CHAPTER - 5

ACTIVE R FILTER

ACTIVE R FILTER

5.1) ACTIVE R FILTERS :-

The active filters are the filter circuits containing active devices and passive components.It is because of losses associted with and large size the use of inductor is usually avoided.This is also true for integrated circuit versions.Hence, most of the circuits use R and C and they are called active 'RC' filters.

More attention is being given to production of monolithic linear circuits , to minimize the cost of a circuit and to increase the circuit density.Thus, it is implied that the size of the circuit must be as small as possible .Basically,in integrated circuit,a capacitor requires more area than a resistor, which,in turn,uses more space than transistor.Due to this reason any filter circuit without external capacitor would have minimum size.Such circuits are called "active R " filters.

5.2) SODERSTRAND CIRCUIT :-

Dr.M.A. Soderstrand has proposed the simplified form of a general second order filter circuit (which use only resistors and operational amplifiers suggested by Schaumann (1975). He has shown that how this simplified version of Schaumann's circuit may be used to obtain general second and third order building blocks.These blocks can be used to realize higher order filters .

Soderstrand's circuit's major contributions

(1) the development of a simplified design procedure called "active R " filter design.

(2) The generation of a general second order building block , and demonstration of its use in finding a filter cuircuit which simultaneously exhibits low-pass,band-pass,high-pass and band-elimination responses.

(3) Development of third order building block , and procedures for extending to higher-order realizations.

The comparisation of above two circuits shows that Soderstrand has reduced the circuit of fig.5.1(a),by setting $R_3 = R_5 = \emptyset$ and $R_4 = R_6 = \infty$. The circuit of fig.5.1(b) is a simple circuit with two op.amps. and three resistors, which gives three outputs simultaneously at various nodes as LP,BP and HP.(This is a state variable type cirucit).

Since ,the low-pass and band-pass outputs are taken from the output terminal of an amplifier , while high-pass output is not , one might think that the high-pass output would have a much more severe loading problem, it is the cautionary note on the high-pass output suggested by Soderstrand. Further, most severe problem with high pass output is concerned with a very low level output which is obtained when the resonant frequency ω_o is substantially below the gain -band width product GB. Analysis of Fig. 5.1(b) yields following transfer functions.

High-pass:

$$T_{HP}(s) = \frac{(1/R_3)s^2}{\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] s^2 + (GB_1/R_2)s + (GB_1GB_2/R_1)} \qquad (5.1)a$$

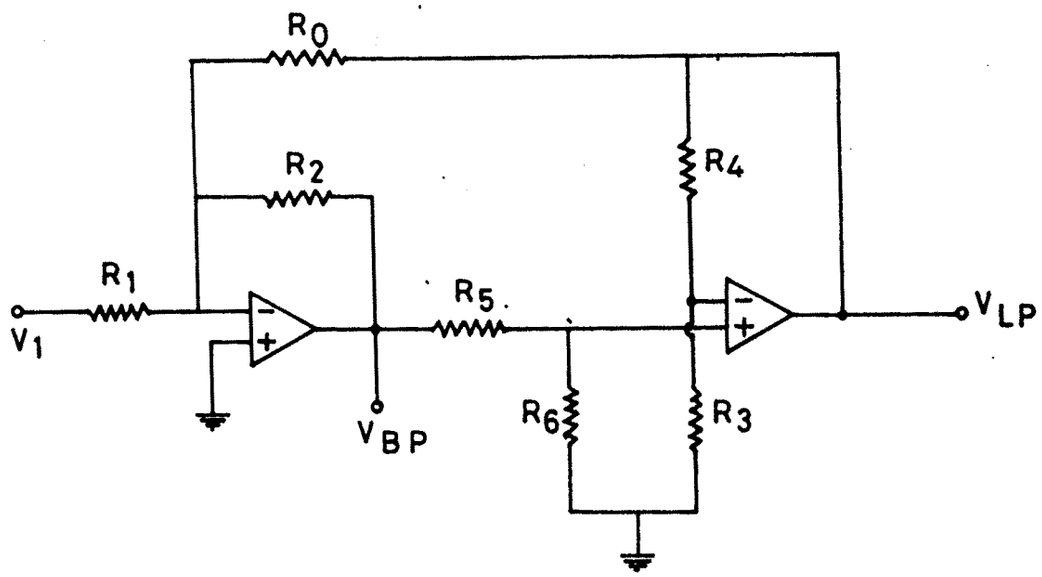

Fig. 5·1 (a) - Schaumann's second-order filter.

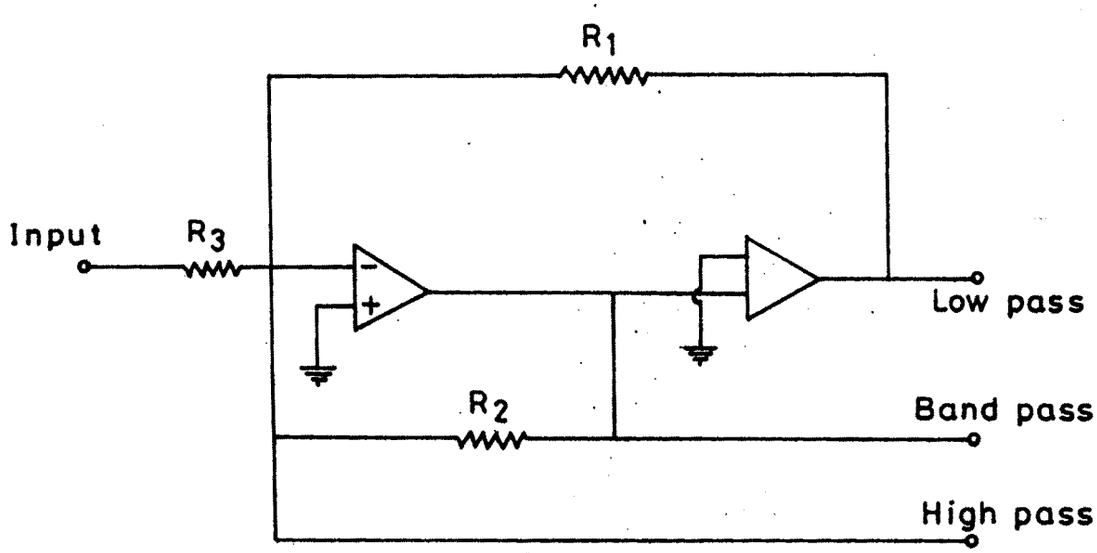

Fig. 5·1 (b) - Second order 'state-veriable' type active R filter (Soderstrand circuit).

Band-pass :

$$T_{BP}(s) = \frac{-(GB_1/R_3)s}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)s^2 + (GB_1/R_2)s + (GB_1GB_2/R_1)} \qquad (5.1)b$$

Low-pass :

$$T_{LP}(s) = \frac{-GB_1GB_2/R_3}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)s^2 + (GB_1/R_2)s + (GB_1GB_2/R_1)} \qquad (5.1)c$$

where, $_1GB$,and $_2GB$ are the gain -band width products of operational amplifiers one and two respectively.

Design of this filter is extremely simple. R_1 sets the pole frequency ω_o, R_2 sets the Q ,and R_3 must be set so that the parallel combination of R_1, R_2 and R_3 is 1 Ω , hence,

$$R_1 = \frac{GB_1 GB_2}{\omega_o^2} \qquad 5.2(a)$$

$$R_2 = \frac{GB_1 Q}{\omega_o} \qquad 5.2(b)$$

$$R_3 = \frac{GB_1GB_2}{GB_1GB_2-(\omega_o/Q)GB_2-\omega_o^2} \qquad 5.2(c)$$

Impedance scaling of resistors R_1, R_2 and R_3 may be used to obtain more practical values. Also, notice that for R_3 to be positive, we must limit ω_o to be some what less than the geometric mean of the gain bandwidth products of the two operational amplifiers.

i.e. $\omega_o < \sqrt{(GB_1GB_2 - GB_2^2/4Q^2)} - GB_2/2Q$

Further, for priactical resistor velues, ω is limited to being no more than a few decades lower than this geometric mean. Thus, the range of the pole frequency is somewhat limited in practice. Notice that, this restriction on ω_o, the resonant or pole frequency of the Second-order section, does not limit ω, the frequency of a signal being filtered. The only restriction on ω is that, it should be possible touse the integrator model for the operational amplifier.

By using one more operational amplifier in summing configuration the band-elimination response is obtained.

5.3) R.L. Patil cicuit :-

N. Mohan & R.L. Patil have studied the same circuit of fig 5.1(b) proposed by Dr.M.A.Soderstrand in low frequency region i.e. for center frequency of 10 KHz.

They have observed and mentioned following points regarding the same circuit in the low frequency region.

(1) The state variable active `R' filter of fig 5.1 (b) can be used for the low frepuency applications provided the (Q < 3)

(2) The band pass section may be used for the low frequency applications with relatively higher values of Q . It works as a resonant circuit for higher values of Q .

(3) As Q is varied, the center fequency remains practically the same. Hence Q can be varied without affecting the center frequency.

(4) For Q greater than 2, an over-shoot appears in the low-pass and high-pass responses.

5.4) MODIFIED CIRCUIT :-

In the present work the circuit of the fig.5.1(b) proposed by M.A.Soderstrand is slightly modified by introduction of positive feedback i.e. the resistor `$R_1$' is split in two parts and the positive feed back is introduced by connecting a resistor `R' between the junction point and the non-inverting input of the second operational amplifier. The modified circuit appears as shown in fig. 5.2.

The circuit is studied in three different ways.

(1) By splitting R_1 exactly in two equal parts i.e $R_1/2$ each (i.e. a=0.5), by keeping R = 1.7 Ω and for various"Q" values at center frequency of 10 kHz.

(2) Splitting of R_1 is same as above but the response of the circuit is studied for various` R 'values like R=4.7 Ω , 6.8 Ω , 10 Ω etc. by keeping Q = 1 & Fo = 10 kHz.

(3) By keeping R = 1.7 Ω and Q = 1 as constants but by varyiing a tapping point "a" as a =0.2, 0.4, 0.6, 0.8 etc.

5.5) THEORETICAL ANALYSIS :-

The open loop gain of the integrated circuit operational amplifier of fig.(5.3) with dominant pole compensation is given by

$$A = \frac{A_o \omega_o}{S + \omega} \qquad (5.3)$$

where A_o is open-loop d-c gain and ω_o is open loop bandwidth.

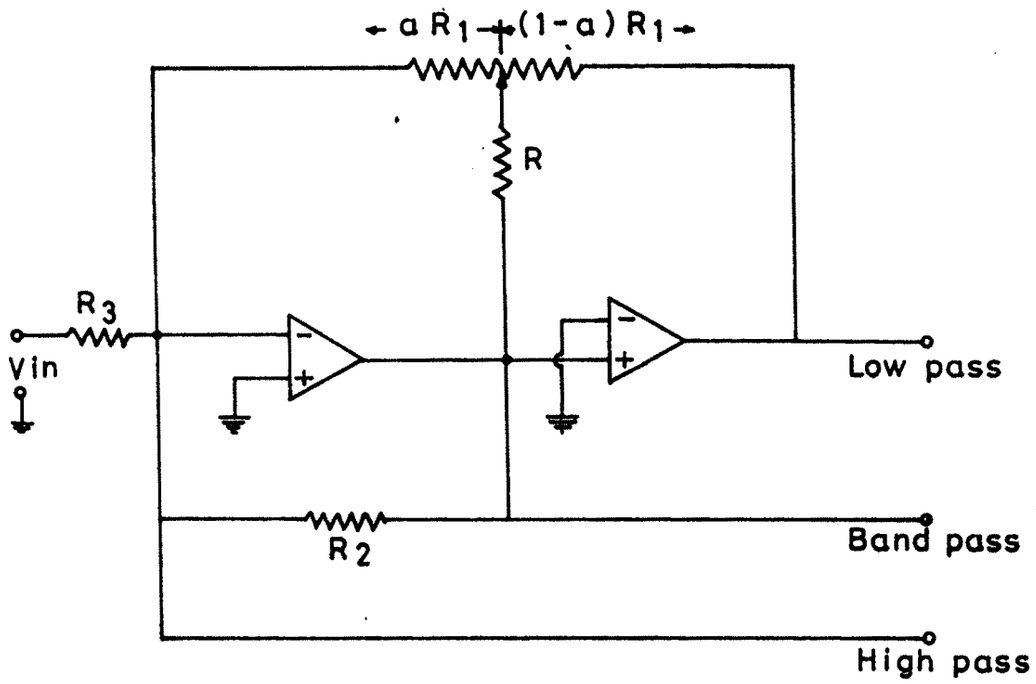

Fig. 5·2

(Modified circuit)

Fig.5.3(a) shows the operational amplifier and fig.3(b) shows typical frequency response for operational amplifier.
The gain-band width product GB is then given by setting.

$|A| = 1$ as

$$GB = A_o \cdot \omega_o \tag{5.4}$$

for $\omega >> \omega_o$, equation (5.3) can be written as

$$A = \frac{A_o \omega_o}{S} = \frac{GB}{S} \tag{5.5}$$

where $GB = A_o \omega_o$ open loop gain bandwidth product.

The active R filter with multiple outputs of Fig.5.2 is studied in detail.

The analysis of the modified circuit of Fig.(5.2) gives the following transfer functions.

1) **High pass :**

$$T_{H.P}(s) = \frac{s^2/R_3}{s^2\left[1/R_1'+1/R_2+1/R_3\right] + sGB_1\left[1/R_2+R_a/R(1-a)R_1\right] + \left[(GB_1GB_2Ra)/a(1-a)R_1^2\right.} \quad \ldots\ldots(5.6)$$

2) **Band pass :**

$$T_{B.P}(s) = \frac{-sGB_1/R_3}{s^2\left[1/R_1'+1/R_2+1/R_3\right] + sGB_1\left[1/R_2+R_a/R(1-a)R_1\right] + \left[(GB_1GB_2Ra)/a(1-a)R_1^2\right.} \quad \ldots\ldots\ldots\ldots(5.7)$$

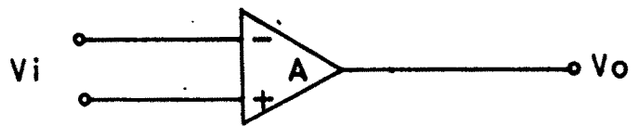

Fig. 5·3 (a) – The operational amplifier.

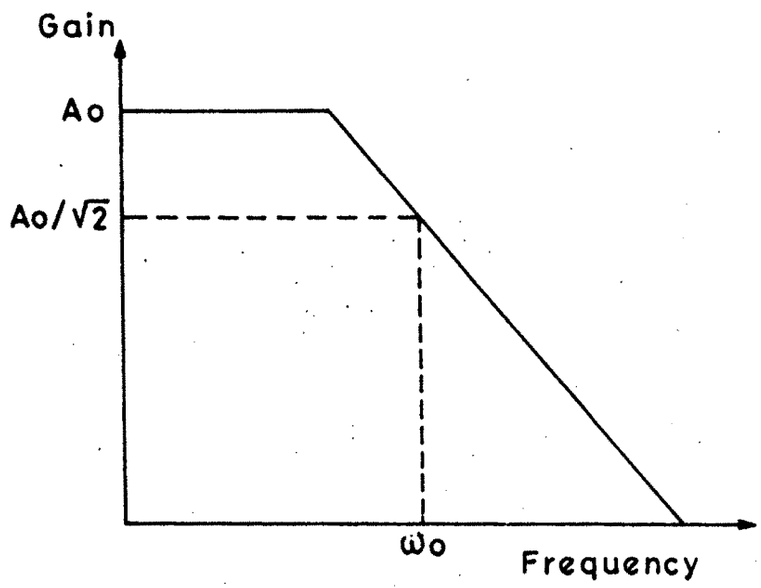

Fig. 5·3 (b) – Typical frequency response for operational amplifier.

3) Low-pass :

$$T_{L.P.}(s)=\frac{-GB_1GB_2/R_3}{s^2\left[1/R_1'+1/R_2+1/R_3\right]+sGB_1\left[1/R_2+R_a/R(1-a)R_1\right]+\left[(GB_1GB_2Ra)/a(1-a)R_1^2\right]} \quad \ldots\ldots\ldots\ldots (5.8)$$

where GB_1, GB_2 are gain band width products of the two operational amplifiers.

$$1/R_a=1/R+1/aR_1+1/(1-a)R_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.9)$$

$$1/R_1'=1/(1-a)R_1-R_a/(1-a)^2R_1^2 \quad \ldots\ldots\ldots\ldots (5.10)$$

If $R = \alpha$ then $R_1' = R_1$ and the original circuit in Fig.(5.1 b) is represented.

The effect of addition of feedback resistor R and the tapping is represented by the transfer function equations 5.6.,5.7, 5.8. If $R = \infty$ the transfer functions are reduced to the transfer function for Soderstand's original circuit. It is noticed that all the coefficients in the denominator are modified as

		Modified Circuit	Original circuit
1)	Coefficient of s^2	$1/R_1' +1/R_2+1/R_3$	$1/R_1+1/R_2+1/R_3$
2)	Coefficient of s	$GB_1[1/R_2+R_a/R(1-a)R_1]$	GB_1/R_2
3)	Last term	$GB_1GB_2R_a/a(1-a)R_1$	GB_1GB_2/R_1

Calculations were made for various R values,Q values and tapping poiints. For small values of R, $R_1' = R_1/2$ and for large values of R, $R_1' = R_1$ Thus the coefficient of s^2 is increased by introduction of R. Similarly, the presence of R leads to increase in ω_o or decrease in Q. It is noticed from the coefficients that a

value of R_1 increases with increase in R, while R_2 decreases with increase in R. Similarly, the variation of Q for different values oe R shows that only R2 changes and R2 decreases with increasing values of R. However, in all cases presence of R introduces positivce feedback and provides higher gain. This is clearly indicated in the response of Band-stop and Low-pass filters. However, the response is controlled by gain-band width prodsuct. The presence of of R also affects wo and as R increases wo also increases. This is observed in the low pass and band pass responses.

5.6) DESIGN CONSIDERATIONS :-

A general second order transfer function is given by

$$T(s)= \frac{\alpha_2 s^2+\alpha_1 s +\alpha_o}{s^2+ (\omega_o/Q)s +\omega_o^2} \qquad \text{.....(5.11)}$$

The comparison of general second order transfer Function of equation (5.11) with the transfer functions of eqations (5.6),(5.7),(5.8) gives the following design equations.

$$1/R_1+1/R_2+1/R_3 = 1 \qquad \text{.....(5.12)}$$

$$1/R_2+R_a/(1-a)R_1 = \omega_o/Q \qquad \text{..... (5.13)}$$

$$GB_1GB_2R_a/a(1-a)R_1^2 = \omega_o^2 \qquad \text{..... ..(5.14)}$$

It is seen that the general transfer function provides only three equations, whereas the design requires the values of four resistors. However, the forth equation can be obtained from

sensitivity of ω_o w.r.t. `R' i.e.

$$S_R^{\omega_o} = \frac{R}{\omega_o} \frac{\partial \omega_o}{\partial R}$$

This equation can be solved together with (5.12) to obtain R as well as R_1 . However, the resulting equations are quite complicated. Hence, a suitable value of R was assumed. For this the response was studied with different values of R and a value R=1.7 was found to be more suitable.

By substituting the proper values of GB_1 GB_2,ω_o and R in equation (5.12) (5.13),(5.14) we get give the experimental values of R_1,$R_2$and R_3.

5.7)<u>Experimental Details</u> :-

In this investigation the circuit of fig.(5.2) is studied in three different ways viz.

A) Variation of Q values.

(b) Variation of "R" values.

(c) Change of tapping point.

5.7(a) <u>Variation of "Q" values</u> :-

The modified circuit was studied to find the effect of variations in Q on the various output respnses. The component values were determined using equation 5.12,5.13,5.14 with R=1.7,a=.5 and fo=10 KHz. All resistance values are then scaled up by a factor of 100 to opbtain practical values for the ciruit. The commonly available operational amplifier μA741 was used for the circuit. The gain-bandwidth product was determined experimentally to be 2π X 7.8 X 10^5radians/sec. Two operational amplifiers with

almost identical GB values were selected for the circuit assembly. The circuit was assembled very carefully to avoid stray capacitances, leakages etc. The input voltage level was adjusted in such a way that the response was not affected by slew rate limitations of the operational amplifier. The response was studied over the frequency range of 100 Hz to 1 MHz. The various outputs are represented graphically in fig.5.4,5.5 5.6 and 5.7.

5.7(1) Low pass Response :-

The low pass response is represented by Fig.5.4. It is observed that the response is satisfactory over the entire frequency range. The upper cut-off frequency agrees with the design value of f_o=10 KHz. It is also noticed that the variation of Q has practically no effect on the output except at high frequency end where gain varies slightly. In order to compare the effect of the modification, the response of the Soderstrand circuit is also plotted. It is noticed that in the pass band the two circuits have almost the same gain. However, above 100 KHz, the modified circuit gives higher rejection of about 25 db as compare to the original circuit.

5.7(2) Band Stop Filter :-

The band stop response is presented in the fig. 5.5 . It is noticed that the response is much better than the response of Soderstand circuit In the modified circuit,the response drops rapidly from 20 KHz onwards upto 500 KHz and then increases upto 1 MHz. The response of unmodified circit, however, flattens from 100 KHz onwards. The design frequency in this case does not agree with the observed frequency.

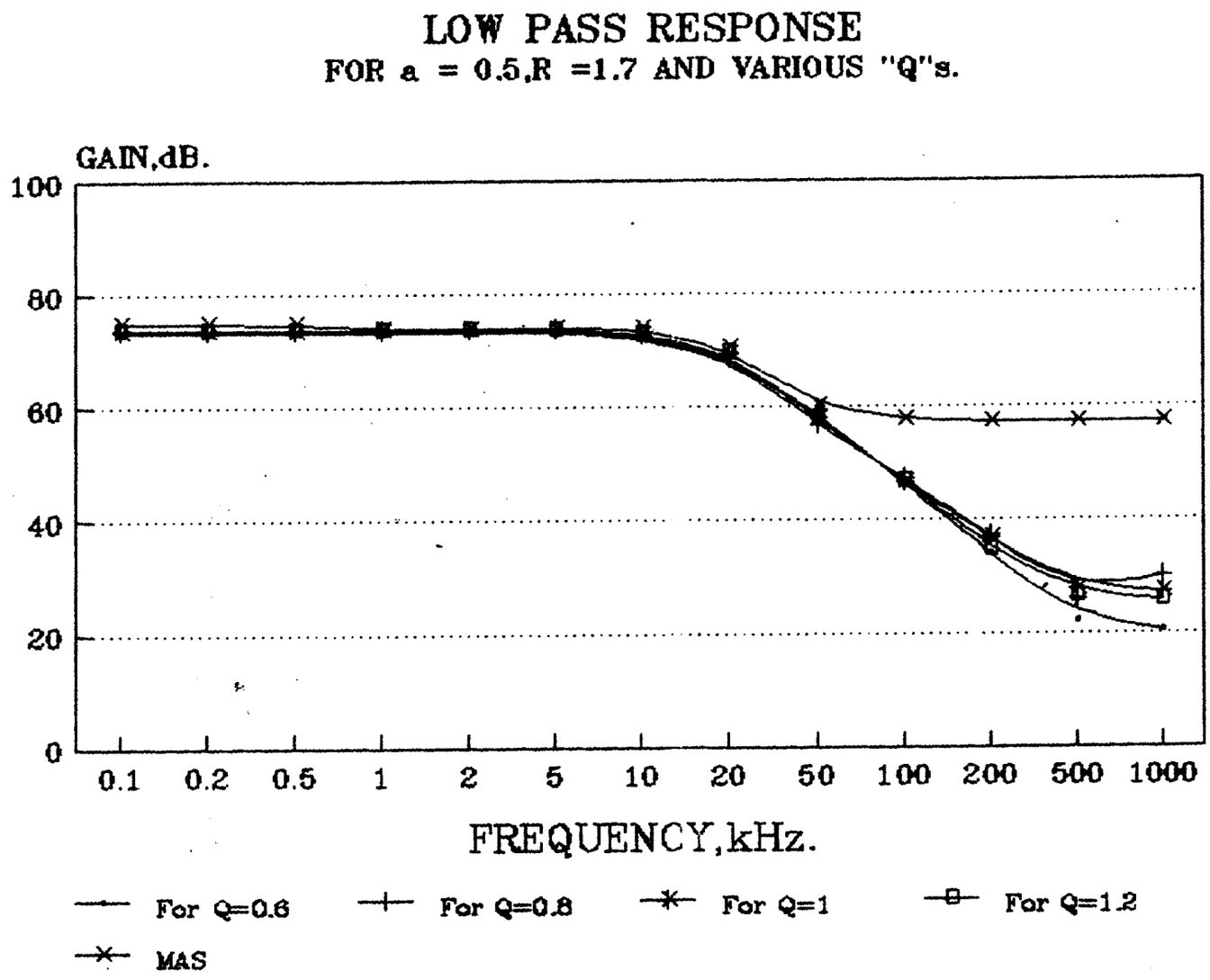
LOW PASS RESPONSE
FOR a = 0.5,R =1.7 AND VARIOUS "Q"s.
GAIN,dB.
100
80
60
40
20
0
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1000
FREQUENCY,kHz.
For Q=0.6
For Q=0.8
For Q=1
For Q=1.2
MAS

Fig.(5.4)

BAND STOP RESPONSE

FOR a=.5,fo=10 kHz,R=1.7 Ohms ,Diff.Q.

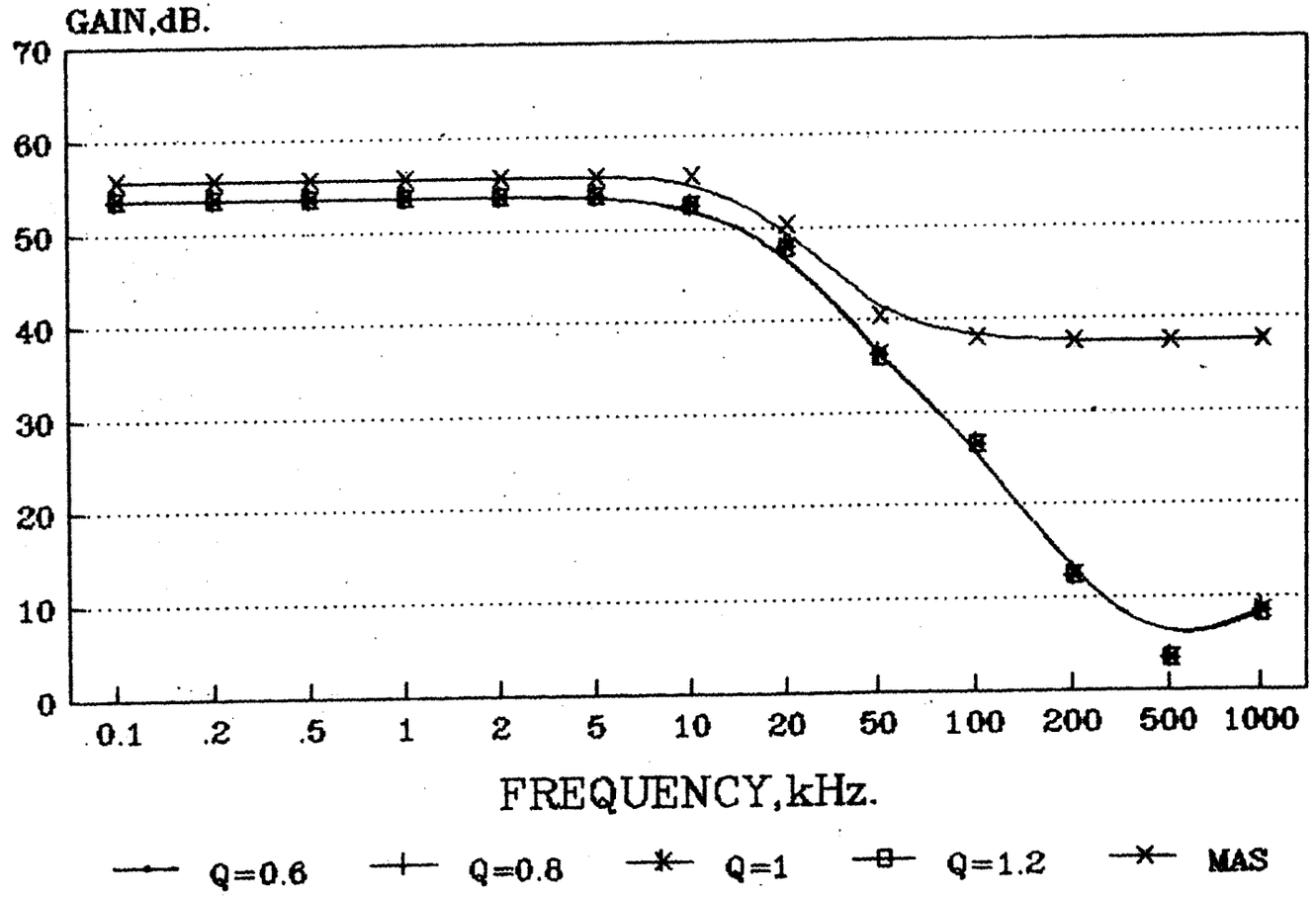

Fig.(5.5)

BAND PASS RESPONSE

FOR a=0.5,R=1.7 Ohms,VARIOUS "Q"s.

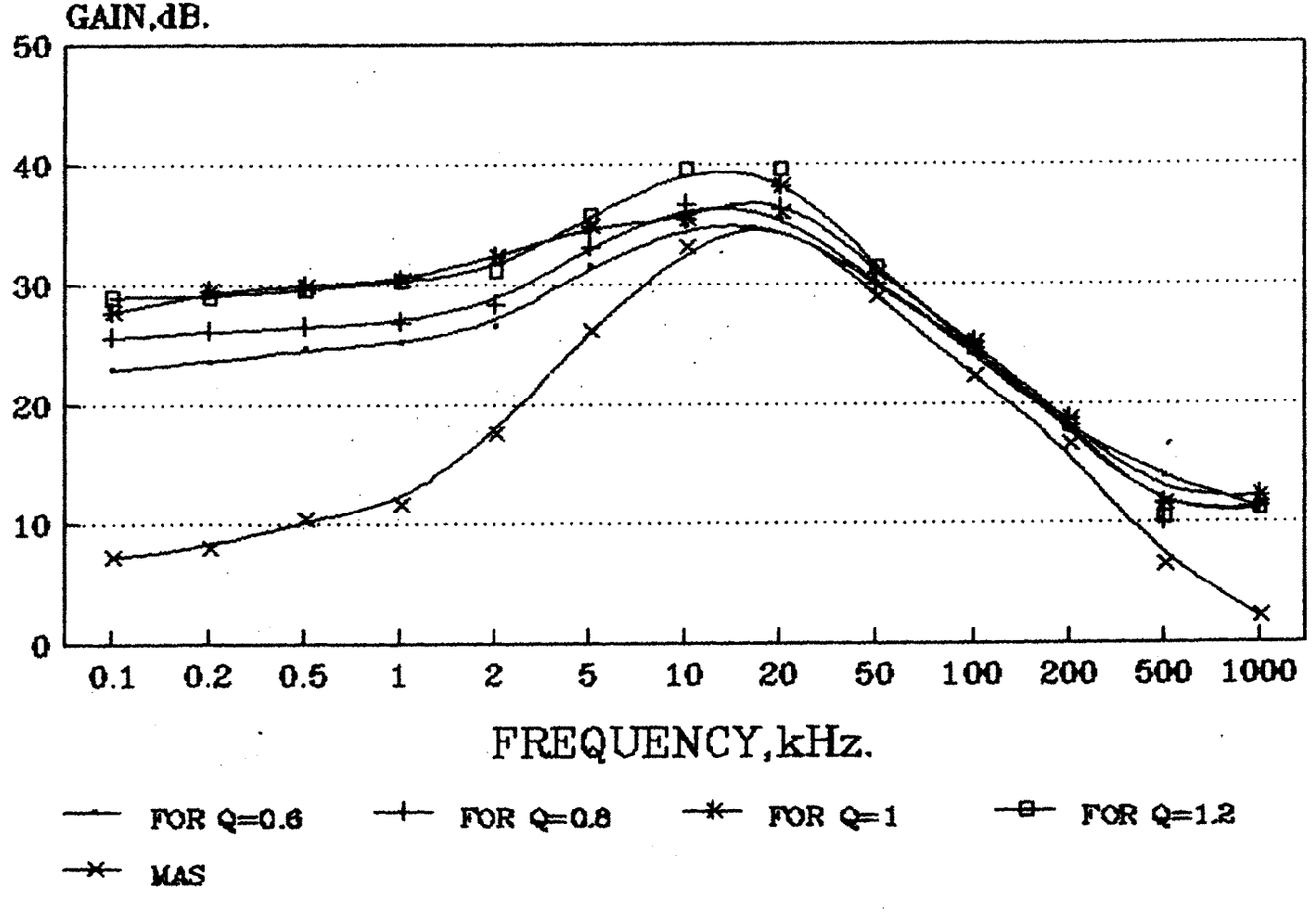

FIG.(5.6)

HIGH PASS RESPONSE

FOR a=0.5,R=1.7Ohms,VARIOUS "Q"s.

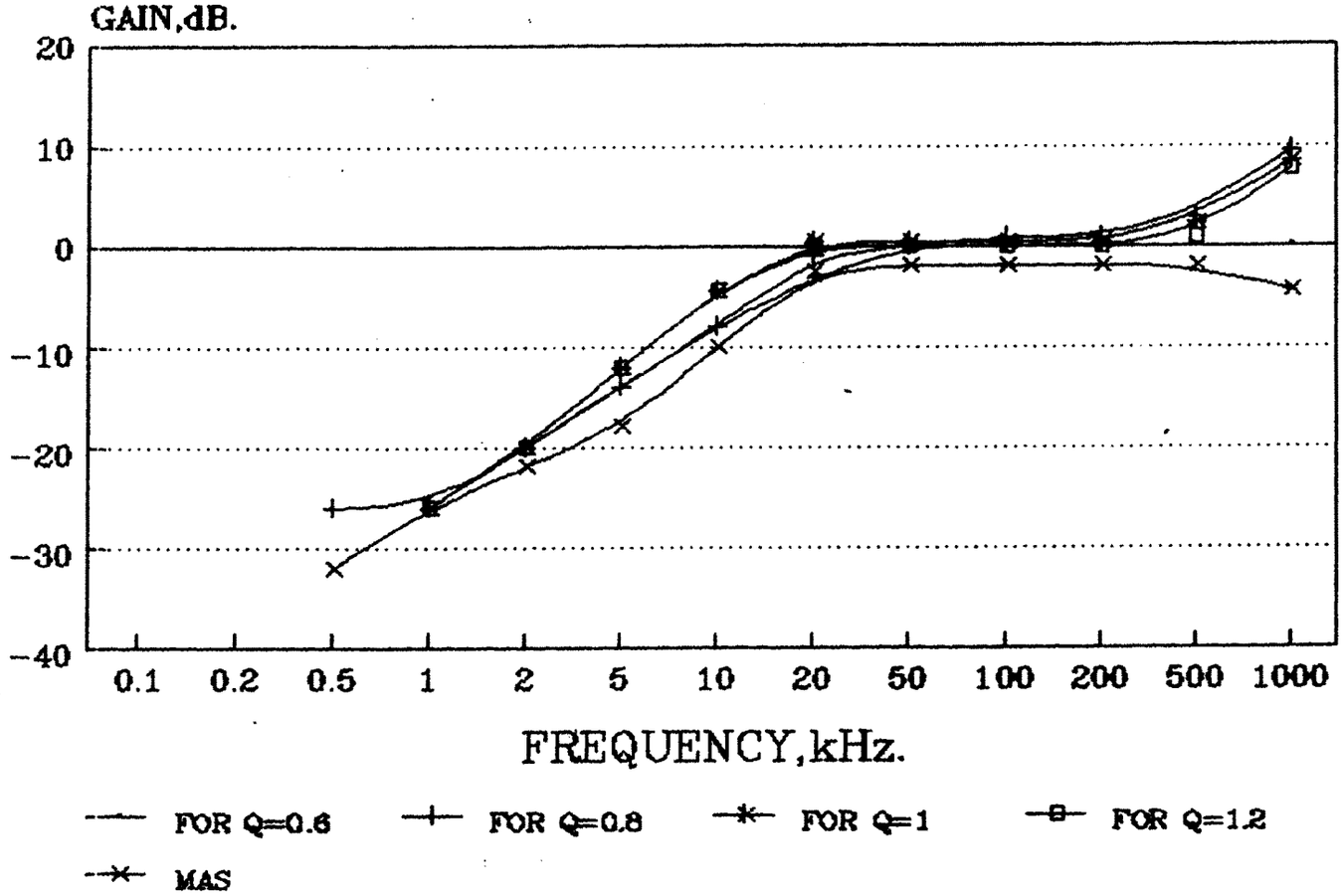

FIG.(5.7)

5.7(3) Band Pass Response :-

The band pass response is shown in fig.5.8. The design frequency matches with the observed peak frequency. Above the peak frequency the gain decreases rapidly. The variation of Q has little effect in this range. It is noticed that the response below the peak frequency is not satisfactory in the sense that the gain does not vary rapidly with the `frequency and characteristics appear to be like those of low-pass filter. The variation in Q has some effect on the gain in this range. The Soderstand circuit response is also represented for Q=1. The response is much better on low frequency side but almost same as that of modified circuit on high frequency side. This may be due to pronounced effect of positive feedback on low frequency side.

5.7(4) High Pass Response :-

The high-pass response for various values of Q is shown in Fig.5.7. It is noticed that the response of modified circuit is almost similar to that of Soderstrand circuit. There is slight increase in gain above 500 KHz which may be due to resonance effect despite the carefull assembly of the circuit.

Thus , the overall response of the modified circuit is very satisfactory. It gives better output as compared to Soderstrand circuit for low-pass and band-stop action. For the high-pass action the response is almost same but in case of band-pass output there is some degradation at low frequencies.

5.7 (B) VARIATION OF `R' VALUES :-

The effect of variation in the R values on the response of the modified circuit is studied and discussed in this section. For

this different values of R are assumed and the other components were calculated for Q=1, fo = 10KHz and a=.5 . Again the same oeprational amplifier pair with almost identical GB values was used for assembly of the circuit. Again the response was observed over the frequency range of 100Hz to 1 MHz and graphically respresented in Fig.5.8,5.9,5.10 and 5.11.

1) Low pass Response :

The low-pass response is shown in Fig.5.8. It is noticed that the response is satsfactory over the entire frequency range. The design value of f_o matches well with observed value of upper cutoff frequency. However, the change in `R' has vary little effect on the response. The response of Soderstand circuit is also represented for comparison .It is noticed that the responses are very similar in the pass band but outside the pass band modified circuit gives higher rejction of about 25dBs.

2) Band stop Response :

The band-stop response is shown in Fig.5.9 . The response is somewhat similar to low pass response. with some degree of rejection. As far as band rejection is desired the response is not satisfactory, although considerable gain is achieved in the low frequency region. The design frequecy also does not match in this case. The response of Soderstand circuit is also presented. The modified circuit shows better rejection in this case.

3) Band Pass Response :

The band pass response is shown in Fig.5.10. It is seen that

LOW PASS RESPONSE

FOR Q=1 ,Fo=10kHz,a=0.5,VARIOUS 'R's.

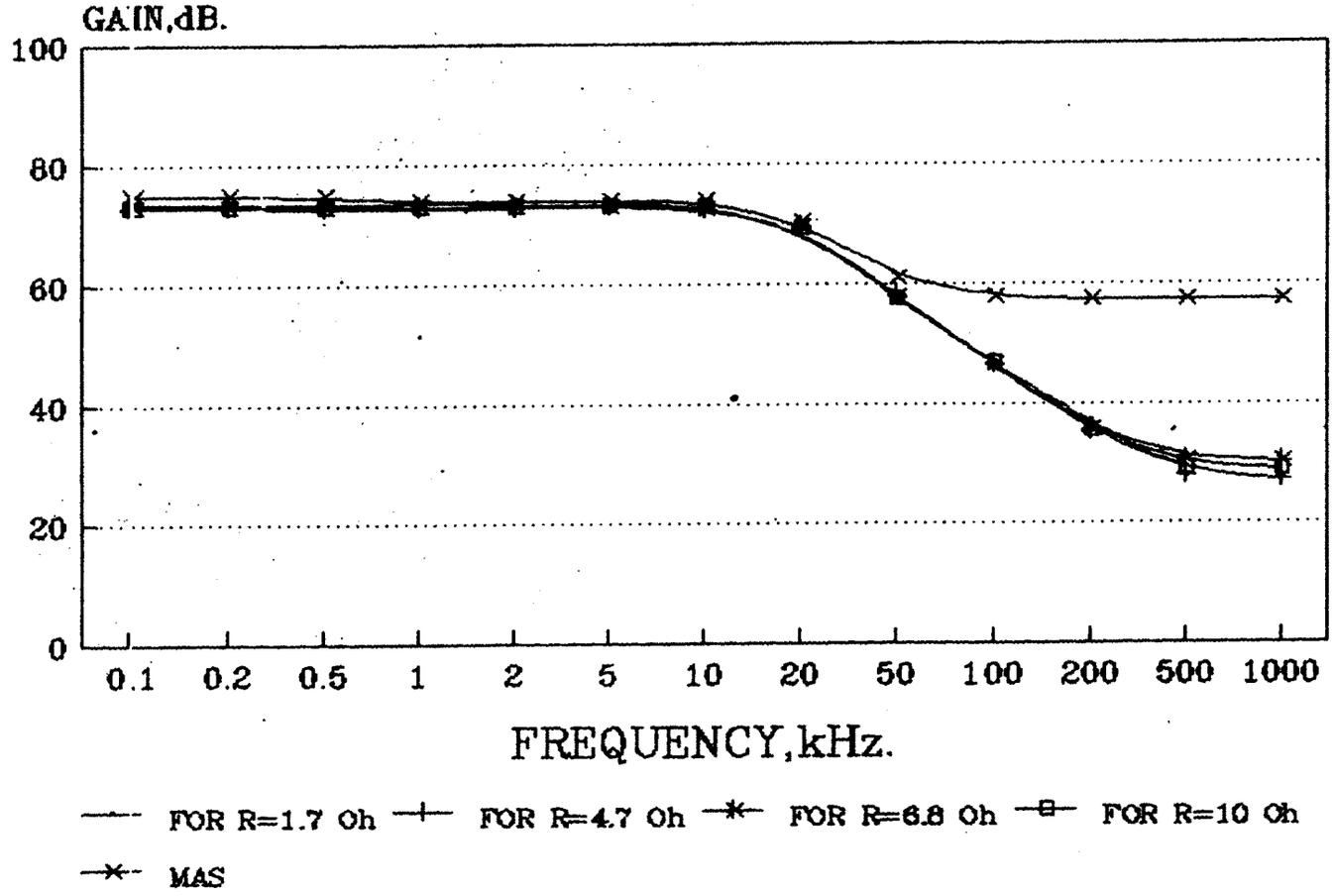

FIG (5.8)

BAND STOP RESPONSE
FOR Q=1,Fo=10 kHz,a=0.5,VARIOUS 'R's.

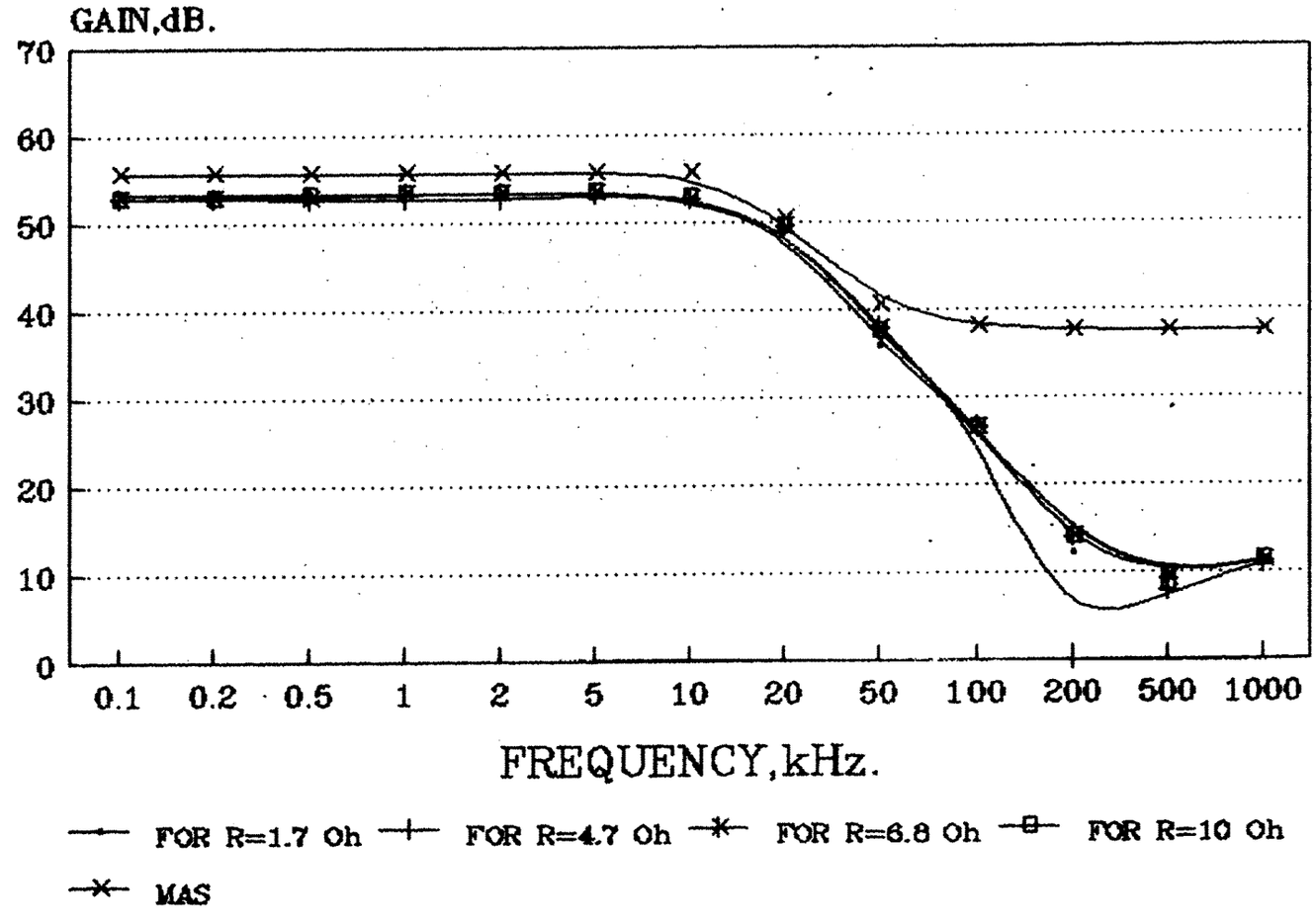

FIG.(5.9)

BAND PASS RESPONSE
FOR Q=1,Fo=10kHz,a=0.5,VARIOUS 'R's.

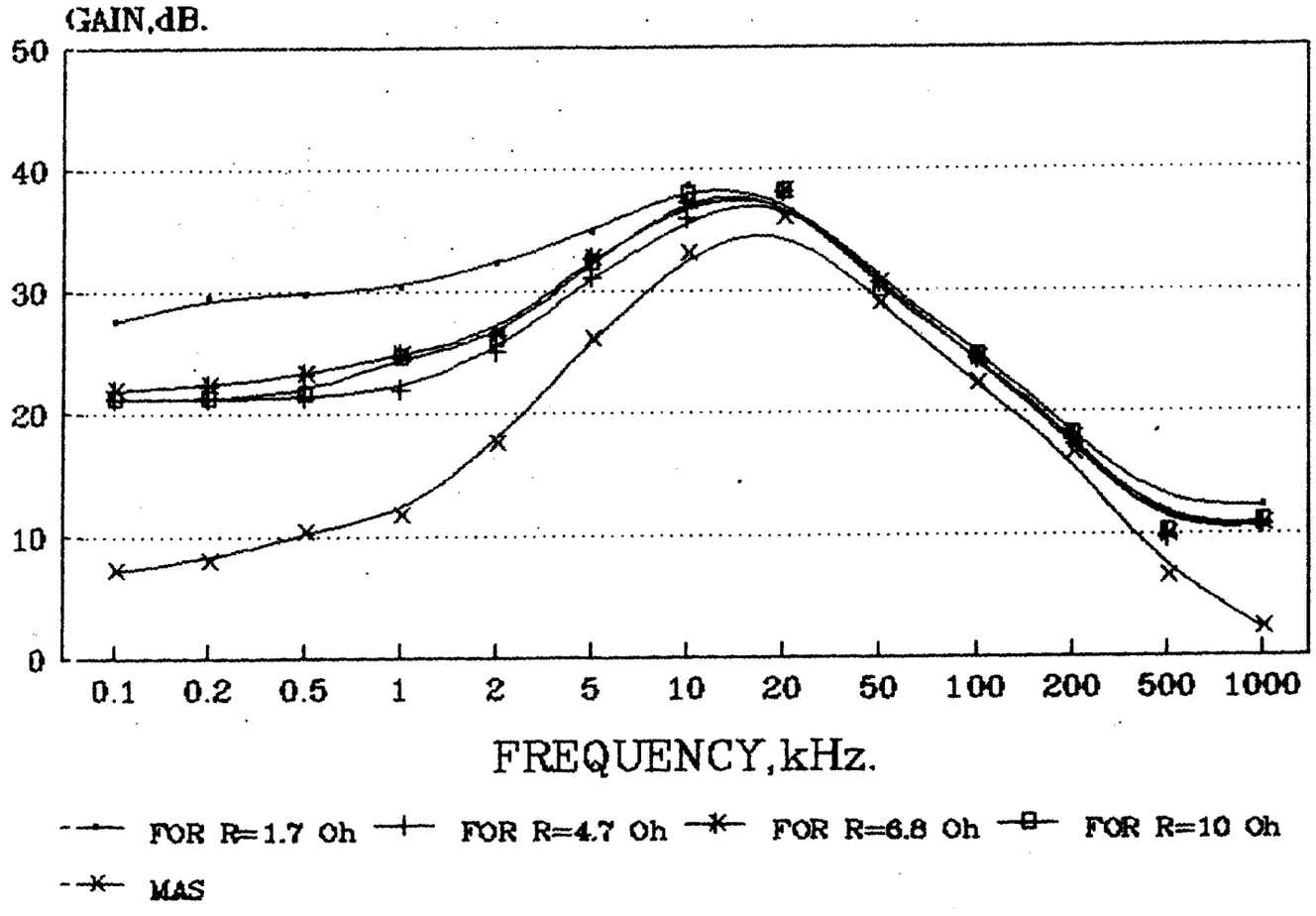

FIG.(5.10)

HIGH PASS RESPONSE
FOR Q=1,Fo=10 kHz,a=0.5,VARIOUS 'R's.

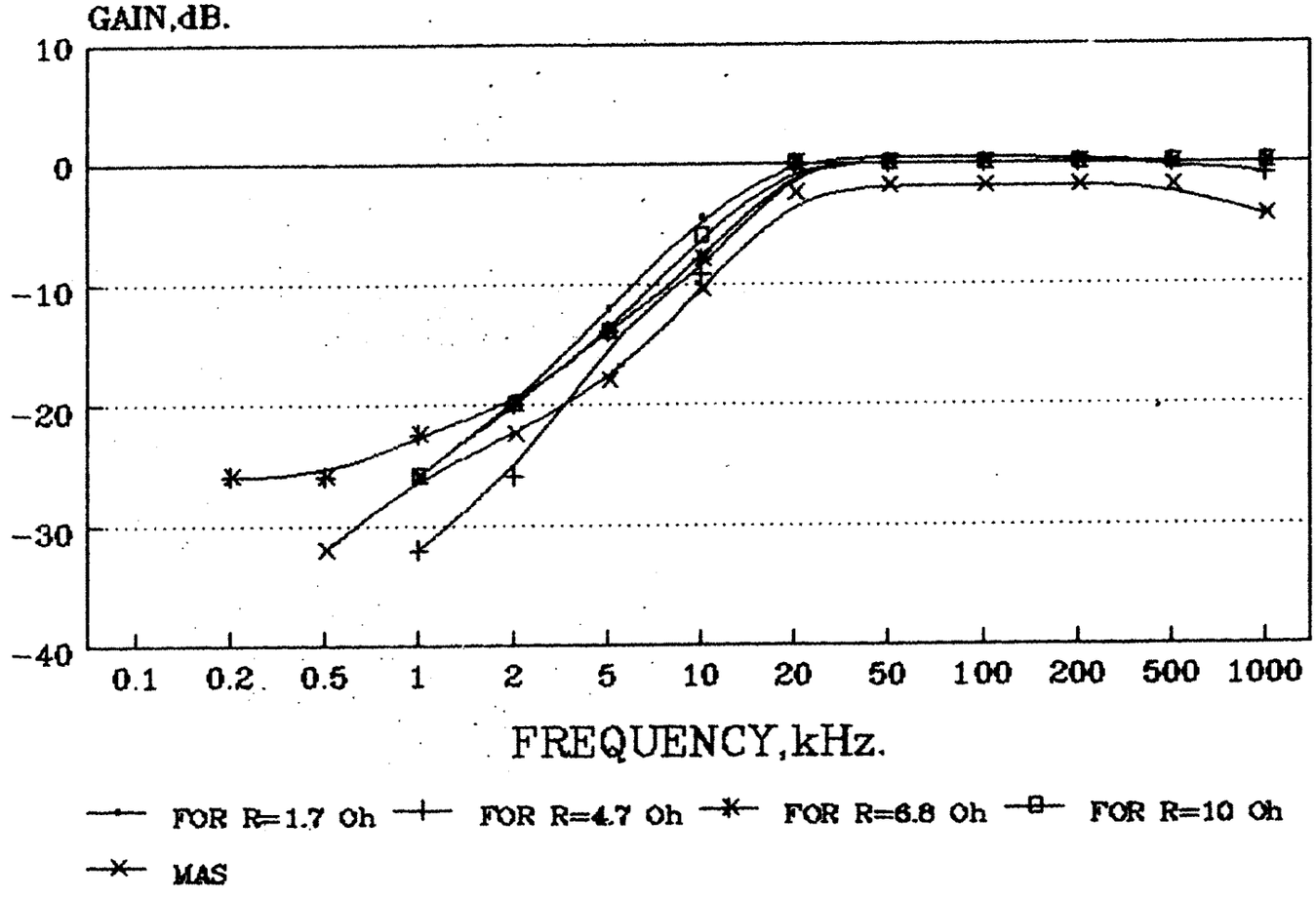

FIG.(5.10)

the response is satisfactory above 20 KHz and peaks in the range from 10 KHz to 20 KHz.This agrees well with the design value of f_o = 10KHz. On low frequency side, however, gain is appreciable i.e. rejction of low frequency signal is rather poor. The comparision of the response of Soderstand circuit shows that the responses are almost simialr in the high frequency range. The Soderstrand circuit shows better rejection on low frequency side.

4) <u>High pass Response</u> :-

The high pass response is represented in Fig.5.11 is quite satisfactory. It is very similar to the response of Soderstand circuit. The response is almost flat from 20 KHz onwards. The cut-off frequencies observed on the graph are slightly higher than the design value of 10 KHz.

Thus the overall response is satisfactory.The band-stop and low-pass response are much better than those of Soderstand circuit. The high-pass response is almost similar in both the cases. The band-pass response is poor on low frequency side.

5.7 (c) <u>Variation of tapping parameter</u> :-

The performance of the cirucit was further evaluated by varying the tapping parameter `a' for the Q=1 ,R=1.7 and f_o=10 KHz the results are represented in Figs.5.12,5.13,5.14 and 5.15. For the design the same pair of operational amplifier with almost same gain-bandwidh product was used. The various outputs are discussed below.

1) <u>Low pass response</u> :

The low pass response is very satisfactory. The design

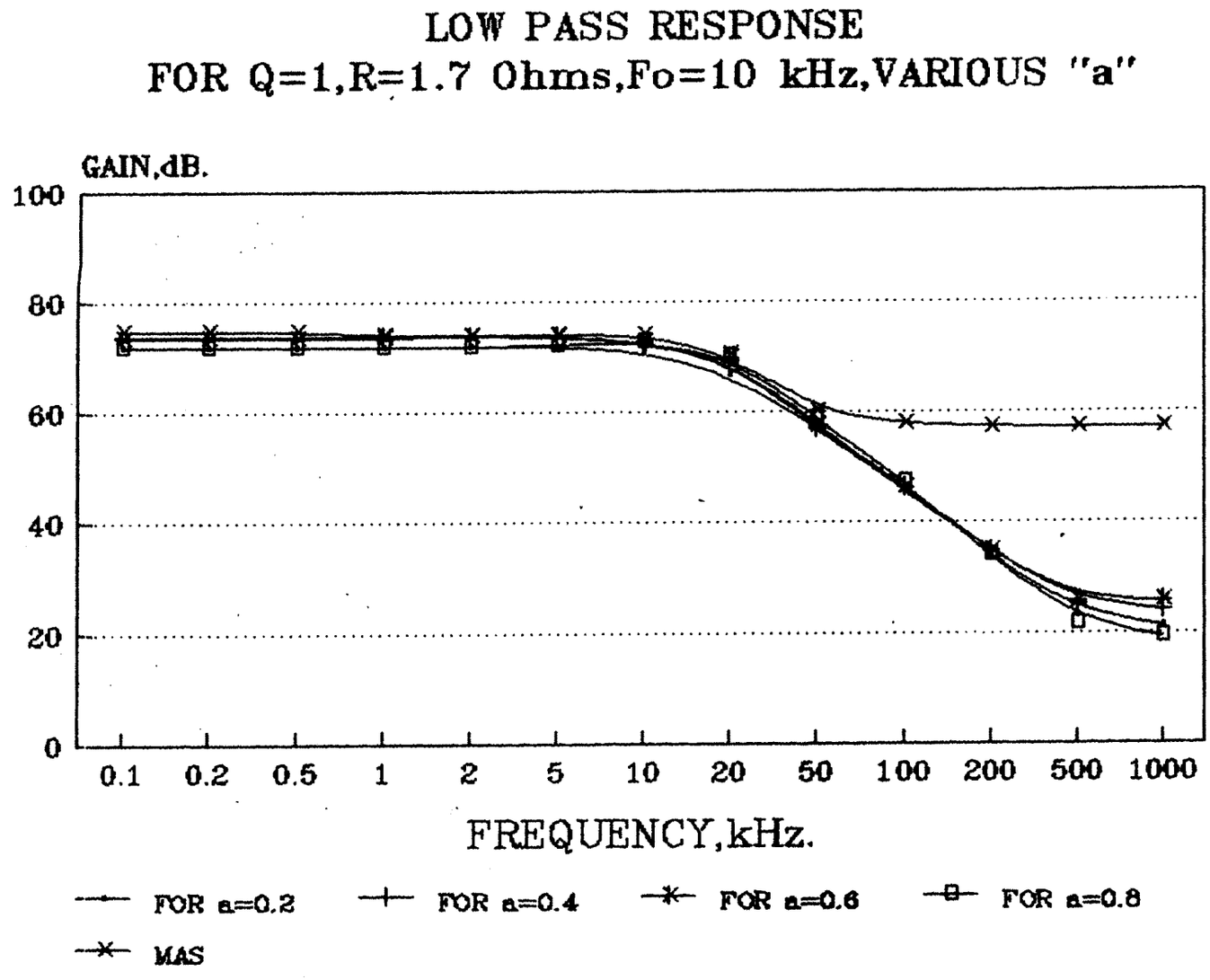
LOW PASS RESPONSE
FOR Q=1,R=1.7 Ohms,Fo=10 kHz,VARIOUS "a"
GAIN,dB.
100
80
60
40
20
0
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1000
FREQUENCY,kHz.
FOR a=0.2
FOR a=0.4
FOR a=0.6
FOR a=0.8
MAS

FIG (5.12)

BAND STOP RESPONSE
FOR Q=1,R=1.7 Ohms,Fo=10 kHz,VARIOUS "a"

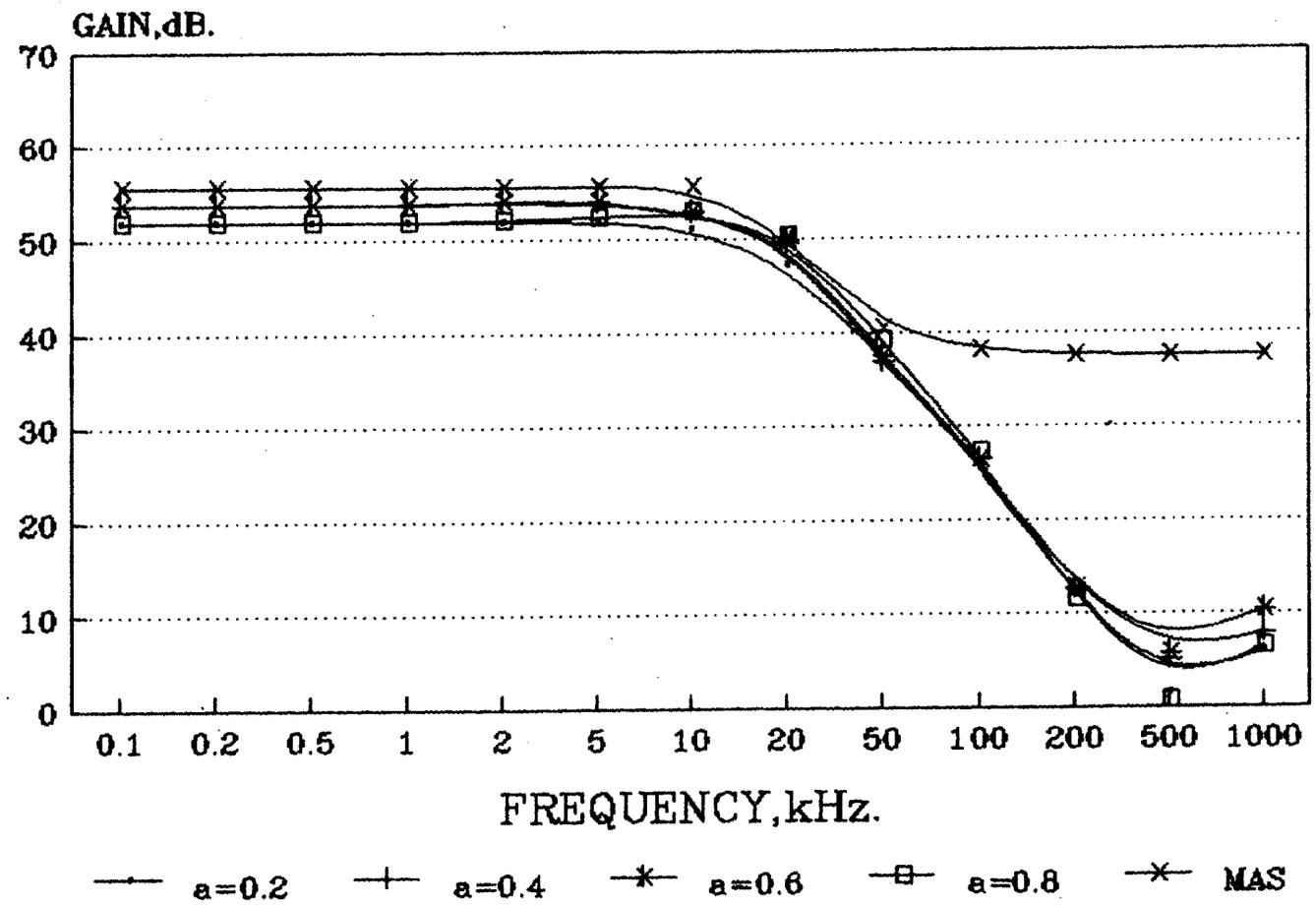

FIG.(5.13)

BAND PASS RESPONSE
FOR Q=1,R=1.7Ohms,Fo=10 kHz,VARIOUS 'a'

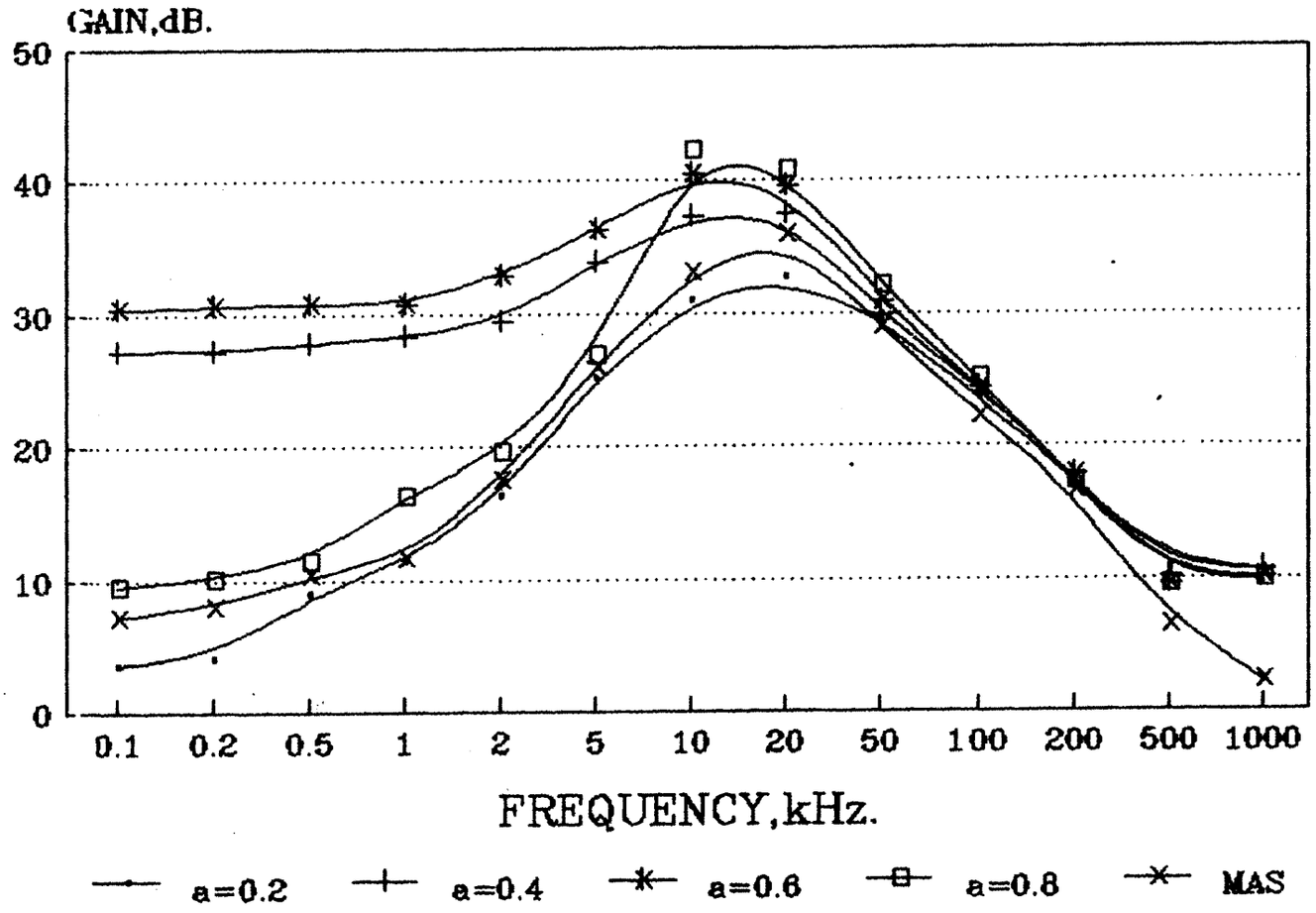

FIG.(5.14)

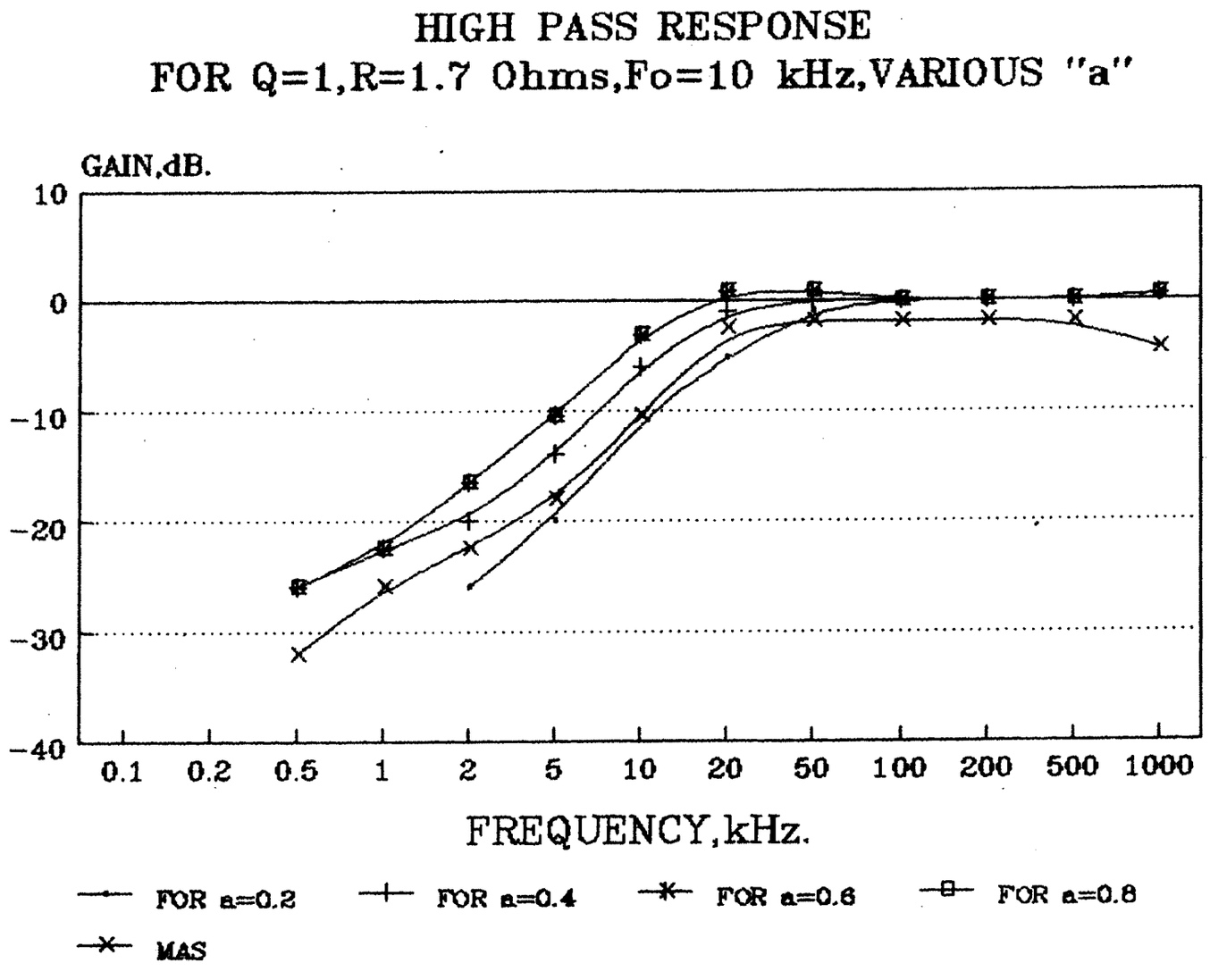
HIGH PASS RESPONSE
FOR Q=1,R=1.7 Ohms,Fo=10 kHz,VARIOUS "a"
GAIN,dB.
10
0
-10
-20
-30
-40
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1000
FREQUENCY,kHz.
FOR a=0.2
FOR a=0.4
FOR a=0.6
FOR a=0.8
MAS

FIG.(5.15)

value of f_o agrees well with the observed value on the graph. For comparison the response of Soderstand circuit is also presented. Below 50 KHz both the responses are almost identical . However, the modified circuit responses reduced continuously. From about 70 dB to 20 dB while the Soderstand circuit response remains constant about 50 KHz at 50 dB.

2) Band stop Response :

The band stop response is represented in Fig.13. The response shows high gain at lower frequencies but the rejection is marginal. The design frequency of f_o also does not match in this case. Variation of "a" has practically no effect on response. This indicate that the response is mainly controlled by the total values of R_1 and not by the tapping parameter "a". The response of Soderstand circuit seems to be very poor in this case also.

3) Band Pass Response :-

The band pass response is shown in Fig.5.14.The centre frequency in this case is same for all values of "a" and agrees well with the design value. On low frequency side gain depends on the parameter "a" for large and small values i.e. a = .2 and a = .8. The responses are quite good and the complete response over entire range is very similiar to the response of Soderstand circuit. For value of a =.4 and a=.6 The response on low frequency side is completely degraded.

4) High Pass Response :

The high pass response is shown in Fig.5.15. It is noted that the variation of "a" has slight effect on the gain on low frequency

side. The best performance is obtained for a=0.2 . Above 20 KHz the response is flat upto 1 MHz.

Comparison with Soderstrand circuit shows that the responses are almost same.

The modification done with the introduction of positive feedback using resistor `R' is quite satisfactory.However,one more additional resistor is required. This may be considered as disadvantage.However,a variable resistor for tapping in the form of voltage dependent resistor and R can be very easily accomodated in the IC design. The choice of f_o and the tapping parameter,restricts Q to very small values.In this case,it is about 1.5.,For higher values,calculated values of components become negative.The overall comparison of modified and unmodified circuit is shown in table 1 and the circuit components in table 2.

TABLE 1

Variation	Soderstrand Ckt.	Modified Ckt.	Type of Filter
	Not satisfactory	*Satisfactory	Low-pass filter
	Quite good	*Satisfactory	Band-stop filter
Q	*Satisfactory	Not satisfactory	Band-pass filter
	Almost same	Almost same	High-pass filter
	Not satisfactory	*Satisfactory	Low-pass filter
R	Quite good	*Satisfactory	Band-stop filter
	*Satisfactory	Not satisfactory	Band-pass filter
	Almost same	Almost same	High-pass filter

	Not satisfactory	*Satisfactory	Low-pass filter
	Quite good	*Satisfactory	Band-stop filter
a	*Satisfactory	Not satisfactory	Band-pass filter
	Almost same	Almost same	High-pass filter

*-->

TABLE -II

COMPONENT VALUES

TYPE OF VARIATION	f_o	Q	a	R	R_1	R_2	R_3
	10 kHz	0.6	0.5	1.7	20K	8.7K	100 Ω
Q	"	0.8	"	"	"	15.7K	"
	"	1	"	"	"	33K	"
	"	1.2	"	"	"	100K	"
	10 KHz	1	0.5	1.7	20K	33K	100Ω
	"	"	"	4.7	33K	15K	"
R	"	"	"	6.8	39K	12K	"
	"	"	"	10	47K	10K	"
	10KHz	1	0.2	1.7	20K	16K	100Ω
	"	"	0.4	"	"	"	"
a	"	"	0.6	"	"	"	"
	"	"	0.8	"	"	"	"

Values of R_1, R_2 and R_3 shown are scaled by factor of 100. The value of R used in the circuit is also scaled by same factor.

For "a" variation part of table-II resistor R_1 is splitted in two parts as "a" and "1-a".Hence,the value of R_1=20K is divided as given below.

	aR_1	$(1-a)R_1$
For a=0.2	4K	16K
For a=0.4	8K	12K
For a=0.6	12k	8K
For a=0.8	16K	4K

Further study is going on to remove the drawbacks observed in the modified circuit and further improvements in the response,i.e. increase in gain,control of gain,control of band-width and control of center frequency etc.