مجلة جامعة تشرين للدراسات والبحوث العلمية - سلسلة العلوم الهندسية المجلد (21) العدد (8) 1999
Tishreen University Journal for Studies and Scientific Research –Engineering Science Series Vol. (21) No (8) 1999

Optimum Design of High-Frequency OTA-C Filters

Dr. Farouq M. AL-TAWIL*

(Received 14/9/1998, Accepted 9/8/1999)

❐ ABSTRACT ❐

An optimization procedure is presented for the design of high frequency second order OTA-C filters. The objective function is set-up so as to determine the design parameters that satisfy the required specification with the least possible influences of the parasitic poles. These poles are introduced as a result of the excess phase of the finite bandwidth of the transconductance gain of the real OTA approximated to one or two pole models.

The complex constrained optimization method is implemented with both implicit and explicit constraints imposed on the design parameters represented by the capacitors and the transconductance gain of the OTA-C.

* **Department of Electrical Engineering, Amman College For Engineering Technology. Albalka University, Amman, Jordan.**

مجلة جامعة تشرين للدراسات والبحوث العلمية - سلسلة العلوم الهندسية المجلد (21) العدد (8) 1999
Tishreen University Journal for Studies and Scientific Research –Engineering Science Series Vol. (21) No (8) 1999

التصميم الأمثل لمرشحات دوائر مكبر عمليات المواصلة التبادلية (OTA-C) ذات التردد العالي

الدكتور فاروق محمد الطويل*

(ورد إلى المجلة في 1998/9/14، قبل للنشر في 1999/8/9)

□ الملخّص □

خطوة مثلى مقدمة لتصميم فلاتر (OTA-C) من الدرجة الثانية ذات الترددات العالية .

الهدف من الاقتران تم تثبيته من أجل تحديد عناصر التصميم، التي تحقق التحديدات المطلوبة مع أقل التأثيرات المحتملة للأقطاب الطفيلية .

هذه الأقطاب مقدمة كنتيجة للطور الزائد لعرض الحزمة النهائي لكسب المواصلة التبادلية لتقريب (OTA) الحقيقي لنماذج ذات قطب أو قطبين .

المركب الذي يحصر الطريقة المثلى يستخدم مع كلا المحصورات بشكل ضمني ، وكذلك المحددة بوضوح، والمفروضة على عناصر التصميم، وممثلة بواسطة المكثفات، وكسب المواصلة التبادلية لـ(OTA-C) .

* قسم الهندسة الكهربائية – كلية عمان للهندسة التكنولوجية - جامعة البلقاء التطبيقية – عمان – الأردن.

1. Introduction

The Operational Transconductance Amplifier (OTA) as an integrated circuit is under industrial production since 1969 [1,2]. It has since gained wide acceptance as a getable, gain controlled building block for instrumentation amplifiers from the nano power range to high current and high speed comparators, and as an active element in conventional active filters applications [2,3].

Monolithic high frequency filters based upon conventional opamps are recognized as impractical due to both the high frequency VOA limitation and inability to practically and accurately control the passive components values [4]. By contrast use of OTAs offers some advantages of extended frequency range, integration facility as only active devices and capacitors are necessary, a reduction in component count and simpler design equations [3], considerable programmability by being able to vary transconductance g_m over several decades and low passive sensitivities of the OTA filter configurations [5,6]. The ideal OTA representation is given in Fig.1 its output current I_o may be expressed as [3]:

$$I_o = g_m (V^+ - V^-) \tag{1}$$

Where g_m is the transconductance gain proportional to external dc bias current I_{ABC} and V^+ and V^- are the noninverting and inverting input voltages of the OTA.

The design of most active filters is usually carried out with the assumption that ideal active devices are being used. This assumption may lead to severe deterioration of network performance [11]. The dominant poles and zeros of the networks will be shifted, thus altering the frequency response or the gain at frequency of importance. Therefore, the nonideal behavior of the OTA devices should be considered, and must be accounted for at design stages [10,11,12].

Several OTA–C biquadratic structures have been reported with different number of OTAs as well as degrees of freedom [4,8]. The maximal frequencies however, were limited to the lower megahertz range [13,14]. In some circumstances, their true frequency response can deviate substantially from what was designed for assuming ideal components [15]. These deviations are mainly due to the nonidealities of the OTA.

2. The OTA Model

One analytically tractable method is to assume a time delay τ through each OTA [15] such that:

$$g_m(s) = g_{mo}\, e^{-s\tau} \tag{2}$$

Where g_{mo} is the dc value of g_m .For the frequencies much lower than τ^{-1} equation (2) can be approximated by the first two terms of its Taylor expression [15,16] :

$$g_m(s) = g_{mo}\,(1 - s\tau) \tag{3}$$

Thus, a model consisting of a single zero on the right–half of the complex frequency s-plan is obtained. This model provides the same degree of approximation for the phase shift as the more conventional model consisting of a signal left-half plane pole [15], or

$$g_m(s) = \frac{g_{mo}}{1 + \tau s} = \frac{g_{mo}}{1 + s/\omega_o} \tag{4}$$

Where $\omega_o = 1 / \tau$ is an "effective" pole characterizing several very high frequency internal mirror poles.
Since the single pole model expressed above is reasonably accurate only to nearly ω_o , g_m may be approximated by two-pole model for applications entering the megahertz range [9] , that is ;

$$g_m(s) = \frac{g_{mo}}{(1 + s/\omega_1)(1 + s/\omega_2)} \tag{5}$$

With ω_1 and ω_2 are the first and second poles of the transconductance gain g_m respectively.

3.Optimization Based Design Procedure

The modern approach of using optimization methods is appropriate to achieve a design that meets or exceeds certain requirements when classical synthesis approach fails to do so.

3.1 Consideration of Constraints

One of the great advantages of computer-aided circuit optimization is that, if the design problem has been properly formulated , a feasible design can always be achieved assuming the initial design is feasible . Although constraints in networks design can take a variety of forms, two types of constraints on the design parameters are considered in the present work:

(i) Upper and lower bounds on design parameters , that is :

$$L_i < x_i < U_i \qquad \text{for } i = 1,2,\ldots,n \tag{6}$$

Where n is the number of design parameters such as, capacitors or transconductance gain and, L_i and U_i are the lower and upper bounds of x_i respectively . These limits for capacitors may be taken from 10 ρF to 1 nF, and for g_m the range of 1μs to 10^4 μs of OTA type CA3280 is chosen, providing good operating temperature range of 0^{o}C to 70^{o}C [2].

(ii) Limiting the spread in the values of two similar design parameters within the specified values is usually required. Such constraint is important especially in IC techniques and monolithic implementations that OTA-C filters provide . Such constraint may be expressed as:

$$R_l < x_l / x_j < R_u \qquad \text{for } i \neq j \tag{7}$$

Where R_l and R_u are the lower and upper ratio spread values respectively. For the same component type they are chosen to be 0.01 and 100 respectively to keep the spread of the component as low as possible, hence, ensuring their close tracking with ambient variations.

3.2 Optimization Method Used

The complex method of Box 1964 which is a modifications to the simplex method of Nelder and Mead, is used to solve the constrained design problem [17] . The basic move is to reflect the point having the greatest function value in the centroid of the simplex (Box made it of $2n$ points rather than $n+1$, and called it complex) formed by the remaining points . This method assumes a prior knowledge of the number of variables (n), the number of constraints (m), the lower and upper and bounds of parameter values (L_i, U_i), and an initial feasible point x_l that satisfies all constraints mentioned earlier , In accordance to the specific OTA based filters structure , n and m are produced automatically with the help of several programming procedures and functions that provide graphical and text aids for user interaction .

For filter specifications, the user can input the design requirements with interactive windows as shown in Fig.2 .In addition to f_o and Q-factor the designer can chosen the suitable transconductance model. If ideal OTAs are selected as to get an initial guess to design parameters that satisfy the filter specification ideally, then the Coefficient Matching Techniques (CMT) is utilized to set up the objective function. This technique which was first proposed by Calahan [18] has been shown to have many advantages compared with amplitude and phase matching techniques . The CMT can be used here to set up the least-square error objective function between the desired and the actual coefficients easily and directly.

4.The Objective Function

When the frequency dependent transconductance gains of the OTAs are expressed by a one pole or a two-pole models, the denominator D(s) of the voltage transfer function will no longer be of second-order as in the case if ideal OTAs are assumed in structures such as those shown in Fig.3. For example, for circuit (a) shown in Fig.3- a if the transconductanse gains of the two OTAs are approximated to two-pole model, the polynomial D(s) is given by the following sixth order polynomial : .

$$D(s) = s^6 + 2Bs^5 + (2A+B^2)s^4 + (\frac{g_{m2}A}{C_2} + 2AB)s^3 + (\frac{g_{m2}AB}{C_2} + A^2)s^2 + \frac{g_{m2}A^2}{C_2}s + \frac{g_{m1}g_{m2}A^2}{C_1 C_2} \quad (8)$$

Where $A=\omega_1\omega_2$, $B=\omega_1+\omega_2$ and ω_1, ω_2 are as given in equation (5). While if one pole model is used, D(s) will be reduced to the following form:

$$D(s) = s^4 + 2\omega_1 s^3 + (\omega_1^2 + \frac{g_{m2}\omega_1}{C_2})s^2 + \frac{g_{m2}\omega_1^2}{C_2} + \frac{g_{m1}g_{m2}\omega_1^2}{C_1 C_2} \quad (9)$$

As a general form, for a two-pole model, the denominator D(s) will be:

$$D(s) = T_6 s^6 + T_5 s^5 + T_4 s^4 + T_3 s^3 + T_1 s + T_o \quad (10)$$

Where the coefficient T_o to T_6 are function of the design parameters for the circuit under consideration.

Now equation (10) may be rewritten in the following factored formed:

$$D(s) = \left\{ s^2 + \frac{\omega_o}{Q} s + \omega_o^2 \right\} (H_4 s^4 + H_3 s^3 + H_2 s^2 + H_1 s + 1) \qquad (11)$$

Where the first factor of equation (11) gives the desirable (ideal) frequency response [20] ,and the second gives the added parasitic pole effect due to g_m dependency on frequency .

By equating coefficients of the same powers of s of equations (10), and (11) , and assuming $\omega_o = 1$ for frequency normalization, the following two equations are obtained after elimination of the coefficients H_1 , H_2 , H_3 and H_4 :

$$T_6 (1 - d^2) + dT_6 + T_2 - dT_1 + T_o (d^2 - 1) - T_4 = 0 \qquad (12\text{-a})$$

$$T_5 - dT_6 + dT_2 - T_1(d^2 - 1) + T_o (d^3 - 2d) - T_3 = 0 \qquad (12\text{-b})$$

Where $d = 1/Q$

In order to set up the objective function these two equations may be written in term of the error function $E_1(x)$ and $E_2(x)$ as in [19] .

$$E_1(x) = T_6(1-d^2) + dT_6 + T_2 - dT_1 + T_o (d^2 - 1) - T_4 \qquad (13\text{-a})$$

$$E_2(x) = T_5 - dT_6 + dT_2 - T_1(d^2 - 1) + T_o(d^3 - 2d) - T_3 \qquad (13\text{-b})$$

The objective function is then formulated using least-square error as:

$$E(x) = W \{ (E_1(x))^2 + (E_2(x))^2 \} \qquad (14)$$

Where W is a weighting factor $W>1$,and x defines the n design parameters i.e.:

$$x = (x_1, x_2, \ldots, x_n)$$

The objective function when one-pole model is used can be obtained easily with the same analysis above. Noting that, $D(s)$ will be of fourth order, and setting H_4, H_3, T_6 and T_5 all to zero in equation (10) and equation (11) , the required error function is obtained.

5.Results

The two-pole model of Fig.4 is used to give first transconductance pole at $6.3MHz$ and the second pole at about $63MHz$ for OTA type CA3280 used in the examples to be considered [10].

Example 1

For the second order structure of circuit (a) shown in Fig.3.a,it is required that f_o =$4MHz$ and Q=5 .details of this design problem are shown in table 1 . It is clear that the filter is initially unstable before the application of the optimization process for the one-pole and two-pole models as expressed by the negative Q-factors of the dominant-pole pair

.

Example 2

Table 2 shows the result of the optimum design for circuit (b) of Fig.3.b for f_o=$4MHz$, and Q=9 and equal values f_o the transconductance gains $g_{m1} = g_{m2} = g_{m3} = g_m$.

Example 3

With the circuit in Fig.3.a, to satisfy f_o=$200\ kHz$, and Q=5 , Table 3 gives the information on poles specification before and after optimization for ideal and nonideal OTA models . The initial points for all design in this example represent the parameter values given in reference [10] which give f_o= $204\ kHz$ before optimization .

6.Conclusion

A computer aided design procedure was adopted for the design of second order OTA-C filters taking into account the frequency dependent on g_m model of the OTAs used. The design requirements are met accurately when this nonideal factor is included. This is achieved with a design procedure based on optimization technique to reduce the effects of the parasitic poles to minimum.

The dominant poles that were shifted from there desired locations due to the presence of the parasitic poles, are forced to return back to the required position in the complex s-plan, therefore, filter specifications can be met exactly with the new predistorted circuit parameters.

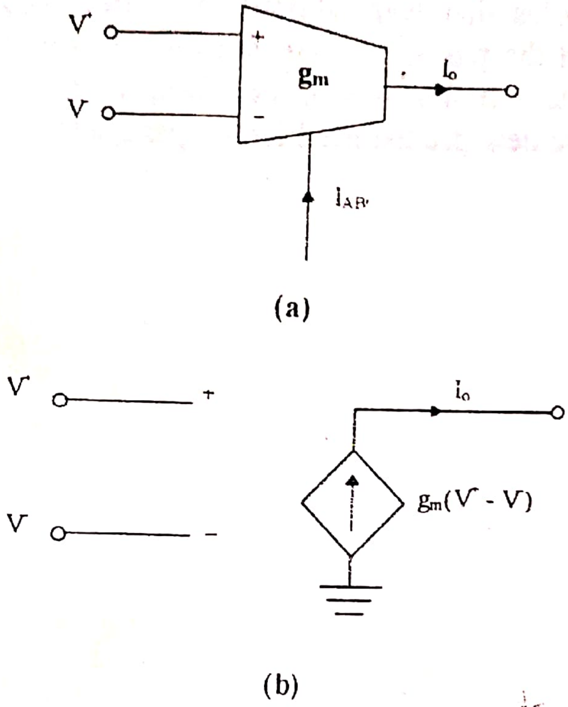


Fig. 1 OTA, (a) Symbol, (b) Equivalent circuit of ideal OTA

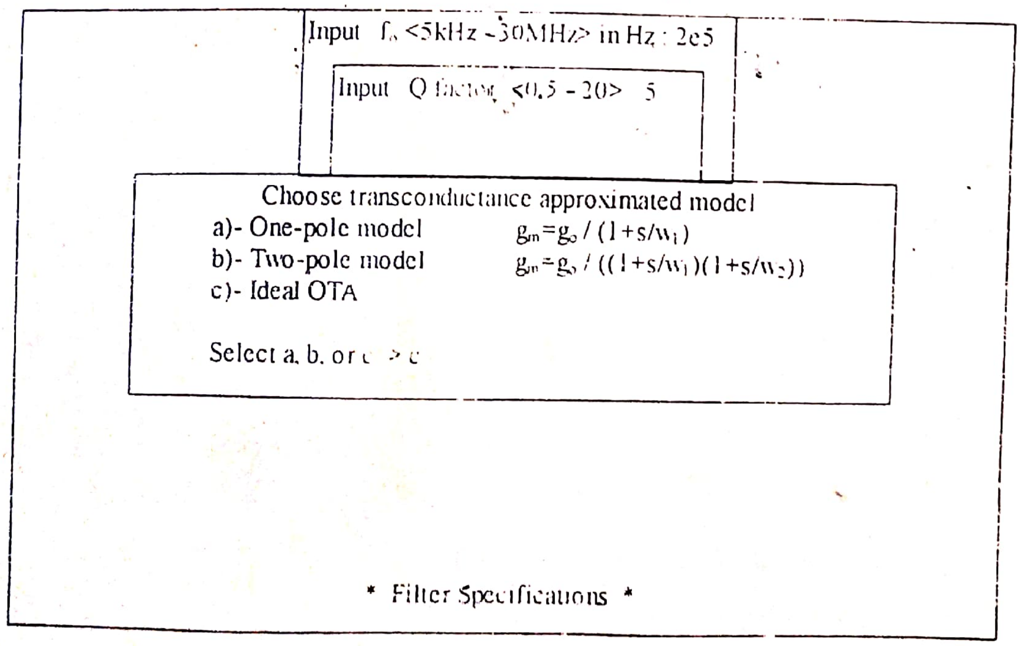
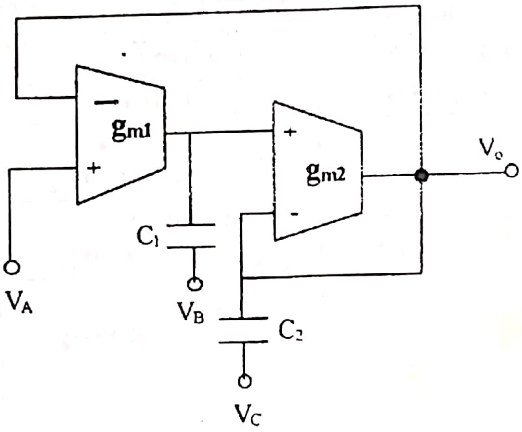
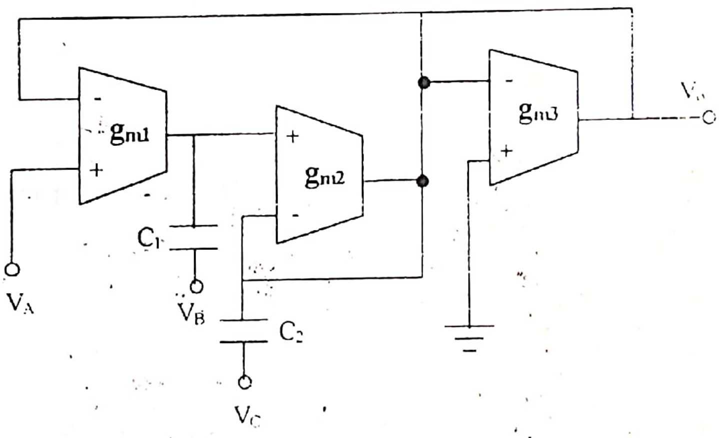


Fig. 2 Entering filter specifications



(a)



(b)

Fig. 3 Second-order structures

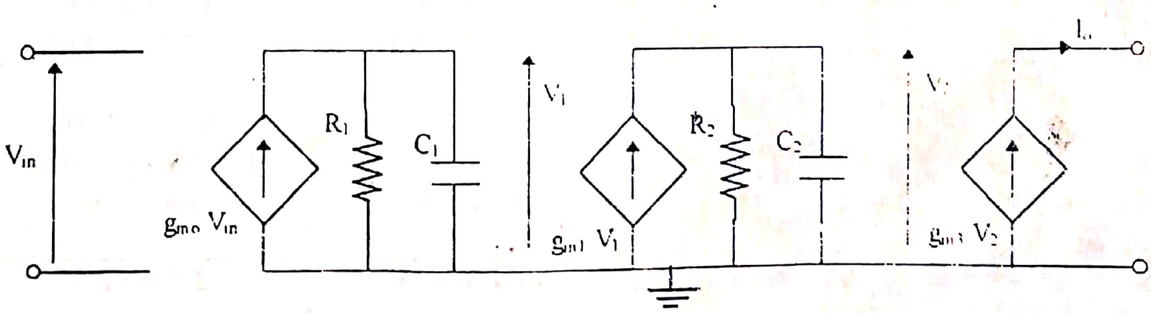


Fig. 4 Linear two-pole transconductance model

Table 1

Example (1) : $f_o = 4$ MHz, $Q = 5$, $g_{m1} \neq g_{m2}$

	Ideal OTA Model	One Pole OTA Model	Two Pole OTA Model
C_1 (Farad)	7.9520 e-11	4.4985 e-10	4.7730 e-10
C_2 (Farad)	1.3690 e-9	2.7516 e-10	2.5395 e-10
g_{m1} (S)	9.9927 e-3	9.9887 e-3	9.8224 e-3
g_{m2} (S)	6.8815 e-3	9.9891 e-3	9.8611 e-3
Dominant Poles*		Q = -1.6942 f_o = 3.20384 MHz	Q = -1.53791 f_o = 3.3165 MHz
Dominant Poles**	Q = 4.9999 f_o = 3.9999 MHz	Q = 4.9999 f_o = 3.9999 MHz	Q = 4.9999 f_o = 3.9999 MHz
Parasitic Poles**	None	Q = 0.6031 f_o = 7.1168 MHz	Q = 0.6341 f_o = 7.0474 MHz Q = 0.5000 f_o = 63.3446 MHz
Initial Function Value*	5.1999	4.9994 e1	3.6311 e6
Minimum Function Value**	9.8912 e-14	3.6694 e-14	8.8288 e-8
Function Evaluations	551	651	551

Notes

1) Initial point for nonideal OTA model is that obtained using CMT, and initial point for ideal OTA model is $C_1 = C_2 = 1$ μF and $g_{m1} = g_{m2} = 1$ μS.

2) * Before optimization. ** After optimization

Table 2

Example (2) $f_o = 4$ MHz, $Q = 9$, $g_{m1} = g_{m2} = g_{m3} = g_m$

	Ideal OTA Model	One Pole OTA Model	Two Pole OTA Model
C_1 (Farad)	2.1918 e-11	1.5667 e-10	1.1529 e-10
C_2 (Farad)	1.7753 e-9	1.1703 e-10	6.9371 e-11
g_m (S)	4.9578 e-3	3.8213 e-3	2.5906 e-3
Dominant Poles	Q = 9 f_o = 4 MHz	Q = 9.0000 f_o = 3.9999 MHz	Q = 8.9999 f_o = 4.0000 MHz
Parasitic Poles	None	Q = 0.5982 f_o = 7.2725 MHz	Q = 0.6285 f_o = 7.2234 MHz Q = 0.5000 f_o = 63.3326 MHz
Initial Function Value	5.0616	5.243 e1	3.8253 e6
Minimum Function Value	2.26008 e-12	1.6921 e-13	2.0067 e-7
Function Evaluations	451	451	551

Table 3

Example (3) : f_o = 200 kHz, Q = 5, $g_{m1} = g_{m2}$

	Poles	Before Optimization		After Optimization	
		Q	f_o (kHz)	Q	f_o (kHz)
Ideal OTA	Dominant	5	204.0366	5	200.0000
One Pole Model	Dominant*	7.3867	204.3781	4.9999	199.9999
	First Parasitic Pair*	0.5002	6289.4721	0.5002	6283.1520
Two Pole Model	Dominant**	7.7578	204.3983	5.000	199.9999
	First Parasitic Pair**	0.5003	6288.6236	0.5003	6280.8895
	Second Parasitic Pair*	0.5000	63002.2897	0.5000	63003.0017

Notes

* : One-pole transconductance model assumed

** : Two-pole transconductance model assumed

Initial Point : C_1 = 300 pF, C_2 = 7500 pF, and $g_{m1} = g_{m2}$ = 1.923 mS.

References المراجع

[1] C.F Wheathley and H.A wittinger , 'OTA Obsletes Opamp', P. Nat Econ.Con., pp. 152-157, Dec. 1969.

[2] RCA Solid-State Division; Data book, Linear Integrated Circuits and MOSFET File No. 1174, pp.260-267, 1984 .

[3] R.L. Geiger and J. Ferrel; " Voltage Controlled Filter Design Using Operation Transconductance Amplifiers;" Proc. , *IEEE/ISCAS*, Vol. 2 New Port Beach USA, PP. 564-597, May 1983 .

[4] T.G Kim. And R.L. Geiger; "Monolithic Programmable RF Filter"; *Electron. Lett.* , Vol.24, No.25, pp. 1569-1571, 8th . Dec. 1988 .

[5] A. Urbas and J. Osiowski; "High-Frequency Realization of C-OTA Second-Order Active Filters," Proc. *IEEE/ISCAS*, pp. 1106-1109, 1982.

[6] E. Sanchez-Sinecio, R.L. Geiger and H. Nevarez-Lozano; "Generation of Continuous-Time Two Integrator Loop OTA Filter Structures" : *IEEE Trans*. Circuits Syst., Vol. 35, pp. 936-946, Aug. 1988 .

[7] R.L. Geiger and E. Sanchez-Sinenicio; "Active Filter Design Using Operation Transconductance Amplifiers: A Tutorial"; *IEEE Circuits and Devices Mag.* Vol. 1, pp. 20-32, March 1985 .

[8] P. V. A. Mohan "Generation of OTA-C Filter Structures Form Active RC Filter Structures" ; *IEEE Trans. Circuits Syst.* , Vol. 37, No.5 , pp. 656-659, May 1990.

[9] H.S Malvar; "Electronically Controlled Active-C Filters and Equalizers with Operational Transconductance Amplifiers"; *IEEE Trans. Circuits Syst.*, Vol. CAS-31, No. 7, pp. 645-649, July 1984 .

[10] P. Bowron and H.M. Dahir : "Modeling of Nonideal Active Devices in Continuous-Time OTA-C Filters"; *IEE Conf Publication* No. 308 , London, England, pp. 128-131 Sept. 1989 .

[11] S. Natrajan, M. Roe and R. Smits ; "Design of Active-RC Filters Including the Effects of Non-Ideal Amplifiers" ; *IEEE/ISCAS* 84, pp. 384-392, 1984 .

[12] Al-Hashimi, J.K. Fidler and P. Garner; " High Frequency Active filters Using OTAS"; *IEE Colloquium on Electric Filters*, Pt. G. No. 97, London, U.K. , 9 June 1980.

[13] Linares-Barraco , A. Rodigues-Vazques, E. Sanchez-Sinecio and J. L. Huertas, ' 10 MHz CMOS OTA-C Voltage-Controlled Quadrature Oscillator, 'Electron. Left., Vol.25 , No. 12, pp. 765-766, 8th June 1989 .

[14] B. Nauta, "CMOS VHF Transconductance-C Filters", *Electron Lett.*, Vol.26 No. 7, pp. 421-422, 29th March 1990 .

[15] H. Nevarez-Lozano, J.A. Hill and E. Sanchez-Sinecio , "Frequency Limitations of Continuous-Time OTA-C Filters", *IEEE/ISCAS* "88" , Vol.3 , Espoo, Finland, pp. 2169-2172, June 7-9, 1988 .

[16] Rodrigues-Vazques, B. Linears-Barranco, J. L. Huertas and E. Sanches-Sinecio, "On the Design of Voltage-Controlled Sinusodial Oscillators Using OTA's", *IEEE Trans. Circuit Syst.*, Vol. 37, No.2, February 1990 .

[17] D. Bunday , *Basic Optimization Methods*, Edward Arnold Pub. Ltd. Pp. 98-106, 1985 .

[18] A. Calahan, *Computer-Aided Network Design* , Chapter 6&11, Revised Edition, Mc-Graw Hill, 1973 .

[19] W. H. Press, S. A. Teukolsky, W. T. Vetteling and B. P. Flannery, *Numerical Recipes in Fortran : The Art of Scientific Computing* , Cambridge Univ. Press, Second Edition, 1992 .

[20] P. Bowron, A. B. Ocarroll and A. A. Daaboul, "Polynominal Reduction in the Analysis of Active-Filter Parasitics," *IEEE Trans. On Circuits & Systems*, Vol.36, No.7, pp. 1020-1023, July 1989 .