CHAPTER 6

BALANCED OTA-C LOW PASS FILTER

CONTENTS :	Page No.

6.0 Balanced OTA-C low pass filters :

6.0.1 Introduction :- The OTA-C approach in particular include operational transconductance amplifier and capacitor which replaces active RC filters. The structural simplicity, electronic tunability, high frequency capability and monolithic intergability are used in generating an interesting new configuration using the concept of wire feedback. The theory of the structured filter helps in studying the relationship between the filter structure and the type of feedback. The limitation of the structure generation in the design of multiple loop feedback OTA-C low pass filters are totally eliminated from this newly introduced structure. The study of the cascade arrangement is analysed and an attempt is made for the synthesis of transmission of poles and zeros of the structures.

The cascade LPF with wire feedback or amplifier feedback exhibit an oscillator character of a particular order. To retain the LPF character of the structure, the feedback arrangement has to be changed. Number of approaches in the feedback technique are made to take up the structure design using the concept of balanced OTA-C filters. The present contribution of the author to the LPF studies involve a new structure consisting of a differential input and a differential output for different order generation. From the modified structure, an experimental study is carried out for the four successive stages which include the analysis of the first order, second order, third order and fourth order. The details of the study are presented in brief for the cascade arrangements.

6.1 Analysis of the first order balanced OTA-C LPF :-

6.1.1 Introduction :- The effect of the feedback on OTA-C LPF filter [5,6] is carried out in the differential input and differential output mode. A simple wire feedback has a differentiating character in 3db pole frequency of the filter. A symmetric arrangement is most suitable in the transmission of poles and zeros in the cascade arrangement. The studied structures are shown in figure 6.1 and 6.2

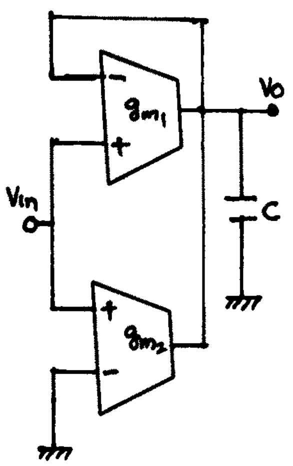

Fig 6.1 : Unbalanced OTA with wire feedback

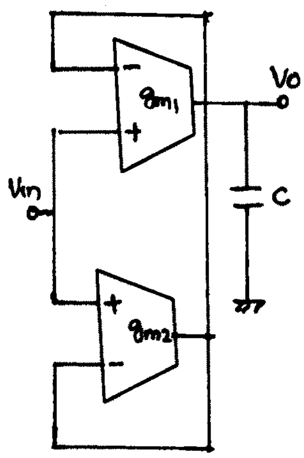

Fig 6.2 : Balanced OTA with wire feedback

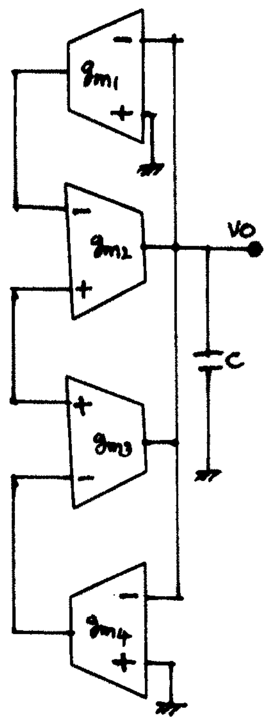

Fig 6.3 : Balanced OTA with amplifier feedback

6.1.2 Theory :- Transconductance adds in parallel

1) $g_{eq} = g_{m1} + g_{m2}$, $H(S) = 1 / sC / g_{meq} = g_{meq} / sC$ this must exhibit LPF for balanced

structure also

2) $H(S) = (\text{gain})\ 1 / sC / g_{meq} = \text{gain}\ \{ 1/ sC / g_{meq} \} = g_m\ \{1 / sC / g_{meq}\} = g_m\ g_{meq} / sC$

3) For unbalanced structures $H(S)\ .\ 1 / sC / g_{m1} \cdot g_{m2} / g_{m1} = 1 / sC / g_{m1}$ (gain). Thus it exhibits LPF.

6.1.3 Experimental :- The two structures shown in figure 6.1 and 6.2 are arranged on a bread board. A 60 mV input with a bias current of 40 μA are applied. The frequency of the input signal is varied to study the filter characters of the two configurations. The two structures differ in feedback arrangement where the first part may be considered as unbalanced and the second as balanced. For characterization of the structures, the observations are shown in table 6.1(a) and 6.2(a) respectively. The structure shown in figure 6.3 is an amplifier feedback balanced structure LPF. This structure has an amplifier feedback in place of the wire feedback of the previous structure. The bias current has no effect on the gain of an OTA. The observations of the LPF structure is presented in the table 6.3(a).

6.1.4 Results and discussions :- The structures exhibit LPF characters. In figure 6.1, the structured filter has a 3db pole frequency of 150 Hz. The 3db pole frequency of the LPF structure shown in figure 6.2 is 300 Hz. Hence the wire feedback arrangement of the balanced structure is useful in obtaining 3db pole frequency at low range.

The phase difference existing between the input and the output increases after the 3db frequency. The structure shown in figure 6.3 is an amplifier feedback balanced structured LPF. The 3db pole frequency shifts from 300 Hz to 900 Hz and the bias current has no effect on the gain of an OTA. The balanced structure with amplifier feedback is non inverting unity gain amplifier which has no phase shift in its output. Hence this type of the feedback with integrators and amplifiers addresses modifications in structure generations [30,31,36,37].

From the study of the observations, an effort is made to develop this technique in the design of continuous time filters using the same OTA-C approach. The balanced structures are successfully used in the cascade arrangement which overcomes the limitations of multiple loop feedback OTA grounded capacitor filters. The studies are carried out with a two-stage structure and some of the studies are compared with the multiple loop feedback results.

6.2 Analysis of the Second order balanced OTA-C LPF :-

6.2.1 Introduction :- Using the same structure generation, a second order configuration is used for the analysis of the LPF. The second order LPF structure is based on the approach of the transmission of pole of the filter. In this generation also minimum component structures are extensively used. The study carried out on the second stage of the balanced loop feedback OTA-C filters helps to generalize the arrangement for cascade. The theory of the structure establishes the relationship between the filter structure and the feedback. The purpose of studying this configuration is to search and to compare LPF structures which are best suited for ordered filters.

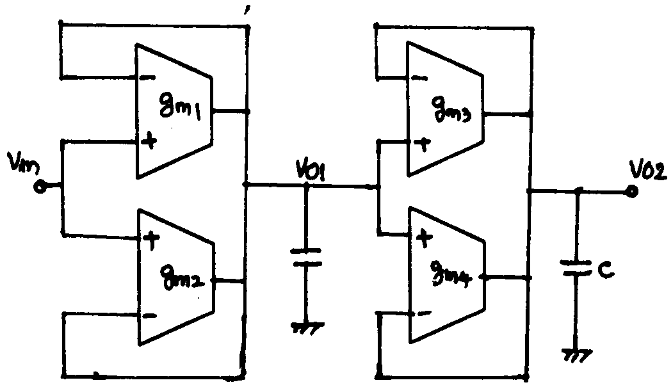

Fig 6.4 :Balanced two stage OTA-C filter

6.2.2 Experimental :- A second order balanced OTA-C filter structure is set up as shown in the figure 6.4 with a bias current of 20 µA, supply voltage of ± 12 V, C = 220nfd and an input of 60 mV. The LPF characters are observed for different input frequencies. The structure has a phase difference between the input and the output which are also recorded and are shown in table 6.4(a). The phase difference continuously increases.

The experimental observations recorded are used to draw some conclusions of using the structure in the next order.

6.2.3 Theory :-

$g_{meq} = g_{m1} + g_{m2}$

$g_{meq2} = g_{m2} + g_{m4}$

g_{m1}, g_{m2}, g_{m3} and g_{m4} are transconductances of OTA's used in the circuit g_{meq1} and g_{meq2} are the equivalent transconductances.

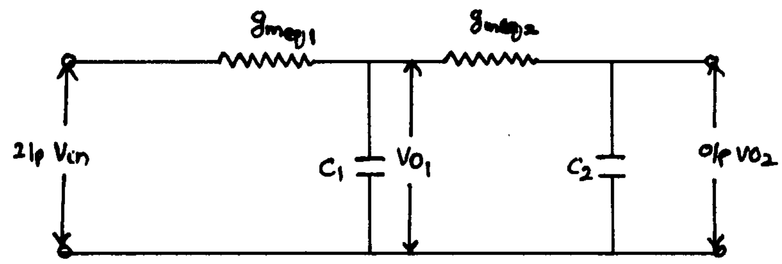

Fig 6(x) : Conventional RC filter

Let $H_1(S)$ be the transfer function of the first stage (g_{meq1} and capacitor C_1)

$H_1(S) = 1 / sC_1 / g_{meq1}$ for the first stage

Similarly Let $H_2(S)$ be the transfer function of the second stage i.e g_{meq2} and capacitor C2)

$H_2(S) = V_{02} / V_{01} = 1 / sC_2 / g_{meq2}$

In the transfer function

$H_1(S) = V_{01} / V_{in} = 1 / sC_1 / g_{meq1} = g_{meq1} / sC_1$

$V_{01} = (g_{meq1} / sC_1)\ V_{in}$

Now

$H_2(S) = V_{02} / V_{01} = (1 / sC_2 / g_{meq2} / 1 / sC_1 / g_{meq1})\ V_{in}$

Now

$H_2(S) = V_{02} / V_{in} = g_{meq2} / sC_2 / g_{meq1} / sC_1$

$g_{meq2} / g_{meq1} \cdot sC_1 / sC_2$

If C_1 / C_2

$H_2(S) = g_{meq2} / g_{meq1}$ which represents the transfer function of the loop feedback OTA-C integrator which explains the LPF character.

6.2.4 Results and discussions :- The balanced two stage filter structure has no effect on the gain and it is used as a non-inverting unity gain amplifier. The observed output of 50mV at an input frequency of 100 Hz of the signal decreases linearly with the increase in frequency. The 3dB pole frequency is at 250 Hz. The feedback network which contain pure wire connections with the integrators is shown in figure 6.4. The balanced structures using differential input and differential output OTA's are popular and have high common mode rejection ratio which will reduce the harmonic distortions, and power supply noise. In respect of observations, it is noticed that only phase difference is observed between the input and the output without any noise signal. The variation in the output impedance in cascade arrangement changes the 3db frequency from a higher value towards a lower value. Hence, a cascade arrangement is a method of altering the output impedance of the OTA [21-25].

The 3db pole frequency of the first order is compared with the second order. It is observed that the 3db pole frequency shifts a little towards the higher value as the order decreases. But the shift in 3db pole frequency is one of the noticed results where a systematic approach of transmission of pole or zero can be applied [30]. An attempt is made to study and analyse the same results on the third order balanced LPF structure.

6.3 Analysis of third order balanced OTA-C LPF :-

6.3.1 Introduction :- The general multiple loop feedback of balanced structure is used for studying the third order. The method is an extended part of the second order in altering the impedance of the output of each stage. This is another generalized structure with different performance in LPF characters. This arrangement is also flexible in selecting the element values similar to the previous first order and the second order filters. The OTA non idealities alter the output impedances effectively since the transconductance is frequency dependent. This noise and non linearity of transconductance character cause harmonic distortions. But these distortions are reduced from the arrangement of balanced structure which has high CMRR. The advantage of this property is used to study the third order structure in comparison with the first and second order.

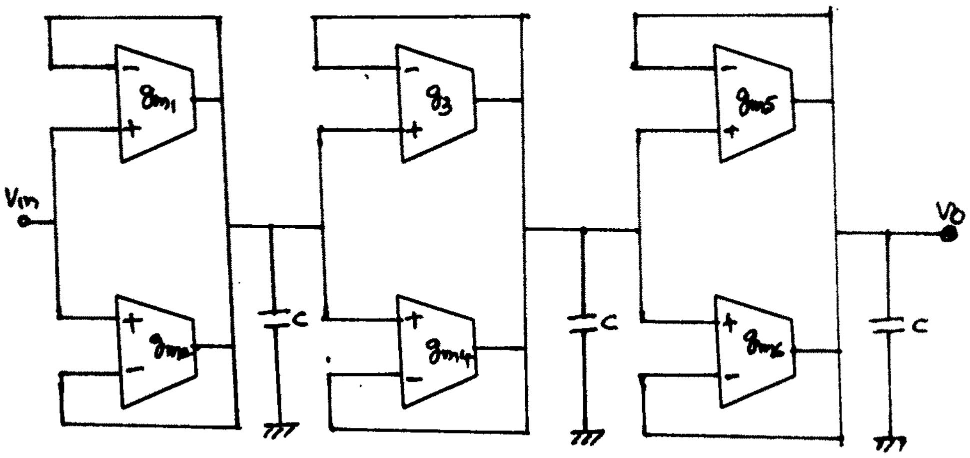

Fig 6.5 : Balanced three stage OTA-C filter

6.3.2 Theory :-

$g_{meq1} = g_{m1} + g_{m2}$

$g_{meq2} = g_{m3} + g_{m4}$

$g_{meq1} = g_{m5} + g_{m6}$

g_{m1}, g_{m2} ,g_{m3}, g_{m4}, g_{m5}, and g_{m6} are the transconductances of OTA in balanced three stage arrangements g_{meq1} g_{meq2} and g_{meq3} are the equivalent transconductances of the OTA in the configuration, since the conductance adds in parallel.

The balanced three stage structure can be considered as a simple RC cascade network shown in figure 6(y).

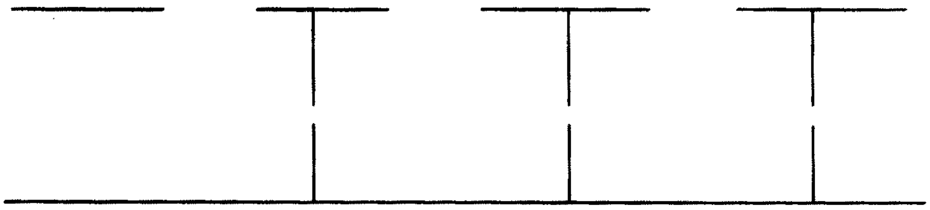

Fig 6(y)

Let the transfer function $H_1(S)$ of first stage be

$H_1(S) = V_{01} / V_{in} = 1 / sC_1 / g_{meq1} = g_{meq1} / sC_1 \therefore V_{01} = g_{meq1} / sC_1 \; V_{in}$

Now the transfer function $H_2(S)$ of the second stage is

$H_2(S) = V_{02} / V_{01} = (1 / sC_2 / g_{meq2} / g_{meq1} / sC_1 \, . \, g_{meq2} / sC_2 / sC_1 / g_{meq1})$

$= (g_{meq2} / g_{meq1}) \quad sC_1 / sC_2) \, V_{in}$ $H_3(S)$ of the third stage is

The transfer function of $H_3(S)$ of third stage is

$H_3(S) = V_{03} / V_{02} = 1 / sC_3 / g_{meq3} / V_{02} = (g_{meq3}. \, g_{meq1} / g_{meq2}) \, (sC_2 / sC_3.sC_1)V_{in}$

Now the overall transfer functions

$H_4(S) = V_{04} / V_{03} = 1 / sC_4 / g_{meq4} / V_{03} = (g_{meq3} \cdot g_{meq1} / g_{meq2} \cdot g_{meq4})$ $(sC_2 \, . \, sC_4 / sC_1 \, sC_3) \, V_{in}$

If $C_1 = C_2 = C_3 = C_4$ the overall transfer function

$H(S) = V_{04} / V_{in} = g_{meq3} \cdot g_{meq1} / g_{meq2} \cdot g_{meq4}$ which is the transfer function of OTA-C continuous LPF.

6.3.3 Experimental :- A third order structure is set up as shown in the figure 6.5. Experimental measurements are carried out for an input of 60 mV with a supply of $\pm$ 12 V, C = 220nfd and a bias current of 165 μA. The increase in the bias current is due to increased number of OTA's. The reading at the output of the third order characterizes the structure as LPF. The strength of the output is recorded for different input frequencies. The bias current even though has increased strength it does not effect the gain of an OTA since it is used as a non-inverting unity gain amplifier. A set of observations characterizing the structure are shown in the table 6.5(a) and has the 3db-pole frequency of 260 Hz.

The 3db pole and the performance of the three structures clearly shows the effect of output impedance for the filter characters.

6.3.4 Results and discussions :- The 3db pole frequency obtained at 250 Hz shows a shift in its value from the first order to the second order and from the second order to the third order when the values are compared. With each order, coupled stage by stage, the third order LPF characters clearly present the technique of transmission of 3db pole frequency towards lower frequency [31]. The non-idealities of the OTA which alters the output impedance is a reason for this change in characteristics of the third order LPF. The roll off value of the output voltages before the 3db frequency has a better response in the first order and this response decreases with increased stages. The phase difference in a successive three stage is observed but it is not of much significance.

6.4 Analysis of fourth order balanced OTA-C low pass filter :

6.4.1 Introduction :-

Any OTA with grounded capacitor functions as LPF [31,35]. A multiple loop feedback OTA grounded capacitor filter in cascade arrangement is used to generate multiple integrators with loop feedback. The OTA-C with all capacitors being grounded [10,18] is shown in figure 6.6. The feedback in balanced structure contain pure wire connections.

In the cascaded LPF of balanced structure only OTA's and capacitors are required and the feedback can be achieved by the direct connection. By changing the output impedance of the OTA's LPF can be obtained.

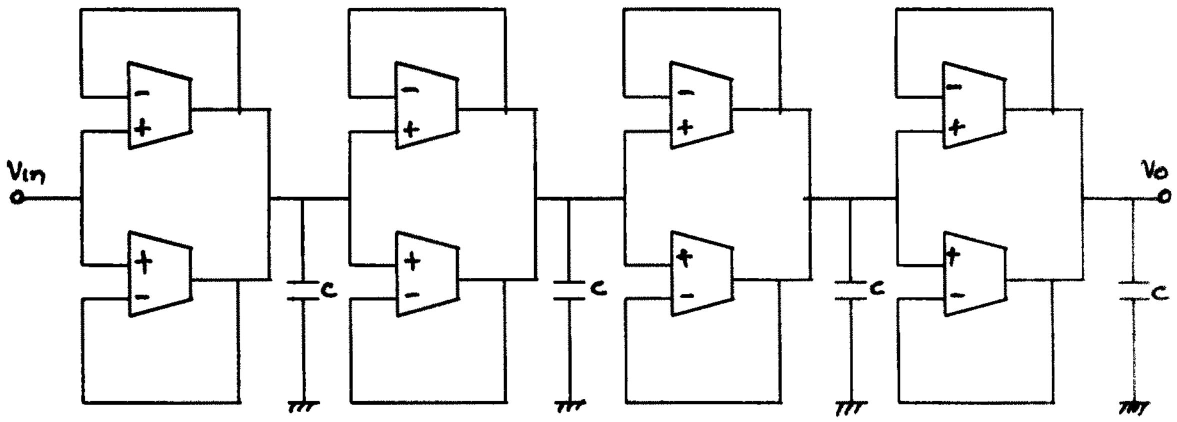

Fig-6.6: Cascaded four stage balanced OTA-C LPF

6.4.2 Theory : In the arrangement of the feedback network, the voltage is given by

$$V_{fi} = \Sigma^n_{j=1}\, f_{ij}\, V_{0j} \quad \text{with } i=1$$

$$V_{fi} = \Sigma^n_{i=j=1}\, f_i\, V_0$$

The coefficient f_1 of the feed back from the integrator output to the input can have zero or non-zero value depending upon the type of feedback.

For the direct wire connection we have unity feedback $f_{ij} = 1$. Hence the equation for the circuit can be expressed as

$$V_f = F V_0$$

where $V_0 = [\, V_{01}, V_{02}, V_{03}, \text{----------}\ V_{on} \,]$

and $V_f = [\, V_{f1}, V_{f2}, V_{f3}, \text{-----------}\ V_{fn} \,]$

The feed back vector $F = [\, f_{ij},]_{n \times n} = 1$

The current flowing into and out of the feedback are zero since they are related to the input terminals of the OTA's in feed forward network circuit or in feed-back network which are ideally infinite impedance. Noting this, and denoting the time constant

We have $T_j = C_i / g_{mj} = C/g_m$ because $i=j=1$

We can write the equation as

$$ST_1 V_{01} = V_{in} - V_{f1}$$

Where S is the complex frequency dependent on the time constant of the integrator

$$(\sigma + jw)\, T_1\, V_{01} = V_{in} - V_f$$

$$V_0 = M(S)^{-1}\, (IV_{in} - V_f)$$

$$M(S) = \begin{bmatrix} ST1, & & & \\ -1 & ST2 & & \\ & -1 & & \\ & & ST3 & \\ & & -1 & \\ & & & ST4 \\ & & & -1 \end{bmatrix}$$

and $I = [1, 0, 0, \text{----}\ 0]^t$

Equation of the system is

$A(S)\ V_0 = IV_{in}$ -------- (I)

$A(S) = M(S) + F$

$H(S) = V_0/V_{in} = 1 / |A(S)|$

Equation (I) establishes the relationship between the overall circuit and the integrator output including the overall circuit output. Using this equation we can formulate the transfer function.

$V_0/V_{in} = 1 / \ A(S)\ \ I$

Since the overall circuit output Vout = Vin.

$H(S) = 1 / |A(S)|$

The determinant $|A(S)|$ is the n^{th} order polynomal of S.

The transfer function H(S) may therefore have the characteristic.

form of all pole low pass transfer function expressed as

$H(S) = A_0 / (B_nS^n + B_{n-1}S^{n-1} +$ ------ $+ B_1S + 1)$

Where $A_0 = g_0\ (T_n, f)$

Based on $H(S) = 1 / |A(S)|$

$H(S) = g_0\ (T_n\ , f_{ij}) / g_n\ (T_n\ , f_{ij})\ S^n + g^{n-1}\ (T_n\ , f_{ij})\ S^{n-1} +$

------- $+ g1(T_n\ , f_{ij})\ S + 1$

Co-efficient $B_1 = g_1\ (T_n\ , f_{ij})\ \ A_0 = g_0\ (T_n\ , f_{ij})$

$B_{n-1} = g_{n-1}\ (T_n\ , f_{ij})$

$B_n = g_n\ (T_n\ , f_{ij})$

The transfer function shows the all pole transfer function of polynomial S^n.

The transfer function

$H(S) = A_0 / B_nS^n + B_{n-1}S^{n-1} +$ ---------- $+ B_1S + 1$ where B_n,

B_{n-1} .... B_1 are the values of the time constants which vary with g_m. Since $T = C / g_m$

$H(S) = A_0\, \Sigma(S\text{-}Zi) / \Sigma(S\text{-}Pi)$

S is a complex frequency where H(S) becomes zero and Pi is complex frequency at which H(S) becomes infinity. Hence the cascade arrangement of grounded capacitor has multiple zeros.

6.4.3 Experimental : A successive four stage balanced OTA low pass filter is connected as shown in the figure 6.6. Vin is the pure sinusoidal signal of 60mV with variable frequency in low range.

The successive stage connected one after the other decreases the 3db pole frequency of the filter from the technique of all pole low pass filter transfer function.

A mere connection in cascade has the advantage of lowering 3db pole frequency keeping OTA-C and the value of capacitance same. The method presented in the paper has the monolithic integrablity. The arrangement has structural simplicity and tunability in the design of low pass filters.

The readings recorded in successive four stages are presented in table 6.6(a) at a bias current 16 μA, a supply voltage of ± 12V, C=220nF and input of 60 mV with all capacitors being grounded.

6.4.4 Results and Discussions : A general method of balanced structures in the cascade form presented has the advantage of reducing the even order harmonic distortion, reducing the noises generated from the power supply [10,18,21] and from high CMRR. From the formulated general relations for the all pole and the finite transmission zero realizations, it is possible to change the pole successively by altering the output impedance of the network [18,21].

Observations of the low pass filter characteristic presented in the table 6.6(a) has a comparative study in their 3db pole frequency. The cascading arrangement has the effect in reducing 3db pole in successive stages. The reduction in the 3db pole frequency is of 1KHz in the first order. It is reduced to 550Hz in the fourth order. Continuing the cascade arrangement it is possible to reduce the 3db pole frequency further, in which non idealities such as frequency dependent transconductance, noise and non linearity of transcondctance, finite output impedance etc are effective. These parameters are responsible for the dynamic range of LPF [10,18] in cascade arrangement.

The roll-off values of the output voltage before the 3db frequency has better responses in the first order. The roll-of response in the higher order has more steeper cutoff in its output. Thus it is advantageous to have higher order for sharp cutoff. However the response characteristics before 3db consists of non-linearity, noise etc in its output. Thus an appropriate choice has to be made to optimize the response before and after the 3db towards the ideal characteristics. This response eliminates with increased cascade stages, before the 3db pole frequency. All capacitors are grounded and cannonical realization can guarantee LPF characteristics with change of responses [18,21]. The relevant graph corresponding to 6.6(a) is presented in figure 6.6(a1).

The essence of the present work is to reduce the 3db pole frequency from the cascade arrangement which has application in personal communication systems.

Table 6.1(a)

Ibias = 40μA, Vin =60mV, Us = ± 12V

Sl.No	Freq in Hz	Log f	O/P in mV	Gain in db	ϕ
1	1	0	100	4.44	25°
2	10	1.0	90	3.52	30°
3	100	2.1	80	2.5	40°
4	200	2.3	60	0.0	72°
5	230	2.36	56	-0.6	72°
6	300	2.48	45	-2.5	76°
7	400	2.60	40	-3.52	78°
8	500	2.70	30	-6.02	128°
9	600	2.78	26	-7.26	130°
10	700	2.85	20	-9.54	160°
11	1000	3.0	14	-12.64	170°

Table 6.2(a)

Ibias = 40μA, Vin =60mV, Us = ± 12V

Sl.No	Freq in Hz	Log f	O/P in mV	Gain in db	ϕ
1	1	0.0	60	0	34°
2	10	1.0	55	0.75	36°
3	100	2.0	50	-1.58	38°
4	200	2.3	45	-2.5	40°
5	300	2.36	42	-3.10	40°
6	350	2.54	36	-4.44	48°
7	400	2.60	32	-5.46	90°
8	500	2.70	28	-6.62	92°
9	1000	3.0	14	-12.64	100°

Table 6.3(a)

Ibias = 40μA, Vin =60mV, Us = ± 12V

Sl.No	Freq in Hz	Log f	O/P in mV	Gain in db
1	1	0	60	0
2	10	1.0	60	0
3	100	2.0	60	0
4	200	2.3	55	-0.75
5	300	2.36	50	-1.58
6	400	2.6	50	-1.58
7	600	2.7	50	-1.58
8	700	2.85	45	-2.5
9	800	2.90	45	-2.5
10	900	2.95	40	-3.52
11	1000	3.0	35	-4.68
12	2000	3.30	25	-7.60
13	3000	3.48	20	-9.54
14	4000	3.60	15	-12.04
15	5000	3.70	10	-15.56
16	10000	4.0	10	-15.56

Table 6.4(a)

Ibias = 40μA, Vin =60mV, Us = ± 12V

Sl.No	Freq in Hz	Log f	O/P in mV	Gain in db	ϕ
1	1	0	60	0	0
2	10	1.0	55	-0.75	0
3	100	2.0	50	-1.58	75°
4	200	2.3	45	-2.5	78°
5	300	2.48	35	-4.68	80°
6	350	2.54	32	-5.46	90°
7	400	2.60	30	-6.02	90°
8	500	2.70	25	-7.60	100°
9	600	2.78	22	-8.71	108°
10	700	2.85	16	-11.48	120°
11	800	2.90	14	-12.64	154°
12	900	2.95	10	-15.56	180°
13	1000	3.00	6	-20.0	180°
14	2000	3.30	2.5	-27.6	180°
15	3000	3.48	1.5	-32.04	180°

Table 6.5(a)

Ibias = 40μA, Vin =60mV, Us = ± 12V

Sl.No	Freq in Hz	Log f	O/P in mV	Gain in db
1	1	0	60	0
2	10	1.0	55	-0.75
3	100	2.0	50	-1.58
4	200	2.3	48	-1.93
5	250	2.4	42	-4.69
6	300	2.48	33	-5.19
7	500	2.70	32	-5.46
8	1000	3.0	30	-6.02
9	2000	3.3	8	-17.5
10	3000	3.48	4	-23.52
11	4000	3.60	2	-29.54
12	5000	3.70	2	-29.54

Ibias=16uA, Vs= + or -12V, C=220nF, I/P=60mV
g01=first order gain (1st stage), g02=second order gain (2nd stage),
g03=third order gain (3rd stage), g04=fourth order gain (4th stage)

Table 6.6(a)

Frequency	log f	g01	g02	g03	g04
100	2	0	0	-1.58	0
300	2.3	-1.58	-1.58	-1.58	-1.58
500	2.6	-1.58	-1.58	-1.93	-2.3
700	2.8	-1.93	-2.49	-2.95	-2.95
750	2.87	-2.49	-3.09	-3.52	-3.52
900	2.95	-3.09	-3.52	-4.68	-8.71
1000	3	-6.02	-6.02	-6.93	-17.5
2000	3.3	-7.95	-9.54	-12.04	-23.52
3000	3.4	-9.54	-12.04	-20	-29.54
4000	3.6	-9.54	-15.56	-23.52	-29.54
5000	3.69	-12.04	-17.5	-26.02	-29.54
6000	3.77	-13.98	-21.58	-29.54	-29.54
7000	3.84	-13.98	-23.52	-29.54	-29.54
8000	3.9	-15.56	-26.02	-29.54	-29.54
9000	3.95	-17.5	-29.54	-29.54	-29.54
10000	4	-17.5	-29.54	-29.54	-29.54

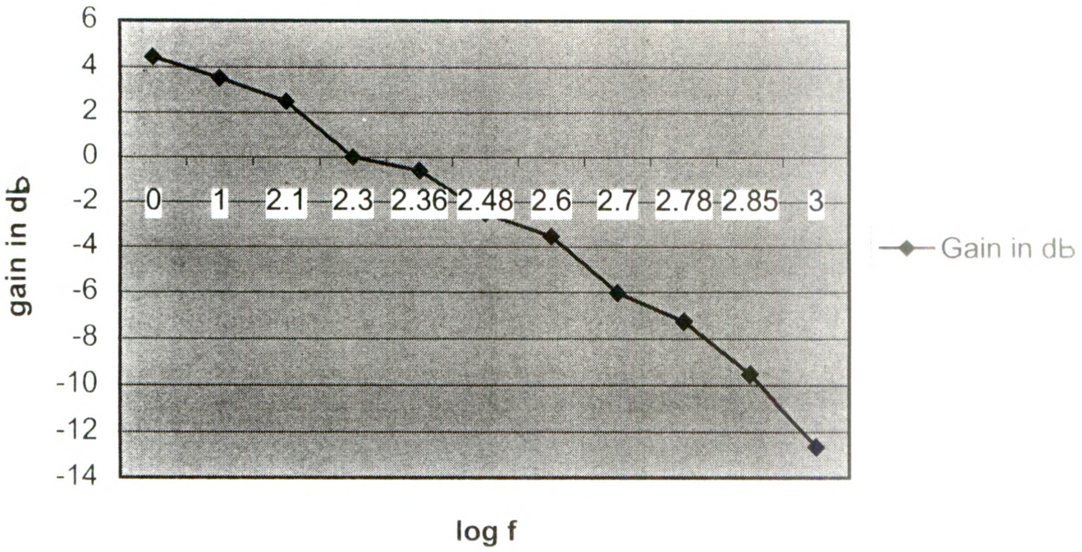

fig 6.1 (a1) : LPF characteristics of an unbalanced OTA with wire feedback

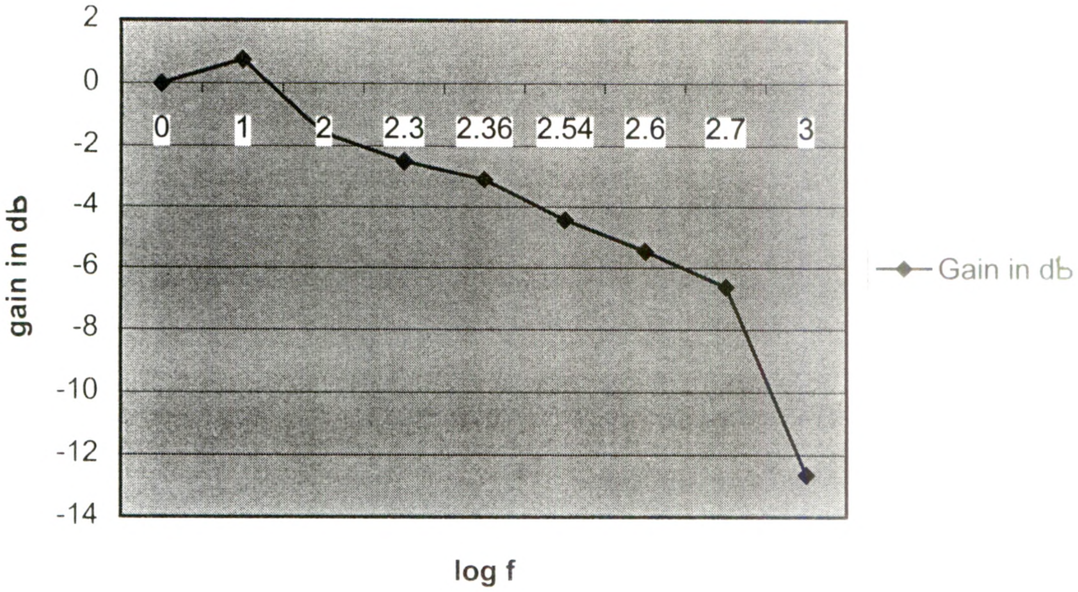

fig 6.2 (a1) : LPF characteristics of a balanced OTA with wire feedback

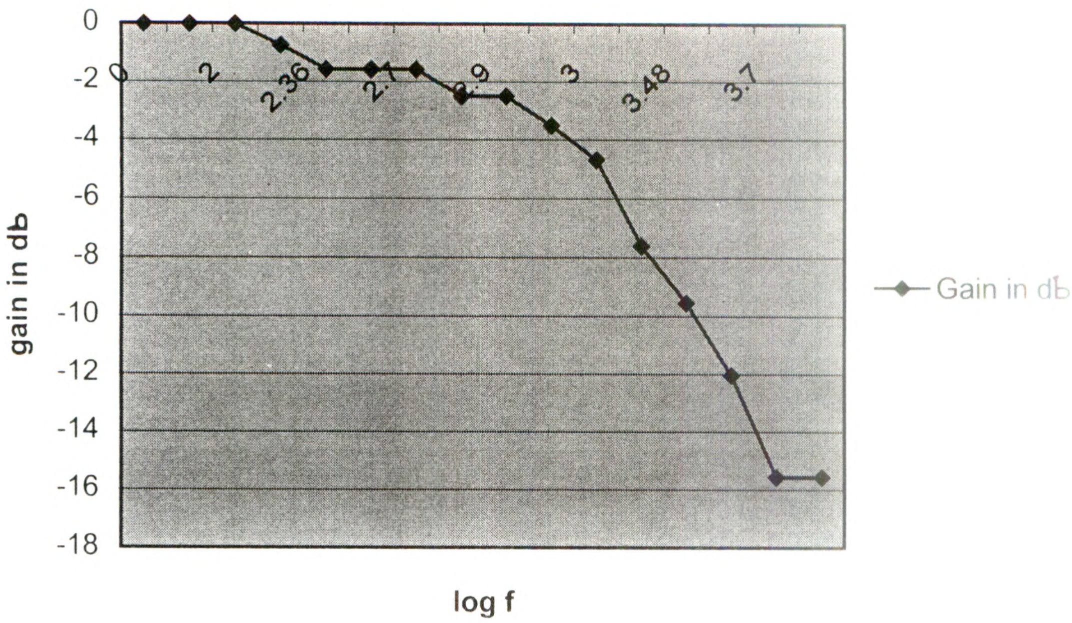

fig 6.3 (a1) : LPF characteristics of a balanced OTA with amplifier feedback

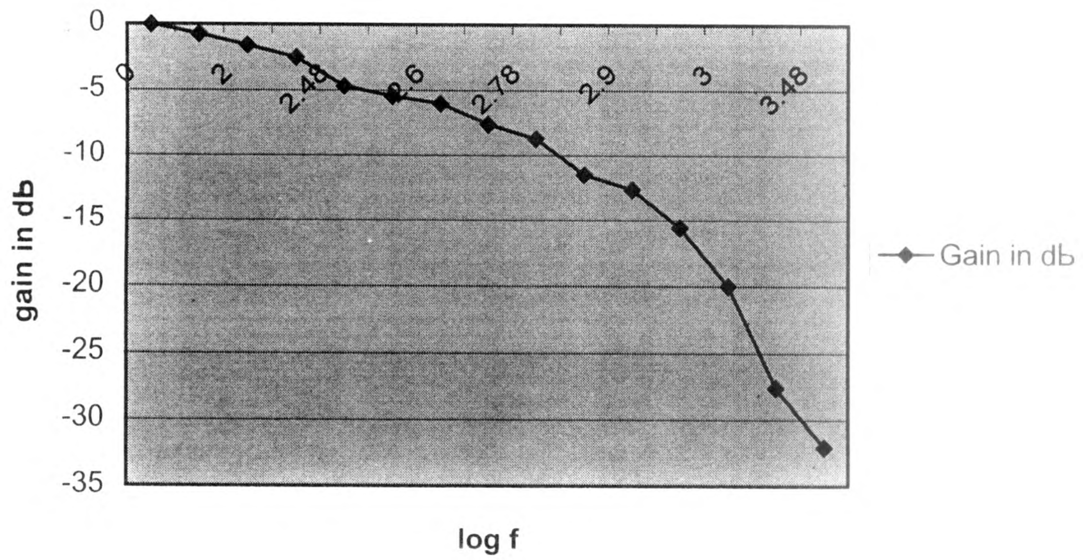

fig 6.4 (a1) : LPF characteristics of a 2nd order balanced OTA-C with wire feedback

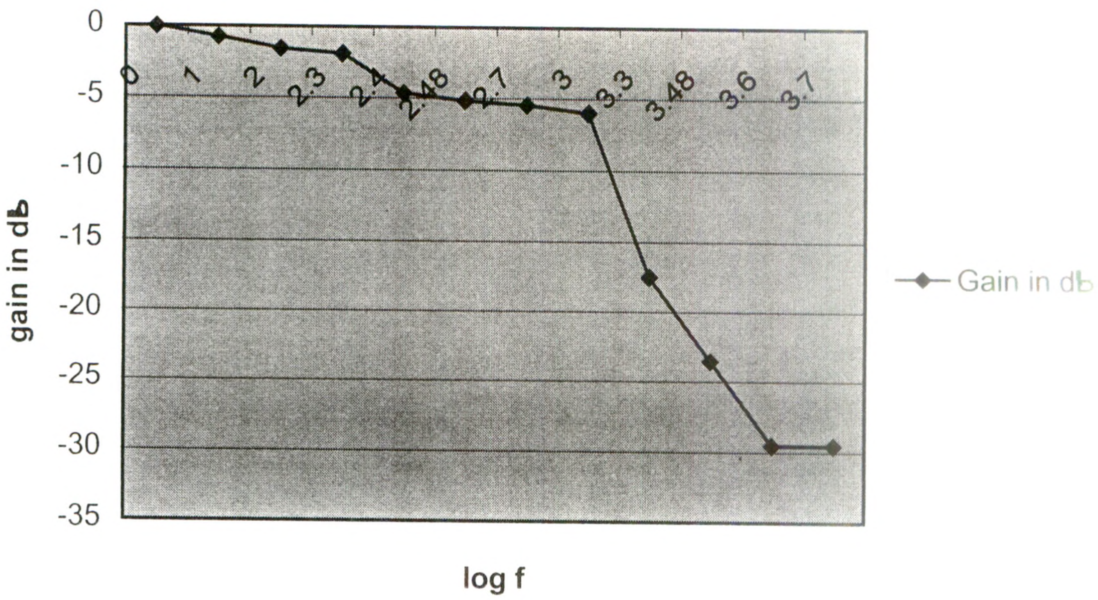

fig 6.5 (a1) : LPF characteristics of a 3rd order balanced OTA-C filter with wire feedback

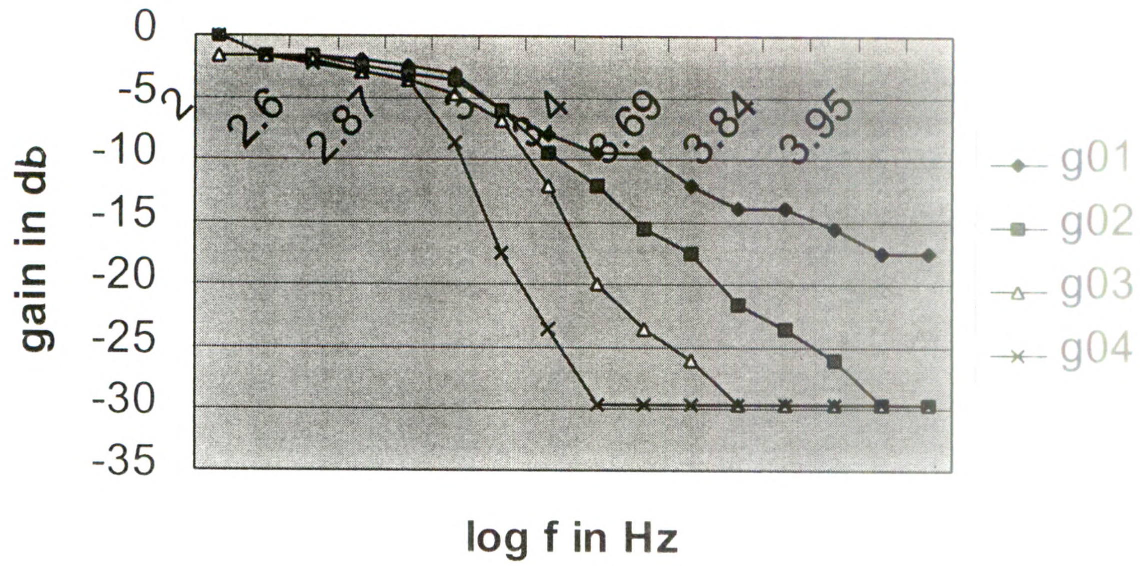

Figure 6.6(a1) : LPF characteristics at different stages of a four stage balanced OTA-C filter