSpice, is shown in fig. 5.5.

### iii) Conclusion :-

The frequency response observed practically and using PSpice are perfectly matched. There is a variation of gain at resonant frequency by comparing two responses with increase of Q resonant gain increases. The resonant frequency observed is 5 K Hz. The gain bandwidth product of the responses remains constant.

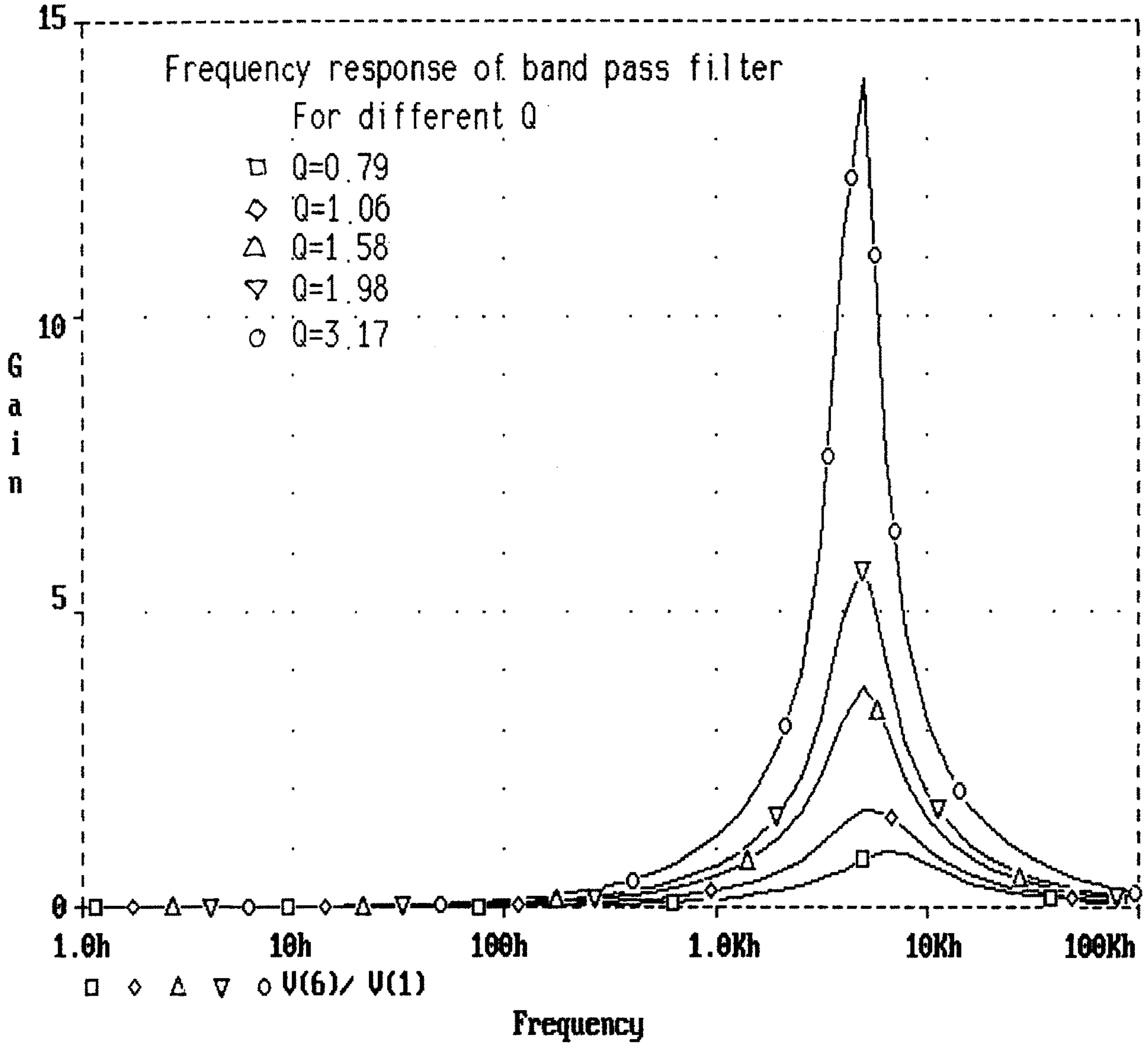

**FIG. 5.5**

**Frequency Response of Bandpass filter for different Q**

## 5.7 STUDY OF BAND REJECT FILTER :-

The most common application of band reject or notch filter is the removal of unwanted frequency components from the signal of interest with minimum of degradation to the adjacent components. Unwanted frequencies are attenuated in the stopband. The desired frequencies are transmitted in the pass band that lies on either side of the notch.

The notch filter is formed using band pass filter and inverting summing amplifier as shown in fig. 5.6.

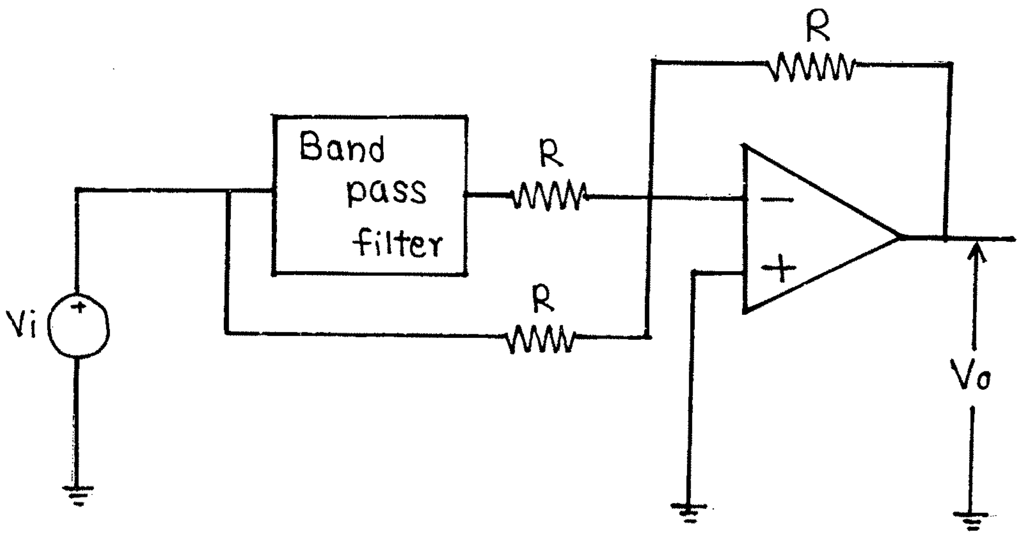

**Fig. 5.6 (Notch filter using band pass filter and summing amplifier)**

The output of bandpass filter is subtracted from original signal using inverting summing amplifier.

The order of band reject filter is determined by the order of band pass filter.

## Design of Second Order Notch Filter :-

To design the second order notch filter at first design, the band pass filter that has the same resonant frequency, band width, Q and order as the notch filter.

The output of band pass filter is given to the one of the input of inverting adder. To the other input of inverting adder the signal is given. For inverting adder equal resistors are used. Suppose that the frequency of Vi is adjusted to resonant frequency fo of narrow band pass filter component.

Vi will exit from the band pass as – Vi and then is inverted by R

To drive Vo to + Vi. However Vi is transmitted via R to drive Vo to –Vi. Thus Vo responds to both inputs of the adder and becomes Vo = Vi – Vi = 0V at fo.

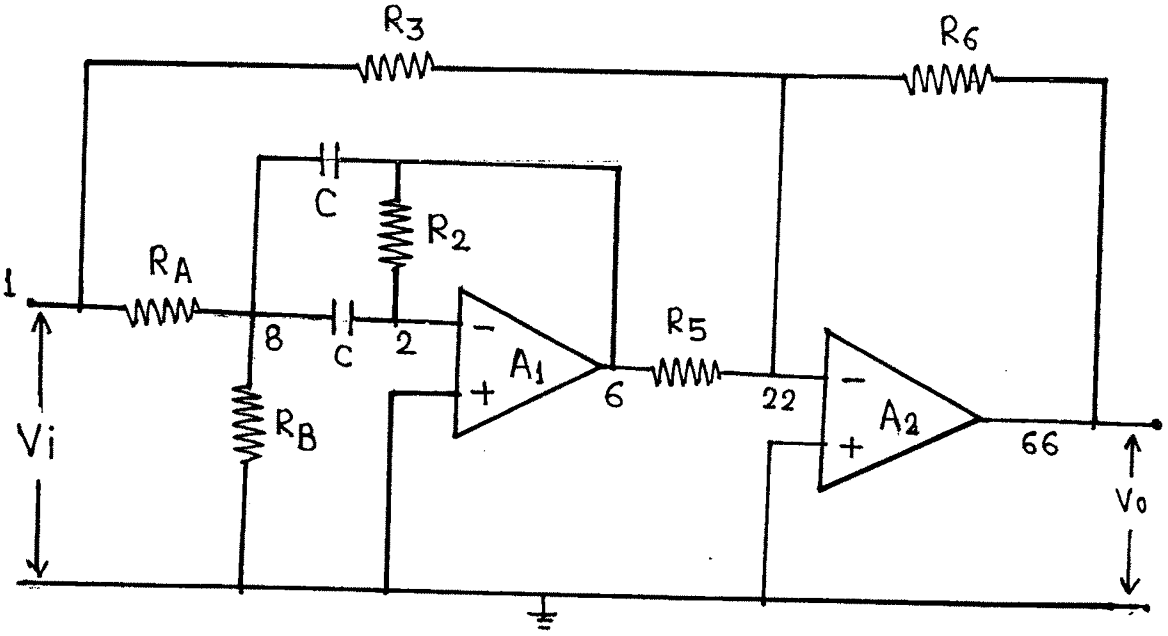

Fig.5.7 (Second Order Notch Filter)

The design formulae for second order band reject filter are

$$fo = \frac{1}{2\pi\sqrt{[R_2\,Req]\,C}} \qquad \ldots\ 5.16$$

where

$$Req = R_A \,||\, R_B = \frac{R_A R_B}{R_A + R_B}$$

$$Q = \frac{1}{2}\left(\frac{R_2}{Req}\right)^{1/2} \qquad \ldots\ 5.17$$

$$R_3 = \frac{R_6}{Av} \qquad \ldots\ 5.18$$

$$Av = \left(\frac{R_2}{2R_A}\right) \qquad \ldots\ 5.19$$

The specifications of band reject filter are given in terms of resonant frequency fo, the quality factor Q, and gain of band pass filter at resonant frequency. The proper value capacitor is selected. Using equations 5.16 to 5.19 the resistance values are calculated.

## A) STUDY OF SECOND ORDER BAND REJECT FILTER FOR DIFFERENT Q :

### i) Practical design of Band reject filter for different Q :-

To study the effect of quality factor Q on the performance of the band reject filter, the gain of the circuit (Av) is kept constant at 2, using equation (5.19). The notch depth is kept constant by using same resistance $R_3$ for all the values of Q. The resonant frequency of band pass filter is kept 1000 Hz. The capacitance used for band pass filter are all mica capacitor with value 0.01 μf. The resistances used in the circuit are all carbon composition type with the tolerance of ± 5%. The operational amplifier used for band pass filter and inverting summing amplifier is μA 741. The circuit diagram of second order notch filter is shown in fig. 5.7.

The quality factor Q of the circuit is controlled by the resistance $R_2$ and Req. Where Req is the equivalent resistance of input attenuator formed by $R_A$ and $R_B$. To study the effect of Q, the components used practically are shown in table 2.

fo = 1000 Hz
Gain Av =2

$R_5 = R_6 = 20$ k
C = 0.01 μf
$R_3 =$ 10 k

**Table 2**

| $R_A$ k ohm | $R_B$ k ohm | Req k ohm | $R_2$ k ohm | Q |
|---|---|---|---|---|
| 16 | 5.6 | 4.148 | 66 | 2 |
| 23.9 | 3.020 | 2.68 | 95 | 3 |
| 32 | 2.2 | 2.05 | 130 | 4 |
| 40 | 1.6 | 1.538 | 160 | 5 |
| 48 | 1.33 | 1.29 | 182 | 6 |
| 56 | 1.116 | 1.094 | 220 | 7 |

The frequency response of second order band reject filter for different Q is shown in fig.5.8.

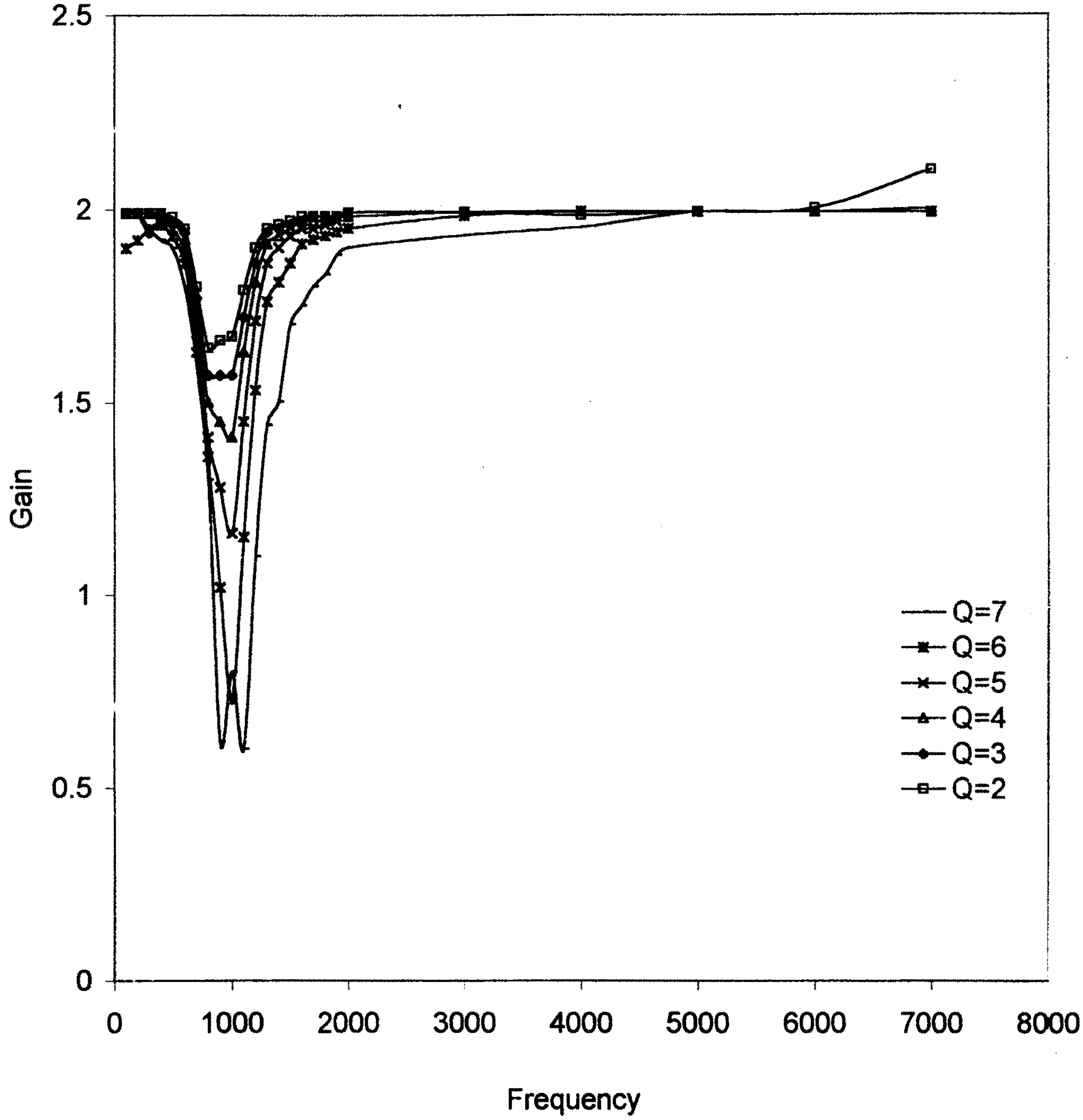

**Fig. 5.8**
**Frequency Response of Band Reject Filter for different Q**

### ii) Study of Second order Band Reject Filter for Different Q Using PSpice :-

To study the effect of variation of Q on the performance of the band reject filter. The simulation software PSpice is used. The dc linear model of operational amplifier is used for simulation. The parameters used for modeling of Op. Amp. are the parameters of practical Op. Amp. μA 741.

In put impedance = 2 M ohm
Output impedance = 75 ohm
Open loop gain = 2 x $10^5$

The parametric analysis is done by changing the value of Q using statement PARAM.

The PSpice programme to stuay the effect of variation of Q on the frequency response of band reject filter is

```
*       Second Order Band Reject Filter
*       For different Q
Vs      1     0     AC    200MV
• PARAM       Q     1
RA      1     8     {Q * 8000}
CB      8     0     {8000/Q}
R2      2     6     {33000 * Q}
C1      8     2     0.01 U
C2      8     6     0.01 U
R3      1     22    10 k
R5      6     2     20 k
R6      22    66    20 k
*       Operational Amplifier 1
```

```
RI1   2    0    2MEG
RO1   4    6    75
EOP1  4    0    2    0    2E+5
*     Operational Amplifier 2
RI2   22   0    2MEG
RO2   44   66   75
EOP2  44   0    22   0    2E+5
*     OUTPUT
•     AC   DEC  10   1    1000 k
•     STEP PARAM Q LIST 2 3 4 5 6 7
•     PROBE
•     END
```

Using PROBE, the graphical coprocessor of PSpice the frequency response of second order band reject filter for different value of Q is shown in fig.5.9.

**iii) Conclusion :-**

The notch depth observed in practical and theoretical response is constant. With increase of Q notch becomes narrower and the circuit becomes more selective. The practically observed response and theoretical response are identical with each other.

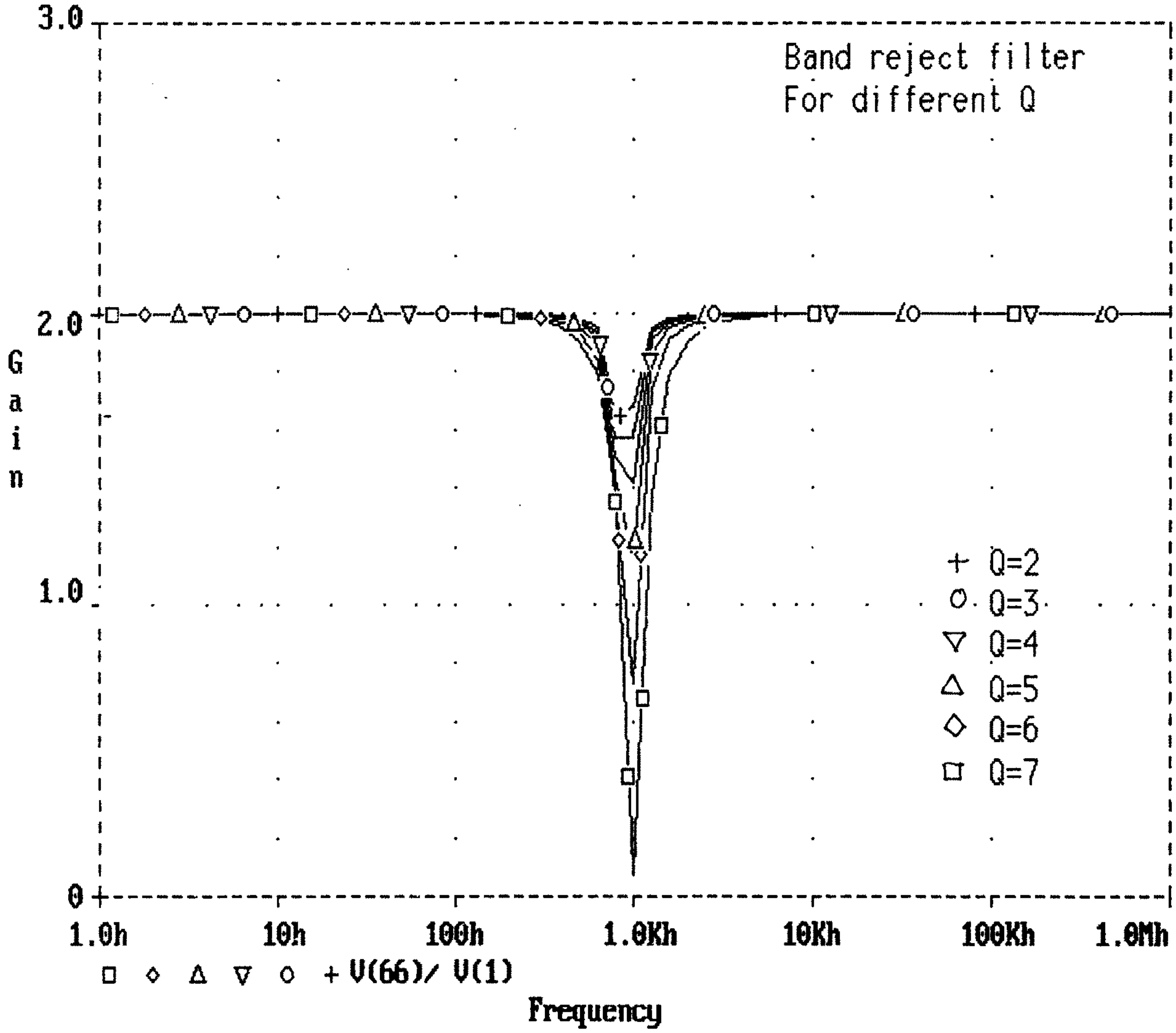

**Fig. 5.9**

**Frequency Response of Band Reject Filter for different Q**

## B) STUDY OF BAND REJECT FILTER FOR DIFFERENT VALUES OF $R_3$

### i) Practical design of band reject filter for different $R_3$ :-

As shown in fig.5.7, a band reject filter is made by subtracting the output of a bandpass filter from the original signal. For frequencies in the pass band of band reject filter. The output of bandpass filter section approaches zero. Therefore input Vi is transmitted via inverting adder input resistor $R_5$ to drive Vo to a value equal to – Vi. Thus Vo = - Vi in both lower and upper pass bands of the band reject filter.

Suppose that the frequency of Vi is adjusted to resonant frequency fo of the bandpass filter. Vi will exit from the bandpass filter as –Vi and then is inverted by $R_5$ to drive Vo to + Vi. However Vi is transmitted via $R_3$ to drive Vo to – Vi. Thus Vo responds to both inputs of the adder and becomes Vo = Vi – Vi = 0 at frequency fo

To study the effect of input resistance $R_3$, of inverting adder circuit, on the frequency response of notch filter. They gain of the adder circuit is made 1 by using equal resistor $R_5 = R_6$. The output of band pass filter, formed by $A_1$ is amplified with unity gain. The input signal Vi is applied to the other input of adder circuit through resistance $R_3$. The output of inverting adder formed by $A_2$ is the difference between input signal Vi and the output of bandpass filter. If the frequency of input signal Vi is equal to the resonant frequency of the band pass filter and the value of resistance $R_3$ is equal to $R_6$ then output of amplifier $A_2$

is zero ideals and we obtain maximum notch depth at resonant frequency. The frequency response is shown in fig. 5.10.

The notch depth of band reject filter is determined by the value of resistor $R_3$. A maximum notch depth is observed when $R_3$ is equal to $R_6/Av$. Where Av is the gain of inverting adder for another input. If value of $R_3$ is different than $R_6/Av$ the notch depth of band reject filter is les than the notch depth when $R_3 = R_6/Av$.

To study the effect of resistance $R_3$ on the notch depth of band reject filter, the practically used components are .

RA = 15.78 K ohm
RB = 2.2 K ohm
R5 = R6 = 40 K ohm
$C_1 = C_2 = C = 0.01$ μf
$R_3$ = 2.7 K, 5.6 K, 10 K, 13.9 K, 15.6 K.

The frequency response observed practically for different $R_3$ is shown in fig. 5.10.

The frequency response shows that the notch depth changes with $R_3$. It is maximum for $R_3$ = 10 K. For other values of $R_3$ notch depth is minimum.

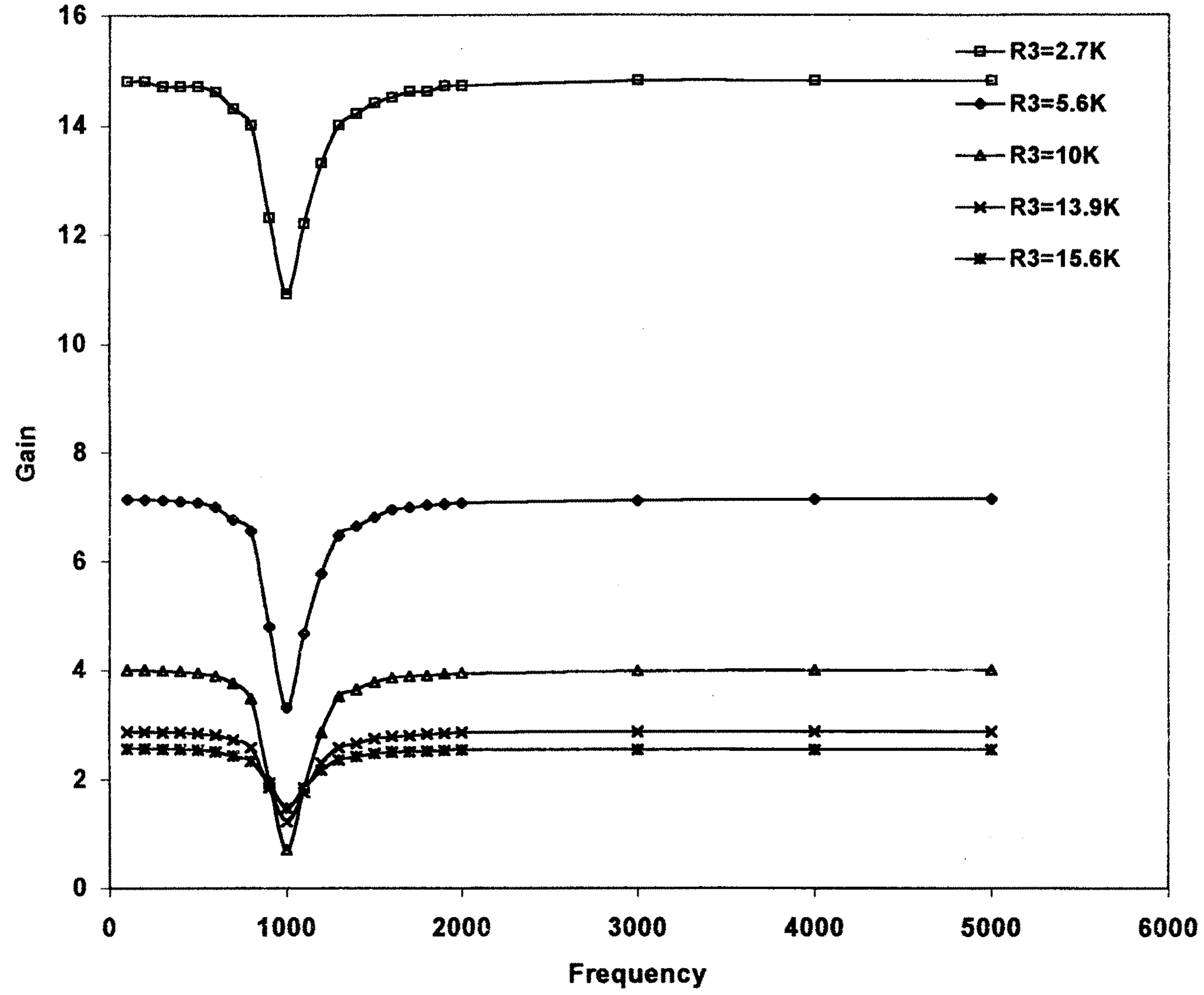

Fig. 5.10

Frequency Response of Band Reject Filter for different $R_3$

### ii) Study of Band reject filter for different $R_3$ using PSpice :-

To study the effect of variation of $R_3$ on the frequency response of band reject filter. The following programme is used

```
*      Band Reject Filter
*      For different R3
Vs     1      0      AC     200MV
• PARAM       A12    1 K
R1     1      8      15.78 K
R2     8      0      2.2 K
C1     8      2      0.01 U
R4     2      6      126 K
C2     8      6      0.01 U
R3     1      22     {A12}
R5     6      22     40 K
R6     22     66     40 K
*      Operational Amplifier 1
RI1    2      0      2MEG
RO1    4      6      75
EOP1   4      0      2      0      2E+5
*      Operational Amplifier 2
RI2    22     0      2MEG
RO2    44     66     75
EOP2   44     0      22     0      2E+5
*  OUTPUT
•  AC DEC  10     1      1000 k
•  STEP  PARAM  A12  LIST  2.7 K  5.6 K  10 K  13.9 K  15.6 K
•  PROBE
•  END
```

The frequency response of band reject filter for different $R_3$ using Pspice is shown in fig. 5.11.

Frequency response shows that the notch depth of band reject filter depends on $R_3$. When $R_3 = 10$ K, maximum notch depth is observed in frequency response.

### iii) Conclusion :-

The notch depth of band reject filter depends on $R_3$. It is maximum when $R_3 = R_6/Av$. When $R_3 = 10$ K maximum notch depth is observed.

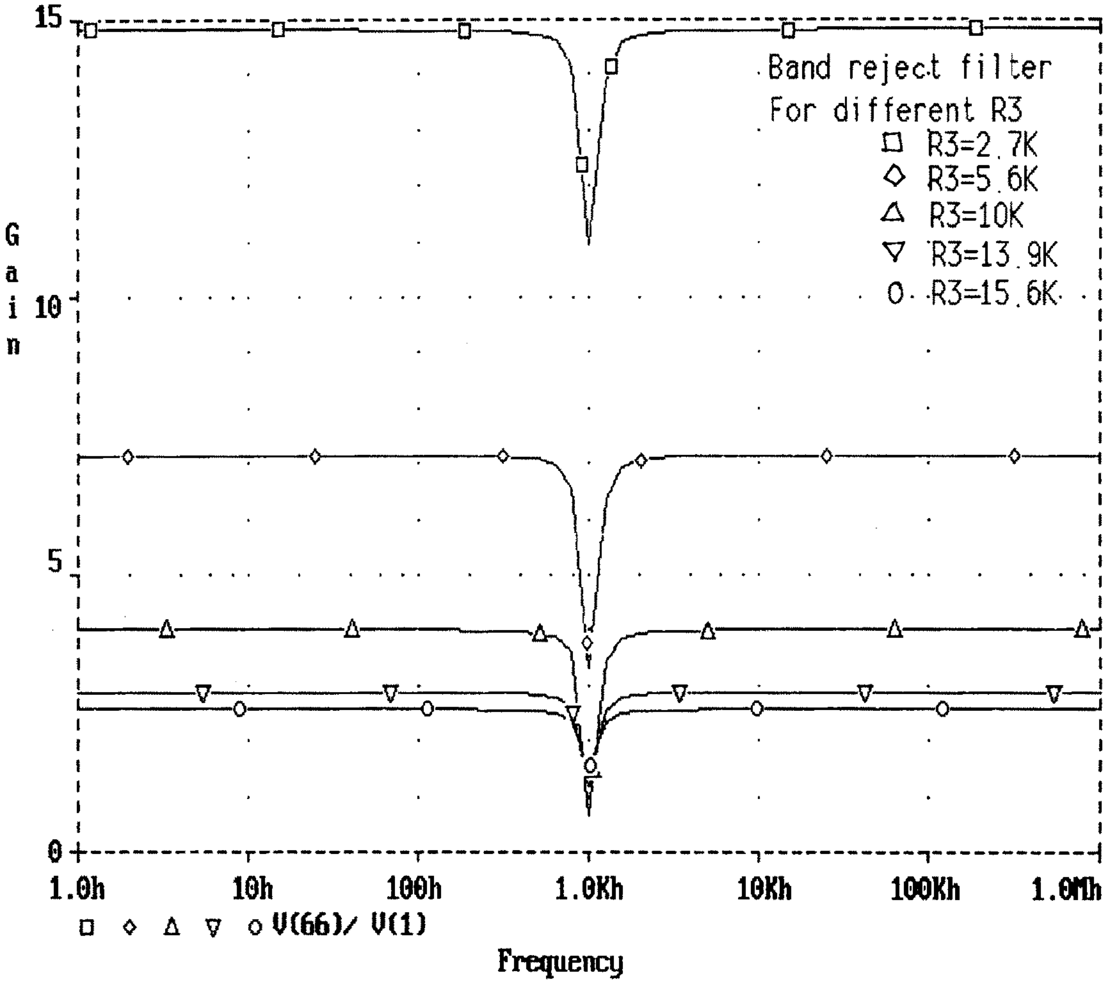

**Fig. 5.11**
**Frequency Response of Band Reject Filter for different $R_3$**