CHAPTER -IV

A SYSTEMATIC WAY OF GENERATING 4-OTA-C BASED HARMONIC OSCILLATORS

4.1 INTRODUCTION

In the previous chapter we have reviewed in detail a systematic method developed by Bhaskar, Senani and Tripathi [1] using which a catalog of three OTA and two Capacitor based sinusoidal oscillators has been presented. In this chapter we have extended the methodology proposed in [1] to generate 4-OTA-2C based sinusoidal oscillators.

4.2 PROPOSED CIRCUIT

OTA-C oscillators with both the capacitors floating having no common node:
The admittance matrix of N is 4×4. In view of the restrictions 1 and 2 proposed in [1]it is easy to see that at least one transconductance must exist in every row and every column. This means that at least four OTAs are needed to implement any of the possible type of $[Y]$ characterization. In view of the restriction 1 and 2 [1], the possibility of four zeros lying in any single row or single column is ruled out. The other possibilities are now examined in detail.

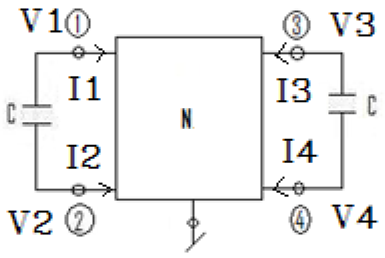


Fig. 4.1 structures for the synthesis of canonic OTA-C sinusoidal oscillators.

The network N can be characterized by the following four port equations:

$$I_1 = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \quad (4.2.1)$$

$$I_2 = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 \quad (4.2.2)$$

$$I_3 = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4 \quad (4.2.3)$$

$$I_4 = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4 \quad (4.2.4)$$

From the figure 4.1, it is clear that

$$I_1 = -I_2 \quad ; \quad I_3 = -I_4 \quad (4.2.5)$$

Then $$I_1 = (V_2 - V_1)sC \quad ; \quad I_3 = (V_4 - V_3)sC \quad (4.2.6)$$

$$I_2 = (V_1 - V_2)sC \quad ; \quad I_4 = (V_3 - V_4)sC \quad (4.2.7)$$

Substituting the value of I_1, I_2, I_3, and I_4 from equation (5), (6), & (7) into (1), (2), (3), & (4) we get

$$(V_2 - V_1)sC = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \quad (4.2.8)$$

$$(V_1 - V_2)sC = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 \quad (4.2.9)$$

$$(V_4 - V_3)sC = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4 \quad (4.2.10)$$

$$(V_3 - V_4)sC = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4 \quad (4.2.11)$$

A rearrangement of the above equations in the following form

$$(Y_{11} + sC)V_1 + (Y_{12} - sC)V_2 + Y_{13}V_3 + Y_{14}V_4 = 0 \quad (4.2.12)$$

$$(Y_{21} - sC)V_1 + (Y_{22} + sC)V_2 + Y_{23}V_3 + Y_{24}V_4 = 0 \quad (4.2.13)$$

$$Y_{31}V_1 + Y_{32}V_2 + (Y_{33} + sC)V_3 + (Y_{34} - sC)V_4 = 0 \quad (4.2.14)$$

$$Y_{41}V_1 + Y_{42}V_2 + (Y_{43} - sC)V_3 + (Y_{34} + sC)V_4 = 0 \quad (4.2.15)$$

yields the following characteristic equation

$$\begin{bmatrix} Y_{11} + sC & Y_{12} - sC & Y_{13} & Y_{14} \\ Y_{21} - sC & Y_{22} + sC & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} + sC & Y_{34} - sC \\ Y_{41} & Y_{42} & Y_{43} - sC & Y_{44} + sC \end{bmatrix} = 0$$

$$(Y_{11}+sC)\ [(Y_{22}+sC)\{(Y_{33}+sC)(Y_{44}+sC)-(Y_{43}-sC)(Y_{34}-sC)\}-Y_{23}\{Y_{32}(Y_{44}+sC)-Y_{42}(Y_{34}-sC)\}+Y_{24}\{Y_{32}(Y_{43}-sC)-Y_{42}(Y_{33}+sC)\}]-(Y_{12}-sC)[(Y_{21}-sC)\{(Y_{33}+sC)(Y_{44}+sC)-(Y_{34}-sC)(Y_{43}-sC)\}-Y_{23}\{Y_{31}(Y_{44}+sC)-Y_{41}(Y_{34}-sC)\}+Y_{24}\{Y_{31}(Y_{43}-sC)-Y_{41}(Y_{33}+sC)\}]+Y_{13}[(Y_{21}-sC)\{Y_{32}(Y_{44}+sC)-Y_{42}(Y_{34}-sC)\}-(Y_{22}+sC)\{Y_{31}(Y_{44}+sC)-Y_{41}(Y_{34}-sC)\}+Y_{24}\{Y_{31}Y_{42}-Y_{41}Y_{32}\}]-Y_{14}[(Y_{21}-sC)\{Y_{32}(Y_{43}-sC)-Y_{42}(Y_{33}+sC)\}-(Y_{22}+sC)\{Y_{31}(Y_{43}-sC)-Y_{41}(Y_{33}+sC)\}+Y_{23}\{Y_{31}Y_{42}-Y_{32}Y_{41}\}]=0 \quad (4.2.16)$$

The final characteristics equation is given below

$$s^2C^2[Y_{11}Y_{33}+Y_{11}Y_{44}+Y_{11}Y_{43}+Y_{11}Y_{34}+Y_{22}Y_{33}+Y_{22}Y_{44}+Y_{22}Y_{43}+Y_{22}Y_{34}-Y_{23}Y_{32}-Y_{23}Y_{42}-Y_{24}Y_{32}-Y_{24}Y_{42}+Y_{12}Y_{33}+Y_{12}Y_{44}+Y_{12}Y_{34}+Y_{12}Y_{43}+Y_{21}Y_{33}+Y_{21}Y_{44}+Y_{21}Y_{34}+Y_{21}Y_{43}-Y_{23}Y_{31}-Y_{23}Y_{41}-Y_{24}Y_{31}-Y_{24}Y_{41}-Y_{13}Y_{32}-Y_{13}Y_{42}-Y_{13}Y_{31}-Y_{13}Y_{41}-Y_{14}Y_{32}-Y_{14}Y_{42}-Y_{14}Y_{31}-Y_{14}Y_{41}] + \mathrm{sC}[Y_{11}Y_{22}Y_{33}+Y_{11}Y_{22}Y_{44}+Y_{11}Y_{22}Y_{43}+Y_{11}Y_{22}Y_{34}+Y_{11}Y_{44}Y_{33}+Y_{44}Y_{22}Y_{33}+Y_{23}Y_{42}Y_{34}+Y_{24}Y_{32}Y_{43}+Y_{12}Y_{44}Y_{33}+Y_{12}Y_{23}Y_{31}+Y_{12}Y_{23}Y_{41}+Y_{12}Y_{24}Y_{31}+Y_{12}Y_{24}Y_{41}+Y_{21}Y_{44}Y_{33}+Y_{41}Y_{23}Y_{34}+Y_{31}Y_{24}Y_{43}+Y_{13}Y_{21}Y_{32}+Y_{13}Y_{21}Y_{42}+Y_{13}Y_{42}Y_{34}+Y_{13}Y_{41}Y_{34}+Y_{14}Y_{21}Y_{32}+Y_{14}Y_{21}Y_{42}+Y_{14}Y_{32}Y_{43}+Y_{14}Y_{31}Y_{43}-Y_{11}Y_{34}Y_{43}-Y_{11}Y_{23}Y_{32}-Y_{11}Y_{23}Y_{42}-Y_{11}Y_{24}Y_{32}-Y_{11}Y_{24}Y_{42}-Y_{22}Y_{34}Y_{43}-Y_{23}Y_{44}Y_{32}-Y_{24}Y_{42}Y_{33}-Y_{12}Y_{21}Y_{33}-Y_{12}Y_{21}Y_{44}-Y_{12}Y_{21}Y_{34}-Y_{12}Y_{21}Y_{43}-Y_{12}Y_{34}Y_{43}-Y_{21}Y_{34}Y_{43}-Y_{23}Y_{31}Y_{44}-Y_{41}Y_{24}Y_{33}-Y_{13}Y_{44}Y_{32}-Y_{13}Y_{22}Y_{31}-Y_{13}Y_{22}Y_{41}-Y_{13}Y_{44}Y_{31}-Y_{14}Y_{42}Y_{33}-Y_{14}Y_{22}Y_{31}-Y_{14}Y_{22}Y_{41}-Y_{14}Y_{41}Y_{33}] + [Y_{11}Y_{22}Y_{33}Y_{44}+Y_{11}Y_{24}Y_{32}Y_{43}+Y_{11}Y_{23}Y_{34}Y_{42}+Y_{12}Y_{21}Y_{34}Y_{43}+Y_{12}Y_{23}Y_{31}Y_{44}+Y_{12}Y_{24}Y_{33}Y_{41}+Y_{13}Y_{21}Y_{32}Y_{44}+Y_{13}Y_{22}Y_{34}Y_{41}+Y_{13}Y_{24}Y_{31}Y_{42}+Y_{14}Y_{21}Y_{33}Y_{42}+Y_{14}Y_{22}Y_{31}Y_{43}+Y_{14}Y_{23}Y_{32}Y_{11}-Y_{11}Y_{22}Y_{34}Y_{43}-Y_{11}Y_{23}Y_{32}Y_{44}-Y_{11}Y_{24}Y_{33}Y_{42}-Y_{12}Y_{21}Y_{33}Y_{44}-Y_{12}Y_{23}Y_{34}Y_{41}-Y_{12}Y_{24}Y_{31}Y_{43}-Y_{13}Y_{21}Y_{34}Y_{42}-Y_{13}Y_{22}Y_{31}Y_{44}-Y_{13}Y_{24}Y_{32}Y_{41}-Y_{14}Y_{21}Y_{32}Y_{33}-Y_{14}Y_{22}Y_{33}Y_{41}-Y_{14}Y_{23}Y_{31}Y_{42}] = 0 \quad (4.2.17)$$

The condition of oscillation and frequency of oscillation are given by

$$[a_{11}+a_{22}] \geq 0 \quad (4.2.18)$$

$$f_0 = \frac{1}{2\pi C}(a_{11}a_{22} - a_{12}a_{21})^{1/2} \quad (4.2.19)$$

Where

$$a_{11}[Y_A Y_B - Y_C Y_D] = (Y_{12}Y_{21} - Y_{11}Y_{22})(Y_{33} + Y_{34} + Y_{43} + Y_{44}) + (Y_{31} + Y_{41})\{Y_{22}(Y_{13} + Y_{14}) - Y_{12}(Y_{23} + Y_{24})\} + (Y_{32} + Y_{42})\{Y_{11}(Y_{23} + Y_{24}) - Y_{21}(Y_{13} + Y_{14})\} \quad (4.2.20)$$

$$a_{12}[Y_A Y_B - Y_C Y_D] = (Y_{13}Y_{24} - Y_{14}Y_{23})(Y_{31} + Y_{32} + Y_{41} + Y_{42}) + (Y_{21} + Y_{22})\{Y_{14}(Y_{33} + Y_{43}) - Y_{13}(Y_{34} + Y_{44})\} + (Y_{11} + Y_{12})\{Y_{23}(Y_{34} + Y_{44}) - Y_{24}(Y_{33} + Y_{43})\} \quad (4.2.21)$$

$$a_{21}[Y_A Y_B - Y_C Y_D] = (Y_{31}Y_{42} - Y_{32}Y_{41})(Y_{13} + Y_{14} + Y_{23} + Y_{24}) + (Y_{11} + Y_{21})\{Y_{32}(Y_{43} + Y_{44}) - Y_{42}(Y_{33} + Y_{34})\} + (Y_{12} + Y_{22})\{Y_{41}(Y_{33} + Y_{34}) - Y_{31}(Y_{43} + Y_{44})\} \quad (4.2.22)$$

$$a_{22}[Y_A Y_B - Y_C Y_D] = (Y_{34}Y_{43} - Y_{33}Y_{44})(Y_{11} + Y_{12} + Y_{21} + Y_{22}) + (Y_{14} + Y_{24})\{Y_{33}(Y_{41} + Y_{42}) - Y_{43}(Y_{31} + Y_{32})\} + (Y_{13} + Y_{23})\{Y_{44}(Y_{31} + Y_{32}) - Y_{34}(Y_{41} + Y_{42})\} \quad (4.2.23)$$

$$Y_A = (Y_{11} + Y_{12} + Y_{21} + Y_{22}) \quad (4.2.24)$$

$$Y_B = (Y_{33} + Y_{34} + Y_{43} + Y_{44}) \quad (4.2.25)$$

$$Y_C = (Y_{13} + Y_{14} + Y_{23} + Y_{24}) \quad (4.2.26)$$

and

$$Y_D = (Y_{31} + Y_{32} + Y_{41} + Y_{42}) \quad (4.2.27)$$

The different ways of choosing Zeros in $[Y]$ matrix by applying some restriction given in [1]. are given below:

(i) If number of Zeros entries (ZE) are up-to seven(One, Two, Three, Four, Five, Six, Seven) in $[Y]$

If zero are distributed such that one row does not contain any ZE (this row will then have four transconductances and would require at least two OTAs), (maximum seven ZEs) one row contains no ZE, one row contains one ZE and the rest six zeros appear in the remaining two rows, then the resulting matrix cannot be realized with only four OTAs.

Thus, any $[Y]$ matrix characterization having only seven ZEs cannot result in a four-OTA structure of the desired type.

(ii) Eight ZEs in $[Y]$.

If the zeros are distributed two in each row, then in order to have a four-OTA structure each row must have remaining two entries equal and opposite (i.e. all four-OTAs to be connected in differential mode). Such a situation makes det$[Y]$ = 0 and hence FO becomes zero.

(iii) Nine ZEs in $[Y]$

This implies that OTA circuit corresponding to this would have three OTAs in differential mode and the fourth OTA in single ended mode. Although nine entries can be selected out of sixteen in (16!/9!7!) = 11440 ways, the only meaningful ways are those(keeping in mind restriction 1,2 and 3 as outlined above) where out of the nine ZEs three rows contain two ZEs and a fourth row contains three ZEs. The total number of possible cases having this kind of assignment of ZEs turn out to be 288. The resulting 288 characterizations of $[Y]$ are then checked to find which of these result in four- OTA oscillators possessing independent control of FO. It has been found that none of this set of 288 characterizations of $[Y]$ results in any oscillator of the desired type.

(iv) Ten ZEs in $[Y]$

If the zeros are distributed two in two rows, and three ZEs in remaining two rows. then in order to have a four-OTA structure each row must have remaining two entries equal and opposite (i.e. two OTAs to be connected in differential mode and two OTAs to be connected in single ended mode). Such a situation makes $\det[Y] = 0$ and hence FO becomes zero.

(v) Eleven ZEs in $[Y]$

This implies that OTA circuit corresponding to this would have one OTAs in differential mode and the remaining three OTA in single ended mode. Although eleven entries can be selected out of sixteen in (16!/11!5!) = 4368 ways, the only meaningful ways are those(keeping in mind restriction 1,2 and 3 as outlined above) where out of the eleven ZEs one row contain two ZEs and remaining three rows contain three ZEs. The total number of possible cases having this kind of assignment of ZEs turn out to be 144. The resulting 144 characterizations of $[Y]$ are then checked to find which of these result in four- OTA oscillators possessing independent control of FO. It has been found that none of this set of 144 characterizations of $[Y]$ results in any oscillator of the desired type.

(vi) Twelve ZEs in $[Y]$

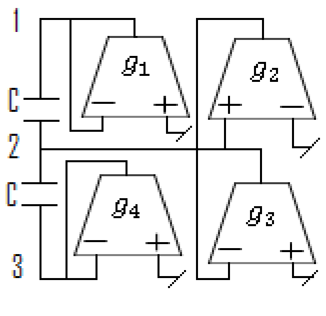
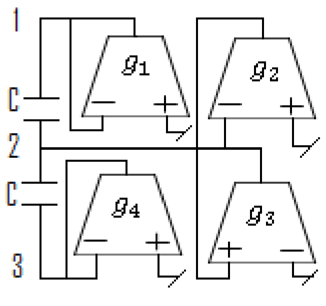
This implies that all four OTAs circuit are to be connected in single ended mode. It is obvious that each row should have one and only one transconductance and, therefore, keeping in mind restriction 1 and 2, the total number of characterizations of interest are only twelve in this case. Although twelve entries can be selected out of sixteen in (16!/12!4!) = 1820 ways, the only meaningful ways are those(keeping in mind restriction 1,2 and 3 as outlined above) where out of the twelve ZEs all four rows contain three ZEs.

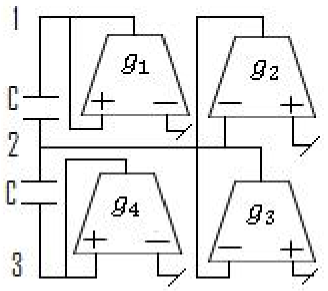
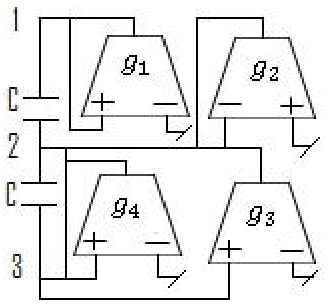
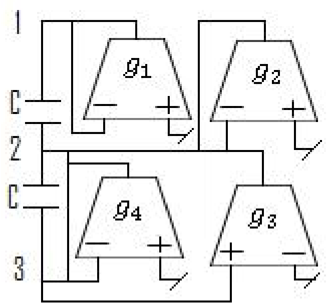
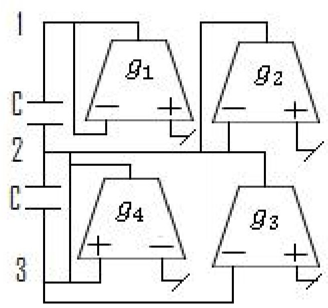
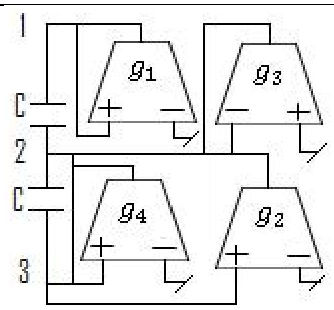
The total number of possible cases having this kind of assignment of ZEs turn out to be 72. The resulting 72 characterizations of $[Y]$ are then checked to find which of these result in four- OTA oscillators possessing independent control of FO. On the basis of the considerations similar to those outlined in (i) and (ii), the total number of possible characterizations corresponding to this case is 72 out of which only 23 qualify to yield four-OTA oscillators of the desired kind.

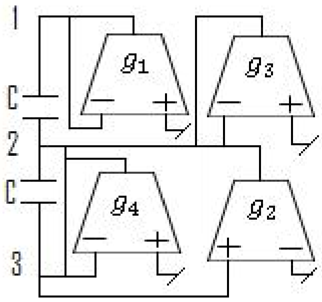
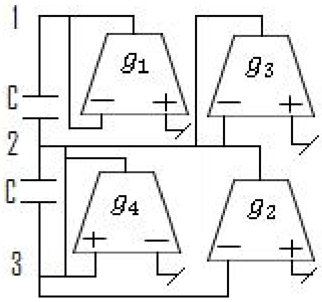
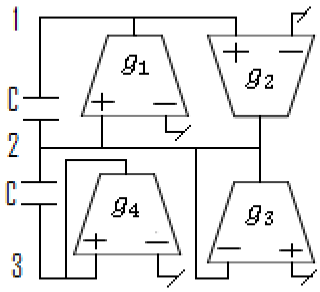
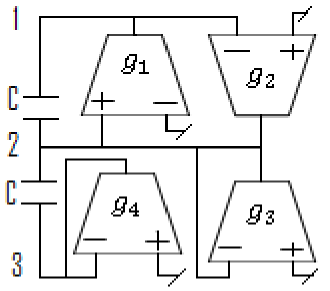
The possibility of having more than twelve ZEs and less eight ZEs in $[Y]$ is ruled out; the former because of resulting in the $[Y]$ matrix not permissible due to restriction 1 and 2[1], the latter because of the reqirement of more than four OTAs.

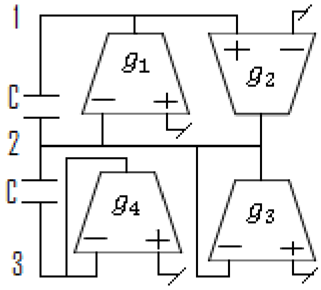
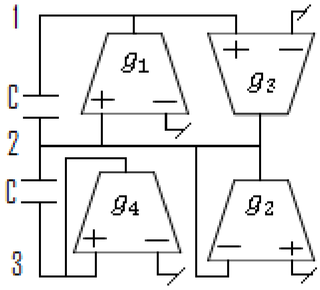
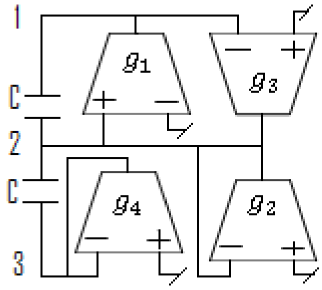
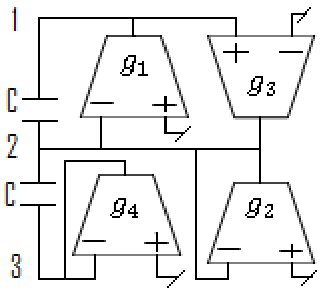
TABLE 4.1

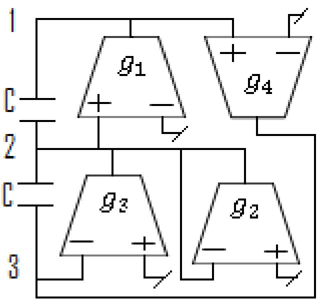
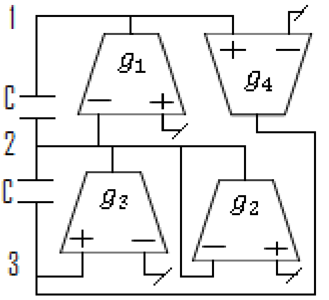
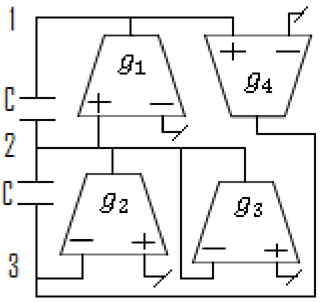
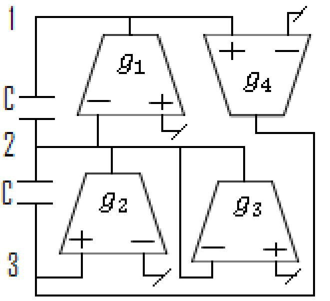
Various oscillator realizations corresponding to schematic of Fig.4.1

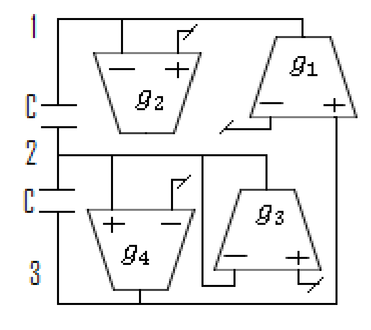
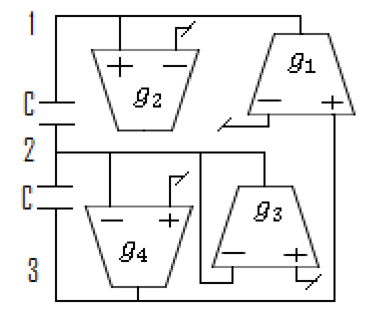
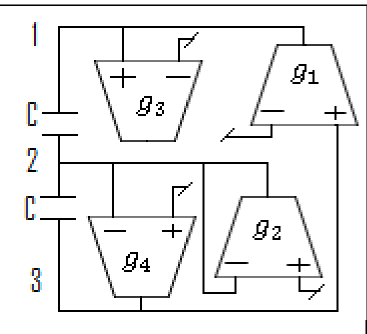
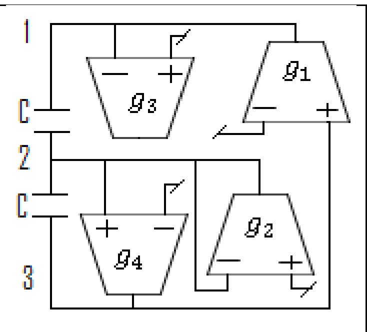
S.No	Generic $[Y]$ matrix	Oscillator circuit	CO and FO
1.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & -g_2 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$g_2(g_1+g_4)-g_1(g_3+g_4)-g_4(g_1+g_3)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_4(g_3-g_4)}{g_1-g_2+g_3+g_4}}$
C.E.:- $s^2c^2(g_1-g_2+g_3+g_4)+sc(-2g_1g_4+g_1g_2-g_1g_3+g_2g_4-g_3g_4)+g_1g_4(g_3-g_2)=0$			
2.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & -g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$g_3(g_1+g_4)-g_1(g_2+g_4)-g_4(g_1+g_2)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_4(g_2-g_3)}{g_1+g_2-g_3+g_4}}$
C.E.:- $s^2c^2(g_1+g_2-g_3+g_4)+sc(-2g_1g_4-g_1g_2+g_1g_3-g_2g_4+g_3g_4)+g_1g_4(g_2-g_3)=0$			

3.	$\begin{bmatrix} -g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & -g_4 \end{bmatrix}$		$g_1(g_2+g_3)+g_4(g_2+g_3)-2g_1g_4=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_4(g_2+g_3)}{-g_1+g_2+g_3-g_4}}$
4.	$\begin{bmatrix} -g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & 0 & -g_3 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$g_1(g_2-g_3)+g_4(g_3-g_1)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{-g_1+g_2-g_3-g_4}}$
C.E.:- $s^2c^2(-g_1+g_2-g_3-g_4)+sc(g_1g_2-g_1g_3-g_1g_4+g_3g_4)+g_1g_3g_4=0$			
5.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & 0 & -g_3 \\ 0 & 0 & g_4 & 0 \end{bmatrix}$		$g_1(g_3-g_2)-g_4(g_3+g_1)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{g_1+g_2-g_3+g_4}}$
C.E.:- $s^2c^2(g_1+g_2-g_3+g_4)+sc(-g_1g_2+g_1g_3-g_1g_4-g_3g_4)+g_1g_3g_4=0$			
6.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & 0 & g_3 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$-g_1(g_3+g_2)+g_4(g_1-g_3)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{g_1+g_2+g_3-g_4}}$
C.E.:- $s^2c^2(g_1+g_2+g_3-g_4)+sc(-g_1g_2-g_1g_3+g_1g_4-g_3g_4)+g_1g_3g_4=0$			
7.	$\begin{bmatrix} -g_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_2 \\ 0 & g_3 & 0 & 0 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$g_1(g_3-g_2)+g_4(g_2-g_1)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_2g_4}{-g_1-g_2+g_3-g_4}}$
C.E.:- $s^2c^2(-g_1-g_2+g_3-g_4)+sc(-g_1g_2+g_1g_3-g_1g_4+g_2g_4)+g_1g_2g_4=0$			

8.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_2 \\ 0 & g_3 & 0 & 0 \\ 0 & 0 & g_4 & 0 \end{bmatrix}$		$g_1(g_2 - g_3) - g_4(g_2 + g_1) = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{g_1 + g_2 - g_3 + g_4}}$
C.E.:-	$s^2c^2(g_1 - g_2 + g_3 + g_4) + sc(g_1g_2 - g_1g_3 - g_1g_4 - g_2g_4) + g_1g_2g_4 = 0$		
9.	$\begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & g_2 \\ 0 & g_3 & 0 & 0 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$-g_1(g_3 + g_2) + g_4(g_1 - g_2) = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{g_1 + g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(g_1 + g_2 + g_3 - g_4) + sc(-g_1g_2 - g_1g_3 + g_1g_4 - g_2g_4) + g_1g_2g_4 = 0$		
10.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ -g_2 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & -g_4 \end{bmatrix}$		$g_1(g_2 - g_4) + g_4(g_3 - g_2) = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 - g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(-g_1 - g_2 + g_3 - g_4) + sc(g_1g_2 - g_2g_4 - g_1g_4 + g_3g_4) + g_1g_2g_4 = 0$		
11.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ g_2 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$g_1(g_4 - g_2) - g_4(g_3 + g_2) = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 + g_2 + g_3 + g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 + g_3 + g_4) + sc(-g_1g_2 + g_1g_4 - g_2g_4 - g_3g_4) + g_1g_2g_4 = 0$		

12.	$\begin{bmatrix} 0 & g_1 & 0 & 0 \\ -g_2 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$-g_1(g_4+g_2)+g_4(g_2-g_3)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_2g_4}{g_1-g_2+g_3+g_4}}$
C.E.:-	$s^2c^2(g_1-g_2+g_3+g_4)+sc(-g_1g_2+g_2g_4-g_1g_4-g_3g_4)+g_1g_2g_4=0$		
13.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ -g_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_4 \end{bmatrix}$		$g_1(g_3-g_4)+g_4(g_2-g_3)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{-g_1+g_2-g_3-g_4}}$
C.E.:-	$s^2c^2(-g_1+g_2-g_3-g_4)+sc(g_1g_3+g_2g_4-g_1g_4-g_3g_4)+g_1g_3g_4=0$		
14.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ g_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$g_1(g_4-g_3)-g_4(g_3+g_2)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{-g_1+g_2+g_3+g_4}}$
C.E.:-	$s^2c^2(-g_1+g_2+g_3+g_4)+sc(-g_1g_3-g_2g_4+g_1g_4-g_3g_4)+g_1g_3g_4=0$		
15.	$\begin{bmatrix} 0 & g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ -g_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix}$		$-g_1(g_3+g_4)+g_4(g_3-g_2)=0$ $f_o=\frac{1}{2\pi C}\sqrt{\frac{g_1g_3g_4}{g_1+g_2-g_3+g_4}}$
C.E.:-	$s^2c^2(g_1+g_2-g_3+g_4)+sc(-g_1g_3-g_2g_4-g_1g_4+g_3g_4)+g_1g_3g_4=0$		

16.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ 0 & 0 & 0 & g_3 \\ -g_4 & 0 & 0 & 0 \end{bmatrix}$		$g_1 - g_3 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_3 g_4}{-g_1 + g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 + g_3 - g_4) + sc(g_1g_4 - g_3g_4) + g_1g_3g_4 = 0$		
17.	$\begin{bmatrix} 0 & g_1 & 0 & 0 \\ 0 & 0 & g_2 & 0 \\ 0 & 0 & 0 & -g_3 \\ -g_4 & 0 & 0 & 0 \end{bmatrix}$		$g_3 - g_1 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_3 g_4}{g_1 + g_2 - g_3 - g_4}}$
C.E.:-	$s^2c^2(g_1 + g_2 - g_3 - g_4) + sc(-g_1g_4 + g_3g_4) + g_1g_3g_4 = 0$		
18.	$\begin{bmatrix} 0 & -g_1 & 0 & 0 \\ 0 & 0 & 0 & g_2 \\ 0 & 0 & g_3 & 0 \\ -g_4 & 0 & 0 & 0 \end{bmatrix}$		$g_1 - g_2 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 + g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 + g_3 - g_4) + sc(g_1g_4 - g_2g_4) + g_1g_2g_4 = 0$		
19.	$\begin{bmatrix} 0 & g_1 & 0 & 0 \\ 0 & 0 & 0 & -g_2 \\ 0 & 0 & g_3 & 0 \\ -g_4 & 0 & 0 & 0 \end{bmatrix}$		$g_2 - g_1 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{g_1 - g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(g_1 - g_2 + g_3 - g_4) + sc(-g_1g_4 + g_2g_4) + g_1g_2g_4 = 0$		

20.	$\begin{bmatrix} 0 & 0 & 0 & -g_1 \\ g_2 & 0 & 0 & 0 \\ 0 & g_3 & 0 & 0 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$g_4 - g_2 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 + g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 + g_3 - g_4) + sc(g_1 g_4 - g_1 g_2) + g_1 g_2 g_4 = 0$		
21.	$\begin{bmatrix} 0 & 0 & 0 & -g_1 \\ -g_2 & 0 & 0 & 0 \\ 0 & g_3 & 0 & 0 \\ 0 & 0 & g_4 & 0 \end{bmatrix}$		$g_2 - g_4 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 - g_2 + g_3 + g_4}}$
C.E.:-	$s^2c^2(-g_1 - g_2 + g_3 + g_4) + sc(-g_1 g_4 + g_1 g_2) + g_1 g_2 g_4 = 0$		
22.	$\begin{bmatrix} 0 & 0 & 0 & -g_1 \\ 0 & g_2 & 0 & 0 \\ -g_3 & 0 & 0 & 0 \\ 0 & 0 & g_4 & 0 \end{bmatrix}$		$g_3 - g_4 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_3 g_4}{-g_1 + g_2 - g_3 + g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 - g_3 + g_4) + sc(-g_1 g_4 + g_1 g_3) + g_1 g_3 g_4 = 0$		
23.	$\begin{bmatrix} 0 & 0 & 0 & -g_1 \\ 0 & g_2 & 0 & 0 \\ g_3 & 0 & 0 & 0 \\ 0 & 0 & -g_4 & 0 \end{bmatrix}$		$g_4 - g_3 = 0$ $f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_3 g_4}{-g_1 + g_2 + g_3 - g_4}}$
C.E.:-	$s^2c^2(-g_1 + g_2 + g_3 - g_4) + sc(g_1 g_4 - g_1 g_3) + g_1 g_3 g_4 = 0$		

4.3 SAMPLE EXPERIMENTAL RESULTS

The workability of all the circuits of Tables 4.1 has been checked experimentally using CA 3080 type IC OTAs biased with the biasing arrangement shown below in Figure 4.2.

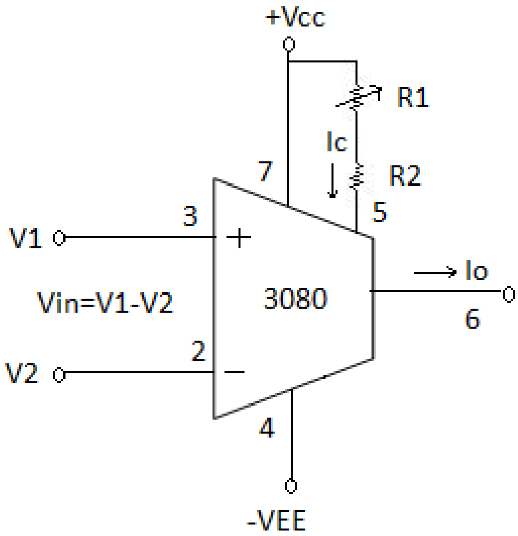


Fig. 4.2 Schematic of CA3080 OTA

The workability of all the circuits of Tables 4.1 has been checked experimentally using CA 3080 type IC OTAs with the biasing arrangement as shown above in Figure 4.2. Some sample experimental results from the structures of table 4.1 are shown in Figures 4.4 and 4.6 . Figures 4.7 and 4.8 shows the variation of the oscillation frequency with the bias current I_{B4} for the oscillator circuit no 16 and 18 of table 4.1. Figure 4.4 and 4.6 show typical waveforms generated by oscillator circuit no. 16 and no. 18 in table 4.1 respectively. The performance of the circuits is thus found to be as predicted by theory

(a) Oscillator no. 16 of table 4.1.

The oscillator has been shown in fig.4.3.

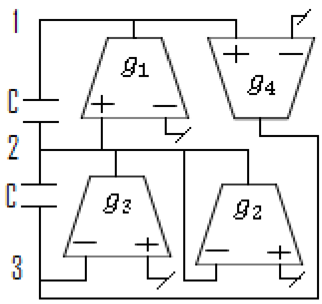


Fig. 4.3 oscillator using 4-OTA-2C

The Condition of oscillation is $(g_1 - g_3) = 0$ and

The frequency of oscillation is

$$f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_3 g_4}{-g_1 + g_2 + g_3 - g_4}}$$

The following values of components were selected to realize a sinusoidal oscillator with a frequency of $f = 0.408kHz$, amplitude = 15 mV (P-P), $C_1 = C_2 = C = 100nF$, $I_{B1} = 15.54\mu A$, $I_{B2} = 10\mu A$, $I_{B3} = 15.54\mu A$, $I_{B4} = 4.24\mu A$ $\pm V_{CC} = \pm 9\ V\ DC$.

The recorded output waveform is shown in Fig. 4.4.

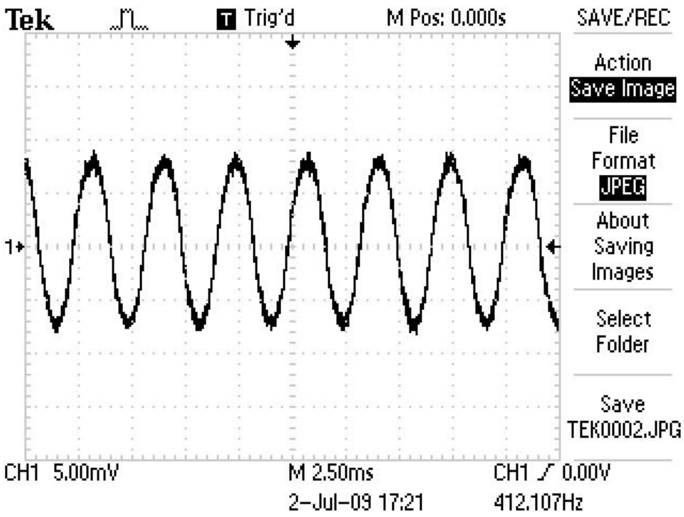


Fig. 4.4 Output Waveform

The result closely matches with the theoretical value of frequency (0.408kHz).

(b) Oscillator no. 18 of table 4.1

The oscillator has been shown in fig.4.5.

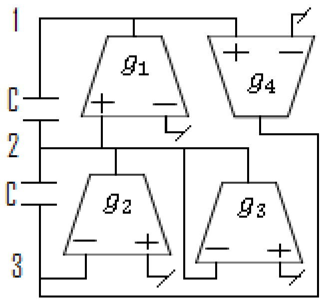


Fig. 4.5 oscillator using 4-OTA-2C

The Condition of oscillation is $(g_1 - g_2) = 0$ and

The frequency of oscillation is

$$f_o = \frac{1}{2\pi C}\sqrt{\frac{g_1 g_2 g_4}{-g_1 + g_2 + g_3 - g_4}}$$

The following values of components were selected to realize a sinusoidal oscillator with a frequency of $f = 0.291kHz$, amplitude = 20 mV (P-P), $C_1 = C_2 = C = 100nF$, $I_{B1} = 15.81\mu A$, $I_{B2} = 15.81\mu A$, $I_{B3} = 17\mu A$, $I_{B4} = 4.53\mu A$ $\pm V_{CC} = \pm 9V\ DC$.

The recorded output waveform is shown in Fig. 4.6.

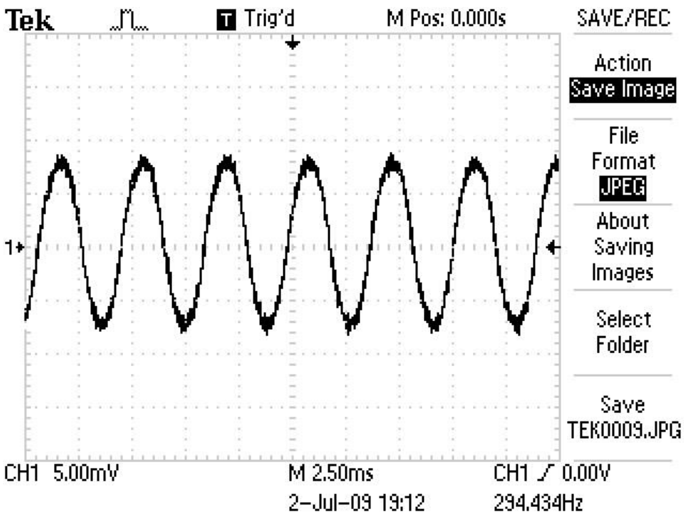


Fig. 4.6 Output Waveform

The result closely matches with the theoretical value of frequency (0.291kHz).

(i) The Variation of the oscillation frequency with the bias current I_{B4} for the oscillator circuit no. 16 of Table V are shown in fig. 4.7. The following component Values were selected to drown this fig. $C_1 = C_2 = C = 100nF$, $I_{B1} = 15.54\mu A$, $I_{B2} = 10\mu A$, $I_{B3} = 15.54\mu A$, I_{B4} Vari$able\ from$ $4\mu A - 6\mu A$ $\pm V_{CC} = \pm 9V\ DC$.

The graph is shown in fig. 4.7.

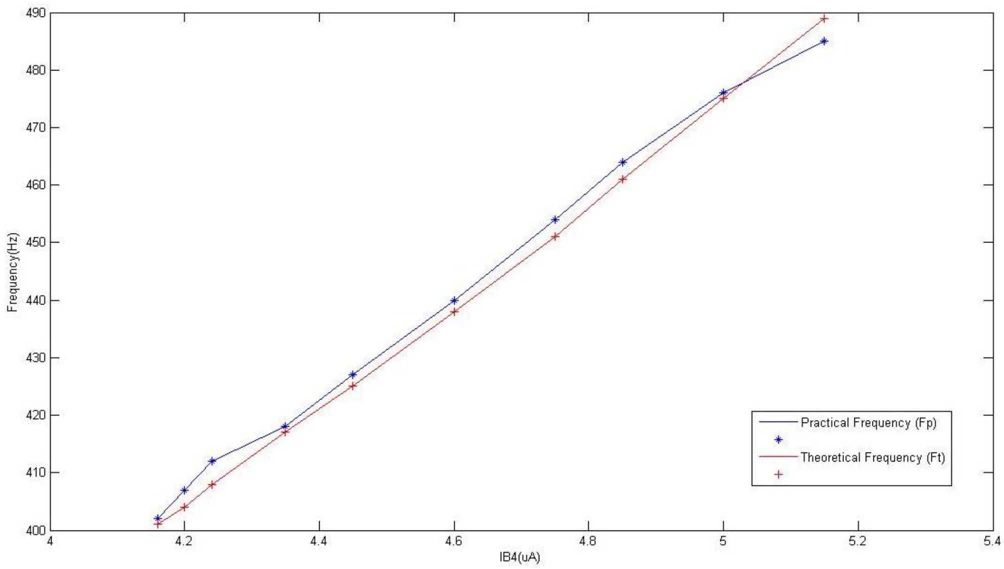


Fig. 4.7 Variation of the oscillation frequency with the bias current I_{B4} for the oscillator circuit no. 16 of Table 4.1.

(ii) The Variation of the oscillation frequency with the bias current I_{B4} for the oscillator circuit no. 16 of Table V are shown in fig. 4.8. The following component Values were selected to drown this fig. $C_1 = C_2 = C = 100nF$, $I_{B1} = 15.81\mu A$, $I_{B2} = 15.81\mu A$, $I_{B3} = 17\mu A$, I_{B4} Variable from $4\mu A - 6\mu A$ $\pm V_{CC} = \pm 9\ V\ DC$.

The graph is shown in fig. 4.8.

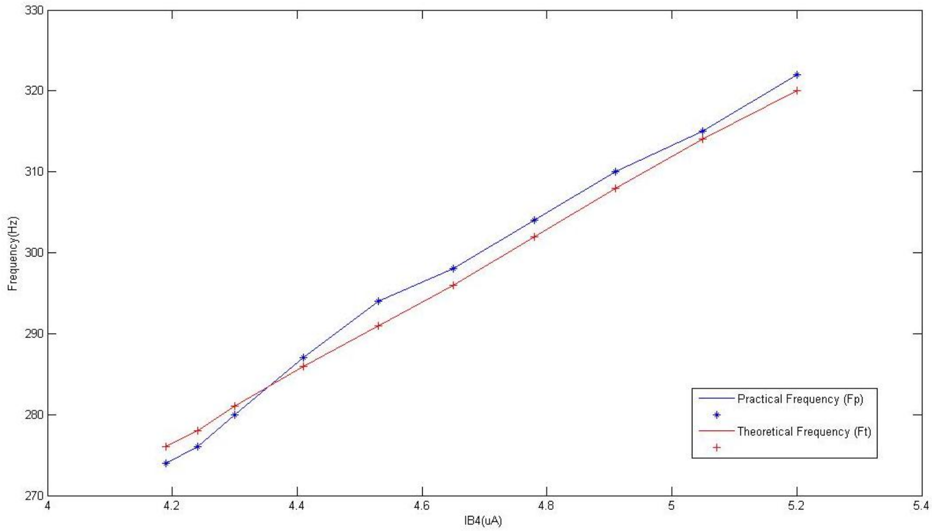


Fig. 4.8 Variation of the oscillation frequency with the bias current I_{B4} for the oscillator circuit no. 18 of Table 4.1.

4.4 CONCLUSION

In this chapter after reviewing the method proposed by R. Senani, D. R. Bhaskar and M. P. Tripathi [1], the approach has been extended to derive a catalogue of 4-OTA-C based sinusoidal oscillators. Some experimental results have also been presented.

REFERENCE

[1] R. Senani, D. R. Bhaskar and M. P. Tripathi, " Systematic Derivation of all Possible Canonic OTA-C Sinusoidal Oscillators ", Journal of the Franklin Institute pergamon Press Ltd., Vol. 330, No. 5, PP. 885-903, 1993.