COMPUTER-AIDED OPTIMIZATION OF A RC - ACTIVE BAND-PASS FILTER

Paraskevas Nikolaou Prokopis

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ABSTRACT

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An ever increasing demand for high circuit density to decrease the size and costs of electronic systems, such as space electronic circuits, has become a major concern of the active filter designers. Several RC-active filter designs have been proposed in the literature in an attempt to meet this demand.

A new RC-active filter design using unity gain-amplifiers is presented in this report. The design realizes a second-order band-pass filter with good stability and sensitivity properties.

The total capacitance and total resistance are minimized in the design through computer optimization procedures. Therefore, the required substrate area for integrated circuit-fabrication is also minimized. Non-linear programming techniques for the minimization algorithms are employed.

Extensive simulation results have been provided to illustrate the validity of the optimization techniques.

ACKNOWLEDGMENTS

I would like to thank Dr. B.B. Bhattacharyya for his warm interest in this study. His guidance and valuable assistance in order to accomplish this work have been of great value.

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My thanks are due also to Professor Chris Charalambou for his assistance in one area of the minimization algorithms. I am grateful to Concordia University Computer Centre for allotting me ample computer time when intensive work was involved.

Finally, I dedicate this work to the memory of my beloved late brother, Gerasimos, and to my parents.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol or Abbreviation	Description	Page
A or A_o	Open-loop d.c. gain of the voltage controlled amplifier using ideal OA	9
A_i	Unit-square area of the capacitive or resistive thin-film in integrated-circuit fabrication	51
Å	Armstrong, length unit ($1Å = 10^{-8}$ cm)	118
A(s)	Open-loop frequency-dependent gain of a practical OA	13
A_1	Aluminum chemical element	50
Al_2O_3	Aluminum-trioxide	118
Au	gold chemical element	50
Ac	Total area of the thin-film occupied by the total capacitance	32
A_r	Total area of the thin-film occupied by the total resistance	32
A_1, A_2	constant-multipliers defined in Table-7	42
B	Zero-dB gain-bandwidth (GB) of the practical OA	14
BPF	Band-pass filter	19
C or C_i (i = 1,2)	Capacitors of the proposed RC-active filter	19
C_T	Total capacitance	25
CCCS	Current-controlled current source	8
CCVS	Current-controlled voltage source	8
d	distance between electrodes in a capacitive film or thickness of a resistive thin-film of the integrated circuit	51
dB	decibel(s) $10\log(\frac{P2}{P1})$ for power ratio and $20\log(\frac{V2}{V1})$ for voltage ratio	13
d.c.	direct current	13

ABBREVIATIONS AND SYMBOLS CONTINUED

Symbol or Abbreviation	Description	Page
ϵ_o	permittivity of free space	51
ϵ_r	Relative dielective constant	51
$\mathcal{E}$	Electric field strength developed between two conducting capacitor plates	114
f_c or f_H	3-dB cut-off frequency of the practical OA ($fc = \frac{\omega_o}{2\pi}$)	13
f_o	center frequency of the BPF ($fo = \frac{\omega_o}{2\pi}$)	20
f	frequency (Hertz or cycles/sec)	14
f(x)	objective function with respect to the single variable	100
$f(\bar{x})$	constrained objective function with respect to the variable-vector	29
$f(\bar{x}_i)$	constrained objective function of of ith iteration	102
$g(\bar{x})$ or $G(\bar{X})$	gradient-vector of the objective function	49
$g_i(\bar{x})(i=1,2,..m)$	ith equality-constraint function related to the objective function	29
GB	gain-bandwidth of a practical OA	13
GVUA	Grounded-voltage unity-gain amplifier	19
H	Hessian matrix of a twice differentiable objective function	100
H_i or H^{-1}	Inverse hessian matrix	49
$h_j(\bar{x})$	jth inequality-constraint of $f(\bar{x})$	29
Hz	Hertz-units of frequency (prefixed k for kilo and M for mega)	14
H_{BP}	Gain or insertion loss of the second-order transfer function at d.c.(for low-pass) or fo (for band-pass) frequency of a RC-active filter	20

ABBREVIATIONS AND SYMBOLS CONTINUED

Symbol or Abbreviation	Description	Page
i	a subscript	11
IC	Integrated-circuit(s)	50
I_i	ith branch current of an electric circuit	93
j	a subscript (or prefix of the angular frequency w)	15
$\overline{k}$	a penalty-function multiplier vector	107
k_i	penalty-function multiplier	107
K	Closed-loop d.c. gain of an ideal OA	20
K_1, K_2	Closed-loop d.c. gain of the ideal OA no. 1 and 2 respectively.	10
KCL	Kirchoff's current loop	93
KVL	Kirchoff's voltage loop	93
K(s)	Closed-loop frequency-dependent gain of a practical OA	16
Ko	Closed-loop d.c. gain of an ideal OA	17
$L(\overline{x}; \lambda_i)$	Unconstrained objective function as a function of the variable-vector and Langrangian multiplier λ.	102
LHP	Left-hand plane of the complex frequency "s"	26
l_i	unit-length of a resistive thin-film in IC fabrication	115
m	an integer	30
mil	one thousandth of an inch	122
MnO_2	Manganese dioxide	50
n	an integer	30
NIC	Negative-impedance converter	8
OA	operational amplifier	8

Symbol or Abbreviation	Description	Page
PIV	Positive impedance inverter (also called gyrator)	8
$P(\bar{x};k_i)$	Unconstrained objective function in quadratic form, as a function of the variable-vector $\bar{x}$ and the penalty-function multiplier ki	47
Q or Qo	Figure of quality of the transfer function of the proposed BPF at fo $(Qo=\frac{fo}{\Delta f})$	20
r	an integer	30
RC	resistor-capacitor (combination)	21
RHP	Right-half plane of the complex frequency "s".	26
Rs	sheet-resistance of a resistive thin-film in IC fabrication	52
R or $R_i(i=1,2,3)$	Resistors of the proposed RC-active filter	19
R_T	Total resistance of the proposed RC-active filter	25
rad/sec	radians per second-units of angular frequency	15
S	complex frequency $(s=\sigma+j\omega)$	14
sec	seconds	15
SiO	Silicon-monoxide	50
SiO_2	Silicon-dioxide	118
Ta	Tantalum	50
TaO_5	Tantalum-pentoxide	50
TiO_2	Titanium-dioxide	118
TCC	Temperature coefficient of a capacitor	118
TCR	Temperature coefficient of a resistor	52
TM	Tantalum-metal (capacitors)	53
TMM	Tantalum-Manganese - Dioxide-Metal (capacitors)	53

Symbol or Abbreviation	Description	Page
$\nabla_x f(\bar{x})$	Gradient vector of $f(\bar{x})$ with respect to x_i	101
$\nabla_{xx} L$	Gradient vector of $L(x;\lambda)$ with respect to x_i	103
$\nabla_{\lambda\lambda} L$	Gradient vector of $L(x;\lambda i)$ with respect to λi	103
$\nabla\nabla_x f(\bar{x})$	First-derivative of $\nabla_x f(\bar{x})$	101
Δf	3-dB bandwidth of the proposed BPF	21
λ_i	Langrangian multiplier of the unconstrained objective function $L(\bar{x}; \lambda i)$ or step-size of the optimizing algorithm	102
$\frac{\partial f}{\partial x}$	Partial derivative of f with respect to the independent variable x.	49
ρ	Specific resistivity of the resistive thin-film in IC fabrication	52
σ	real part (dumping factor) of the complex frequency "s"	14
$S_x^{\omega_o}$, $S_x^{Q_o}$	Sensitivity of ω_o and Q_o, respectively, with respect to the element x(i.e.,$x=C_i,R_i,K_i$)	26
$\sum_n$ or $\sum_{i=1}^{k}$	Summation over all n over i=1,2,...,K.	47
$[\ ]$	Matrix representation of a set of multivariable linear equations.	103
$[\ ]^T$	Transposed matrix	110

Chapter One

INTRODUCTION

1.1 General

Filter design consists of the realization of a specific transfer function that represents a gain and phase response by means of a synthesis procedure and implementation of the realization in the form of an electric two-port network.

A wide range of filter types exist, such as passive RLC, RC-active, crystal, digital, and lately, switched-capacitor (SC) filters.

RC-active filter design is one of the areas of electronic circuit technology that has evolved very fast and has accumulated a vast amount of literature in a very short time.

One of the most significant impacts on the design of the active filters has been provided in recent years by the introduction of inexpensive monolithic OAs as active elements. These elements are available as off-the-shelf components in large quantities and low cost. Needless to say, the abundance of these active elements made has possible large volume production of high performance active inductorless filters, in particular filters using hybrid IC design and fabrication techniques.

A major concern of the active filter designers, as related to the hybrid IC implementation, is the following.

To minimize the cost of a circuit, more components must be contained in a given substrate area; thus, the size of a circuit must be minimized. Basically, in an integrated circuit, a capacitor requires more space than a resistor, which in turn uses more space than a transistor.

As a result, for economic production of an integrated circuit active filter, and in order to increase the system capacity, such as in satellite communication systems where microelectronics play an important role in the satellite payload, the circuit must be designed with a minimum number of components, particularly capacitors.

In addition, an attempt must be made to minimize the total capacitance and resistance in the circuit.

1.2 Scope of the Report

In this report, procedures are described to minimize the total capacitance and total resistance of a low frequency low Q second-order band-pass active filter by using computer-aided minimization algorithms. Towards this end, a brief discussion of active filters, their related synthesis methods and the associated active elements with their characteristics are briefly discussed in chapter two.

The proposed active filter is described and analyzed in chapter three.

The total capacitance and total resistance of this filter are briefly outlined, and a discussion on the principles of minimization is given in chaper four.

The minimization procedures and several relevant aspects of the problem, such as the constraints, gradients, etc, and appropriate concepts of thin-film component designs are described in chapter five. An important part of this report is the solution of the optimization procedures formulated by means of appropriate computer programs. Certain steps must be taken in order to make the computer programs effective. These steps are important considerations in order to guarantee a feasible solution. These considerations, along with the comments on the computer programs results and conclusions are given in chapter six.

A list of references and appendices conclude the context of this report. The appendices contain the calculations, theory on optimization, concepts of thin-film fabrication and computer programs with description and output results.

Chapter Two

ACTIVE FILTERS

2.1 Brief Background

Spurred by technological advancements and requirements, modern filter theory has produced a class of networks called RC-active networks. These networks include only resistors, capacitors, and active elements.

The active elements have evolved from the vacuum tubes, through the transistors to the integrated circuit OAs in present use. This evolution stems from the need to operate the filter in reduced size, cost, and power consumption, as well as in increased system reliability and functional performance.

RC active filters are now available in hybrid integrated circuit forms and are used in many areas. Some applications are: telephony, where they are used as pilot, voice-channel and some channel-bank filters; telemetry and tracking for satellite systems; phase-lock loop (PLL) filters; instrumentation, used as spring-dumping filters; medical instrumentation and equipment, due to very low frequency signal processing; digital data communications, used as carrier and time reference-recovery filters, sync-pulse recovery and clock generation filters, etc...

RC-active networks offer some attractive advantages over the RLC networks, such as:

1) Increased operating speed, since they are confined in compact, solid state form; propagation delay and parasitics are minimized.
2) The input impedance is high, compared to the source impedance; this reduces the need for signal power.
3) The output impedance is low; this feature keeps the input impedance of the next filter-stage unloaded, thus providing isolation between stages.
4) They can realize functions not realizable by RLC networks since the restrictions of passivity and reciprocity of the RLC networks are inoperative in RC-active networks.

Nevertheless, design of RC-active networks should be exercised carefully, otherwise, oscillations will cause unstable performance. Last, but not least, sensitivity analysis of the resulting networks should be done before implementing the networks.

2.2 Synthesis Methods for RC-Active Filters

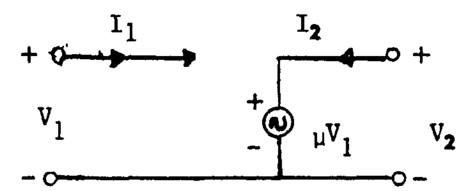
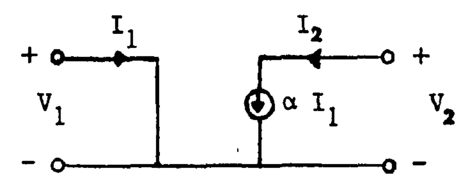
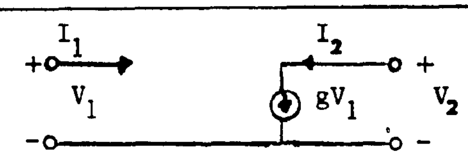
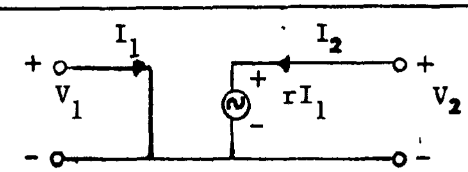
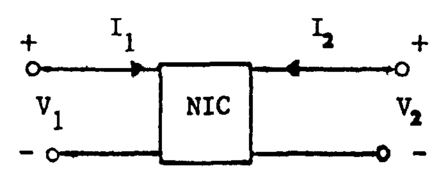
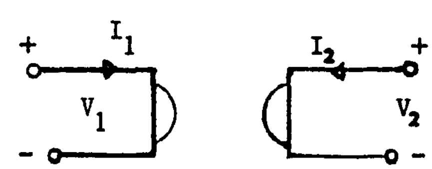
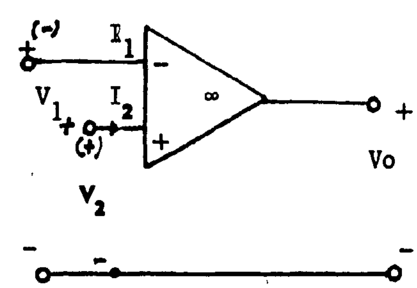
2.2.1 Methods

Considering recent synthesis methods, there are several classifications available. One such classification is based on the feedback representation of the active network configuration.(1) Another classification is based on the way by which the passive and active elements are identified. Still, another classification divides the RC-active filter literature into: 1) the conventional active-synthesis approach 2) the coefficient-matching approach and 3) the simulated-inductor approach.

The design presented in this work can be described as an application of the coefficient-matching technique. The technique is briefly described below.

Coefficient-matching technique: A RC-active network, employing a given type of active elements, is selected and its network function is analyzed. The analyzed network function is compared with a specific function. The element values are determined by equating coefficients of the same power in the complex frequency "s".(2)

Table 1 - Linear active elements used in the active-filter design:

Active-Network Element	Input-Output Relations	Network Symbol
VCVS	$V_2 = \mu V_1$ $I_1 = 0$	
CCCS	$I_2 = \alpha I_1$ $V_1 = 0$	
VCCS	$I_2 = gV_1$ $I_1 = 0$	
CCVS	$V_2 = rI_1$ $V_1 = 0$	
NIC	$V_1 = K_1 V_2$ $I_2 = K_2 I_1$	
PIV or active gyrator	$I_1 = G_2 V_2$ $I = -G_1 V_1$	
OA	$V_o = A(V_2 - V_1)$ $A \to \infty$ $I_1 = I_2 = 0$	

2.2.2 Active Network Elements[3]

Numerous papers have been written on active-filter synthesis using a variety of active elements.

Table-I shows some of these active elements with their characteristics.

One of the major contributions to the active-filter designs has come from the use of a particular type of active elements, namely, OAs.

The OA

Considering the ideal OA, and from the input-output relationship of OA in Table-1, as the open-loop d.c gain "A" approaches infinity, $V_2 - V_1$ approaches zero, where V_1 and V_2 are the inverting and non-inverting imput-terminal voltages, respectively. Hence, the output voltage "V_o" approaches zero. As is shown in Table-1, the ideal OA is an ideal two-input one-output VCVS with A approaching infinity. A is independent of frequency, temperature and input-voltage levels. Figure 2.1 shows a typical representation of the equivalent circuit of an ideal OA.

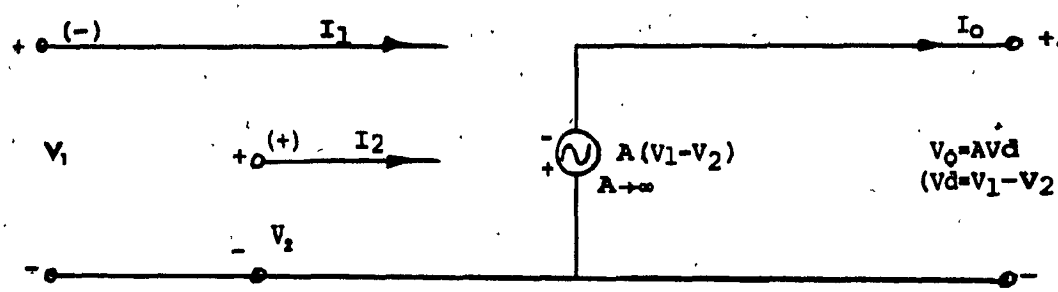


Figure 2.1 - Controlled-source model of an ideal differential input OA.

The output voltage V_o is always of the same polarity with the input voltage, when the latter is applied at the non-inverting input terminal, and of opposite polarity when it is applied at the inverting terminal.

The corresponding closed-loop d.c. gain (K_1 or K_2) follows the input-terminal sign; the closed-loop connected OA is referred to as non-inverting or inverting OA, respectively.

The non-inverting OA and its equivalent circuit are shown in Figure 2.2, connected in a closed-loop gain configuration.

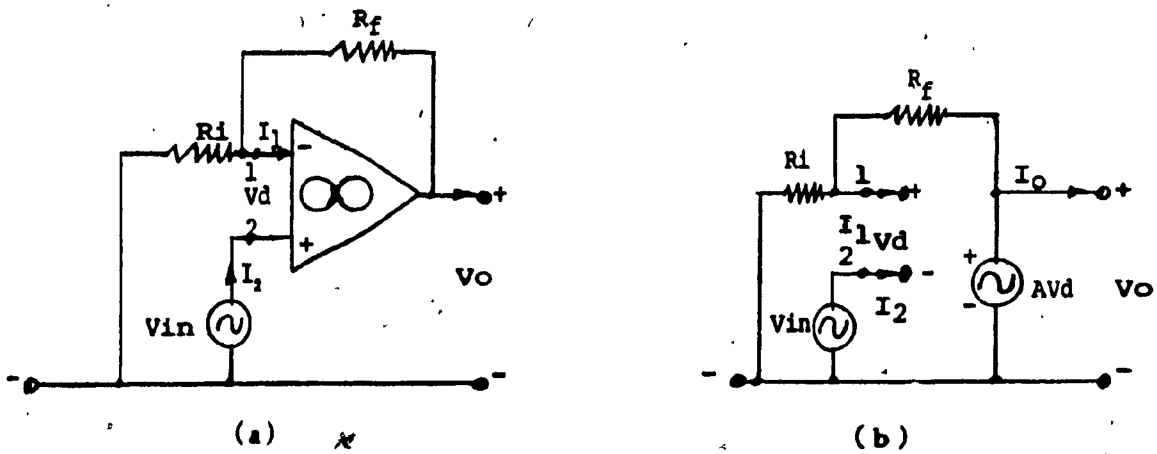


Figure 2.2 - A typical ideal OA in non-inverting gain configuration: (a) Actual circuit, (b) equivalent circuit.

The closed loop d.c. gain[4] is given by:

$$\frac{V_o}{V_1} = 1 + \frac{R_f}{R_1} = G + 1 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

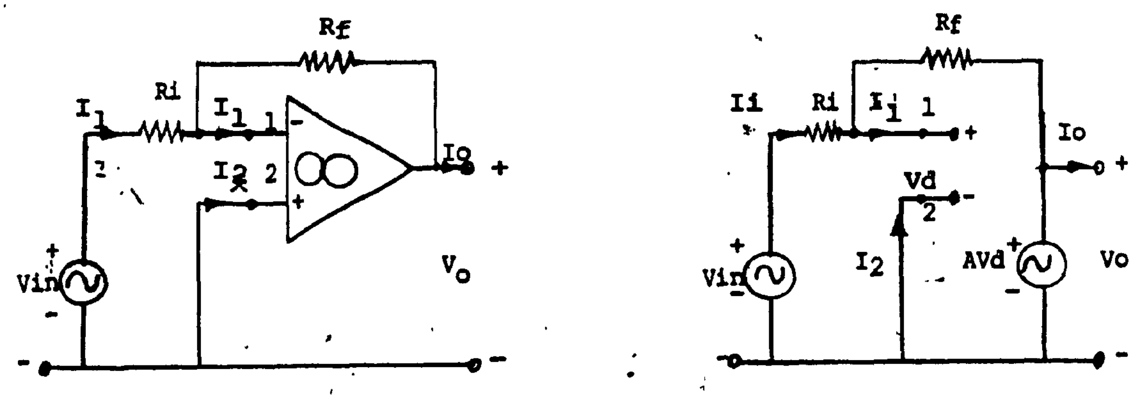
From eq. (2.1) $\frac{V_o}{V_i} \geq 1$, for real positive value, in R_f and R_i. By adjusting R_f and R_i, the d.c. gain of the OA can attain a large range of values.

The d.c. gain is independent of any source-impedance variations, since the non-inverting terminal draws zero current.

The inverting OA and its equivalent circuit are shown in Figure 2.3. The closed-loop d.c. gain is given by:

$$\frac{V_o}{V_i} = -\frac{R_f}{R_i} = -G \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

From eq. (2.2), any real positive value (limited by design-constraints) of $\frac{V_o}{V_i}$ can be obtained by adjusting R_f and Ri.



(a) (b)

Figure 2.3 - A typical ideal OA in inverting gain configuration: (a) Actual circuit, (b) equivalent circuit.

From the equivalent circuit in figure 2.3 it is obvious that if the source-voltage V_i exhibits an impedance R_i it may be incorporated in series with R_i . Hence, the source-voltage V_i must be able to deliver a current $\frac{V_i}{R_i}$.

The output-impedance approaches zero, consequently the load-resistance R_L does not enter the expression for the d.c.-gain. However, the OA must be able to deliver output-current, required by the feedback current $\frac{V_o}{R_f}$ and the load current $\frac{V_o}{R_L}$, where R_L is the load resistance.

Additional performance characteristics of the OAs,[5] when manufactured in silicon monolithic form, are: i) Close matching and tracking of the active and passive components over a wide range of temperature variations; ii)limited constraint on the number and geometry of the active devices, and iii) excellent thermal coupling through the circuit.

However, the integrated OAs are complex circuits, composed of versatile differential-amplifier cascaded stages with appropriate output stages.

The practical OA is a non-ideal device characterized by a frequency and temperature-dependent finite gain A(s). This open-loop gain decreases monotonically with frequency at frequencies higher than its limited corner frequency (or 3 dB cut-off frequency) value ω_H . The input and output impedances are finite and the input and output signal levels are limited by the dynamic characteristics of the OA. Other non-ideal characteristics of the practical OA are: input offset-voltage and offset-current, common-mode rejection error, and finite unequal common-mode impedances of the two input-terminals. The Bode-plot of a typical practical OA with internal compensation is shown in Figure 2.4 Near d.c., the open-loop gain A_0 is in the range of 200,000 or 106 dB, but at ω_H, the voltage gain starts decreasing with a steady slope of 6dB/octave, or 20dB/decade.

The value of B usually depends on the model. The best OAs attain values of B in the range 1 to 65 MHZ. At frequencies above B, the roll-off of the gain-slope is steeper than 12dB/octave. The OA then begins to appear as an attenuator which is useful in some cases, when stability is needed.

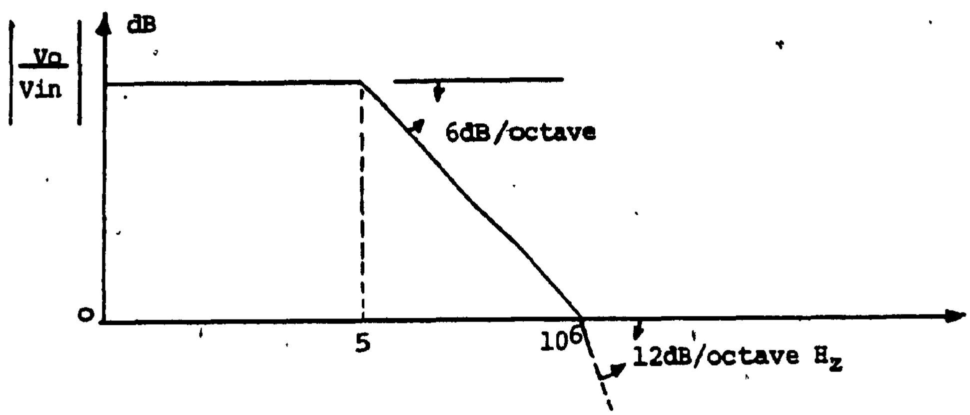
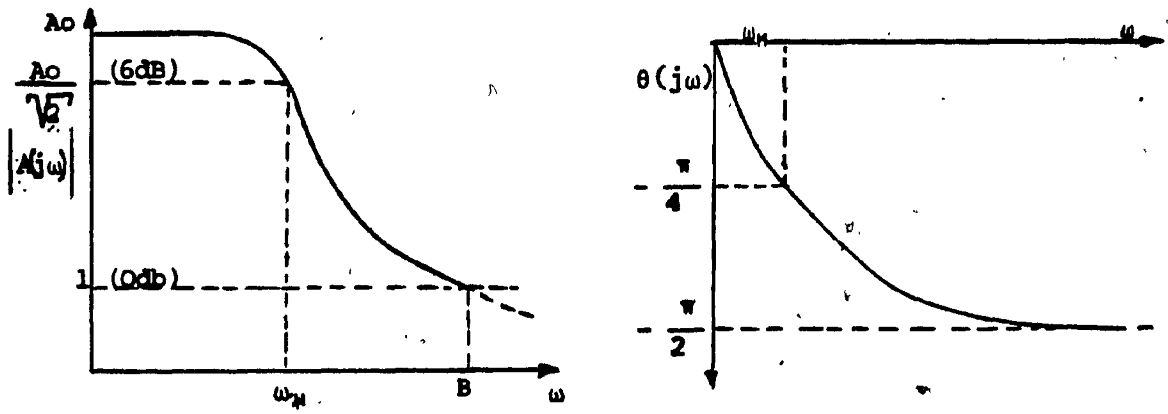


Figure 2.4 - Open-loop gain response versus frequency of a practical OA.

Most OAs are designed so that, for small signal operation, A(s) is represented by a first-order transfer function (ignoring the higher-order terms) that exhibits low-pass characteristics. The transfer-function of the practical OA, in open-loop configuration, is given by: $A(s) = \frac{A_O \omega_H}{S + \omega_H} = \frac{B}{S + \omega_H}$ ...(2.3)

The gain and phase characteristics are shown in Figure 2.5



(a) (b)

Figure 2.5 - Transfer function characteristics of the practical frequency-dependent OA.
(a) Gain characteristics (b) Phase characteristics

Electronic-circuit designers must operate the OAs in the linear region of their transfer characteristics, in closed-loop modes, and with small input signal, otherwise the above small signal model is not valid. Furthermore, temperature variations may cause fluctuations on A_o characteristics, even with temperature-compensation circuits. For these reasons, closed-loop gain configurations should be used, by connecting external resistors, as in Figure 2.2 and 2.3 for the non-inverting and inverting-input OA configurations, respectively.

For the ideal OA, K is:

$$1 + \frac{R_f}{R_i} = G + 1 \quad \text{.......... (2.4)}$$

and $$-\frac{R_f}{R_i} = -G \quad \text{.......... (2.5)}$$

for the non-inverting and inverting OA configurations, respectively.

When the dominal-pole model of the practical OA is considered, K(s), for the non-inverting configuratino is:

$$K(s) = \frac{\frac{1}{\beta}}{\frac{s}{\beta B} + \frac{\omega_H}{\beta B} + 1} = \frac{B}{s+\omega_H + \beta B} = \frac{B}{s+\omega_H + \frac{B}{G}} \quad \text{.......... (2.6)}$$

where

$$\beta = \frac{R_i}{R_i + R_f}$$

Similarly, for the inverting-input configuration,

$$K(s) = -\gamma \frac{\frac{1}{\beta}}{\frac{s}{\beta B} + \frac{\omega_H}{\beta B} + 1} = \frac{-G}{G+1} \cdot \frac{B}{s + \omega_H + \frac{B}{G+1}} \quad \text{.......... (2.7)}$$

where $$\gamma = \frac{R_f}{R_i + R_f}$$

For $\frac{B}{G} \gg \omega_H$, the corresponding gains are:

$$K(s) = \frac{B}{s + \frac{B}{G+1}} \quad \text{.......... (2.8)}$$

and

$$K(s) = \frac{-G}{G+1} \cdot \frac{B}{s + \frac{B}{G+1}} \quad \text{.......... (2.9)}$$

respectively.

At zero frequency, the gains in equations (2.8) and (2.9) reduce to: $K(s)\big|_{s=0} = 1 + G$ and $K(s)\big|_{s=0} = -G$, respectively, which are identical to the d.c. gains of equations (2.1) and (2.2) respectively. From equations (2.6) and (2.7) the 3-dB bandwidths (ω_{-3dB}) of the closed-loop practical OA are:

$$\omega_{-3dB} = \omega_H + \frac{B}{G+1} = \frac{B}{G+1}\left(1+\frac{G+1}{Ao}\right) \quad (2.10)$$

and

$$\omega_{-3dB} = \omega_H + \frac{B}{G+2} = \frac{B}{G+2}\left(1+\frac{G+2}{Ao}\right) \quad (2.11)$$

for the non-inverting and inverting-input OAs, respectively. It can be observed that, for $Ao \gg G+1$ and $Ao \gg G+2$, the corresponding 3-dB bandwidths are:

$$\omega_{-3dB} = \frac{B}{G+1} \quad (2.12)$$

and

$$\omega_{-3dB} = \frac{B}{G+2} \quad (2.13)$$

Comparing equations (2.12) and (2.13), ω_{-3dB} for the non-inverting practical OA is greater than that of inverting OA. It can be seen, also, that the smaller the term G the wider the 3-dB bandwidth.

The unity-gain of the non-inventing OA is given by

$$Ko = \frac{R_f}{R_i} + 1 = G + 1 = 1 \quad (2.14)$$

since R_f is zero. Therefore, equation (2.12) becomes:

$$\omega_{-3dB} = B \quad (2.15)$$

since $Ao \gg 1$ and $G = 0$.

From equations (2.12) and (2.15), it is obvious that the cut-off frequency ω_H is at its maximum value B when the OA is configured for unity-gain. The phase reponse varies between zero and $-\frac{\pi}{2}$ radians at the maximum cut-off frequency B.

Other imperfections of the practical OA are the closed-loop input and output impedances Zin and Zout, respectively, which are represented by the expressions:

$$Z_{in} = (1 + A(s)\beta)\, Z_i \quad \text{.......(2.16)}$$

and

$$Z_{out} = \frac{Z_o}{1 + A(s)\beta} \quad \text{.......(2.17)}$$

Here, Z_i and Z_o are the input and output impedances of the open-loop OA, respectively. When Z_i is in the order of 50,000 ohms Z_{in} is in the range of 50 to 100 megohms. Z_o decreases to $Z_{out} = \frac{Z}{1+A\beta}$. When Z_o is in the order of 200 ohms, the corresponding impedance Z_{out} is in the order of 0.1 ohms.

From equations (2.16) and (2.17) it is clear that a unity-gain OA would offer the largest value of input impedance and the smallest value of output impedance.

Some of the other advantages of operating an OA in the unity-gain mode are simplicity, low cost and high stability.

Chapter Three

DESIGN OF A RC-ACTIVE BAND-PASS FILTER(BPF)

3.1 The Proposed Band-Pass Filter

It is quite common to use second-order transfer-function sections in cascade, in order to realize higher order active filter, due to low-sensitivity and post-design adjustment considerations.(6)

In this report a new band-pass second-order RC-active filter using unity-gain amplifiers is discussed. As described in the previous section, UGAs can be realized conveniently by OAs. The filter is shown in Figure 3.1.

The required OA circuit in closed-loop configuration, to form the positive unity-gain amplifier, is shown in Figure 3.2 Note that ideally Zin and Zout o.

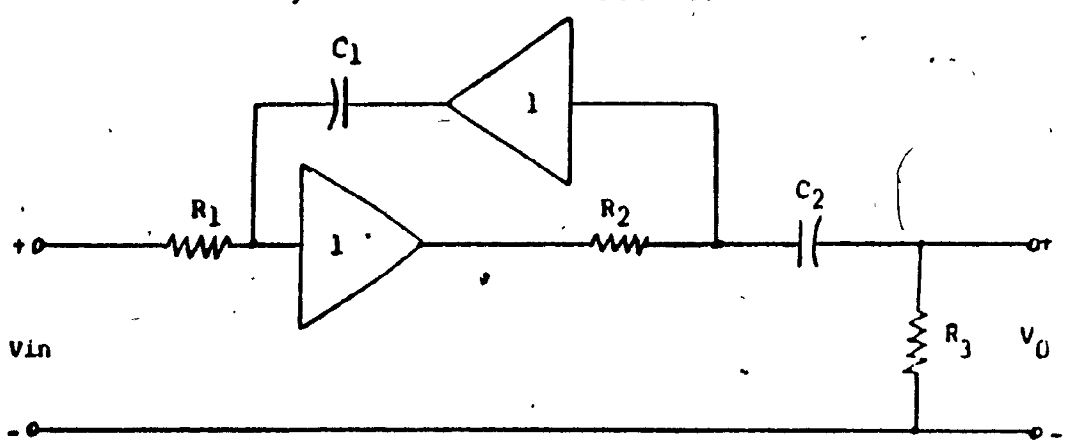


Figure 3.1 - Proposed band-pass RC-Active filter using unity-gain amplifiers.

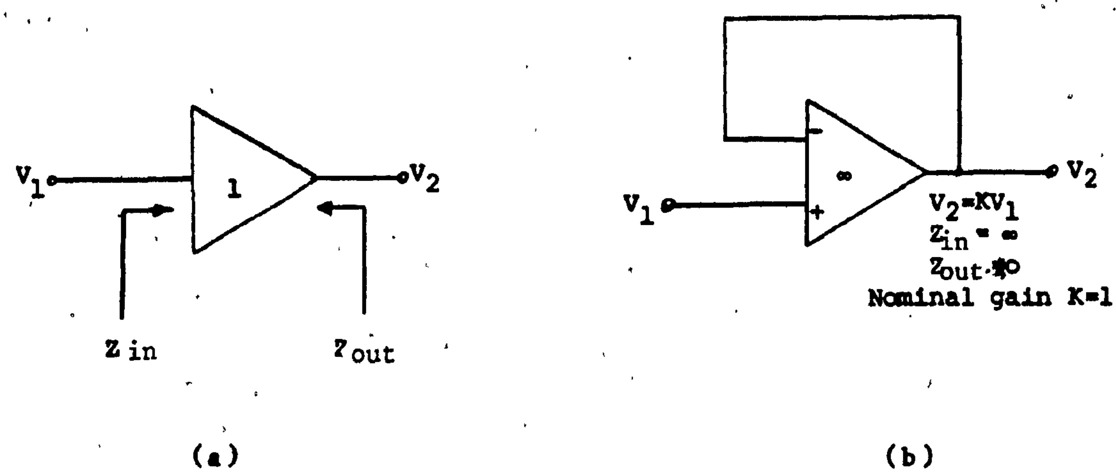


Figure 3.2 - Ideal models of UGAs:

(a) The symbol of the UGA

(b) Construction of UGA

3.2 Voltage Transfer Function

The voltage transfer function for a second-order band-pass filter, in the complex frequency domain "s" is:

$$\frac{Vo}{Vi}(s) = \frac{H_{BP}\,\frac{\omega_o}{Q_o}\,s}{s^2 + \frac{\omega_o}{Q_o}\,s + \omega_o^2} \quad \text{(3.1)}$$

The band-pass filter of figure 3.1 will be analyzed assuming ideal, then practical OAs, unity-gain or non-unity-gain amplifier configuration. The unity-gain amplifier configuration will be used later in the minimization algorithms.

The filter transfer function, Figure 3.1, is given by:

$$\frac{Vo}{Vi}(s) = \frac{\dfrac{R_3}{R_1 R_2 C_1} s}{s^2 + \dfrac{R_2 + R_3}{R_1 R_2 C_1} s + \dfrac{1}{R_1 R_2 C_1 C_2}} \qquad (3.2)$$

and is derived in Appendix A.

Assuming non-unity gain configuration ($K_1, K_2 \neq 1$), figure 3.3, the transfer function of the same filter is given by:

$$\frac{Vo}{Vi}(s) = \frac{\dfrac{K_1 R_3}{R_1 C_1 [R_2 + R_3(1-K_1K_2)]} s}{s^2 + \dfrac{R_1C_1 + R_2C_2 + R_3C_2 - K_1K_2R_1C_1}{R_1C_1C_2[R_2+R_3(1-K_1K_2)]} s + \dfrac{1}{R_1C_1C_2[R_2+R_3(1-K_1K_2)]}} \qquad (3.3)$$

and is derived in Appendix A

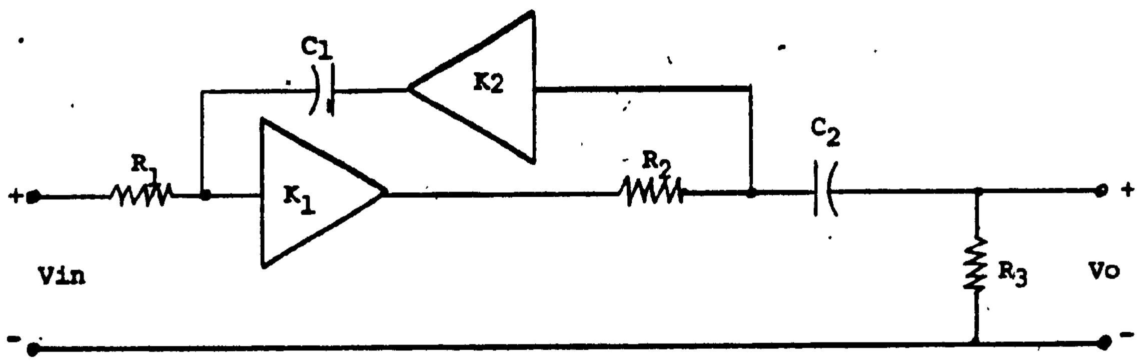


Figure 3.3 - Proposed band-pass RC-active filter of figure 3.1, using non-unity gain amplifiers K_1 and K_2.

Let $K_1 = K_2 = K$

In this case, the transfer functions of eq. (3.3) becomes:

$$\frac{Vo}{Vi}(s) = \frac{\dfrac{KR_3}{R_1 C_1 [R_2 + R_3(1-K^2)]} s}{s^2 + \dfrac{R_1C_1 + R_2C_2 + R_3C_2 - K^2R_1C_1}{R_1C_1C_2[R_2+R_3(1-K^2)]} s + \dfrac{1}{R_1C_1C_2[R_2+R_3(1-K^2)]}} \qquad (3.4)$$

By letting $K = 1$, the transfer function of equation (3.4), reduces to the transfer function of eq. (3.2). When the dominant-pole model is used with unity-gain amplifiers (K=1) then

$$K(s) = \frac{B}{s + B} \qquad \text{.................................}(3.5)$$

Substituting eq. (3.5) in eq. (3.2), then:

$$\frac{Vo}{Vi}(s) = \frac{\dfrac{R_3 \cdot C_2 \; B}{R_1R_2C_1C_2 + R_1R_3C_1C_2} \; s(s + B)}{s^4 + \dfrac{2R_1R_2C_1C_2B + 2R_1R_3C_1C_2B + R_1C_1 + R_2C_2 + R_3C_2}{R_1R_2C_1C_2 + R_1R_3C_1C_2} s^3 + \dfrac{R_1R_2C_1C_2B^2 + 2R_1C_1B + 2R_2C_2B + 2R_3C_2B + 1}{R_1R_2C_1C_2 + R_1R_3C_1C_2} s^2 + \dfrac{R_2C_2B^2 + R_3C_2B^2 + 2B}{R_1R_2C_1C_2 + R_1R_3C_1C_2} s + \dfrac{B^2}{R_1R_2C_1C_2 + R_1R_3C_1C_2}} \qquad \text{...........}(3.6)$$

Again, in an ideal situation, where B approaches infinity, the transfer functions in eq. (3.6) is simplified to:

$$\frac{Vo}{Vi}(s) = \frac{-\dfrac{R_3}{R_1R_2C_1} \; s}{s^2 + \dfrac{R_2 + R_3}{R_1R_2C_1} \; s + \dfrac{1}{R_1R_2C_1C_2}} \qquad \text{........................}(3.7)$$

which is identical to eq. (3.2) derived directly with the assumption of unity-gain ideal amplifiers employing ideal OAs.

3.3 Design - Equations

Due to the complexity of operations involved in solving the fourth-order transfer function to derive the filter parameters ω_o, Q_o and H_{BP}, as well as the element-equations, only the ideal-OA second-order transfer function is analyzed. This implies that the design will be useful only for low frequency applications, that is for $\omega_o \ll B$. Comparing eq. (3.1) and (3.2) the following equations are derived:

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad \text{.......(3.8)}$$

$$Q_o = \frac{1}{R_2 + R_3} \sqrt{\frac{C_1 R_1 R_2}{C_2}} \quad \text{.......(3.9)}$$

$$H_{BP} = \frac{R_3}{R_2 + R_3} \quad \text{.......(3.10)}$$

From eq. (3.8), ω_o can be adjusted by trimming the values C_1, C_2 and R_1 or R_2. Once ω_o is adjusted, H_{BP} or Q_o (but not both) can be adjusted by varying R_3, without affecting ω_o. The parameters ω_o, Q_o and H_{BP} are usually specified by the filter designer. The corresponding element-values are calculated in Appendix B. All element-value expressions are presented in Table 2-5-6- and -7

The following component-equations will be useful in establishing the initial variable-locations in the minimization algorithms, when minimizing C_T and R_T

TABLE - 2 FILTER ELEMENTS AND TIME CONSTANTS IN TERMS OF THE SPECIFICATIONS AND ANY TWO OF THE OTHER ELEMENTS

Given: $\omega_o = \frac{1}{\sqrt{C_1 C_2 R_1 R_2}}$, $Q_o = \frac{R_3}{R_2 + R_3}\sqrt{\frac{C_1 R_1}{C_2 R_2}}$, $H_{sp} = \frac{R_3}{R_2 + R_3}$

FLOATING ELEMENTS	C_1	C_2	R_1	R_2	R_3	R_1C_1	R_2C_2	R_3C_2	COMMENTS
C_1 and C_2	FLOATING	FLOATING	$\frac{Q_o}{\omega_o C_1 (1-H_{sp})}$	$\frac{1-H_{sp}}{\omega_o Q_o C_1}$	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{C_1}$	-			UNIQUE SOLUTION
C_1 and R_1	FLOATING	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	FLOATING	$\frac{1-H_{sp}}{C_2 \omega_o Q_o}$	$\frac{H_{sp}}{1-H_{sp}} \cdot R_2$	$\frac{Q_o}{\omega_o} \cdot \frac{1}{1-H_{sp}}$	$\frac{1-H_{sp}}{\omega_o Q_o}$	-	R_1C_1 and R_2C_2 are fixed; for solution R_2 or C_2 is required
C_1 and R_2	FLOATING	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	$\frac{Q_o}{\omega_o H_{sp}} \cdot \frac{R_3}{R_2 C_1}$	FLOATING	$\frac{H_{sp} R_2}{1-H_{sp}}$	-	-	-	UNIQUE SOLUTION
C_1 and R_3	FLOATING	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	$\frac{1}{\omega_o^2 C_1 R_2 C_2}$	$\frac{1-H_{sp}}{H_{sp}} \cdot R_3$	FLOATING	-	-	-	UNIQUE SOLUTION
C_2 and R_1	$\frac{1}{\omega_o^2 R_1 R_2 C_2}$	FLOATING	FLOATING	$\frac{1-H_{sp}}{H_{sp}} \cdot R_3$	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{C_2}$	-	-	-	UNIQUE SOLUTION
C_2 and R_2	$\frac{1}{\omega_o^2 R_1 R_2 C_2}$	FLOATING	$\frac{Q_o}{\omega_o C_1 (1-H_{sp})}$	FLOATING	$\frac{H_{sp}}{1-H_{sp}} \cdot R_2$	$\frac{Q_o}{\omega_o} \cdot \frac{1}{1-H_{sp}}$	$\frac{1-H_{sp}}{\omega_o Q_o}$	-	R_1C_1 and R_2C_2 are fixed; for solution, R_1 and C_1 is required.
C_2 and R_3	$\frac{1}{\omega_o^2 C_2 R_1 R_2}$	FLOATING	$\frac{1}{\omega_o^2 R_2 C_1 C_2}$	$\frac{1-H_{sp}}{H_{sp}} \cdot R_3$	FLOATING	$\frac{1}{\omega_o^2 R_2 C_2}$	-	$\frac{H_{sp}}{\omega_o Q_o}$	R_3C_2 and R_1C_1 are fixed; for solution R_1 or C_1 is required.
R_1 and R_2	$\frac{1}{\omega_o^2 R_1 R_2 C_2}$	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	FLOATING	FLOATING	$\frac{H_{sp}}{1-H_{sp}} \cdot R_2$	-	-	-	UNIQUE SOLUTION
R_1 and R_3	$\frac{1}{\omega_o^2 R_1 R_2 C_2}$	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	FLOATING	$\frac{1-H_{sp}}{H_{sp}} \cdot R_3$	FLOATING	-	-	-	UNIQUE SOLUTION
R_2 and R_3	$\frac{1}{\omega_o^2 R_1 R_2 C_2}$	$\frac{H_{sp}}{\omega_o Q_o} \cdot \frac{1}{R_3}$	$\frac{1}{\omega_o^2 C_1 R_2 C_2}$	FLOATING	FLOATING	$\frac{1}{\omega_o^2 R_2 C_2}$	-	-	R_2 and R_3 are interdependent

of the proposed filter. It is, therefore, convenient to calculate all the element-values classified in two groups; the resistor-equations, with capacitor-values as variables, and the capacitor-equations, with resistor-values as variables. These calculated values will be used, initially, as arbitrary locations of the variables (X_i) in the minimization algorithms, assuming that the parameters ω_o , Q_o , and H_{BP} are specified. The element-equations are:

$$R_3 = \frac{1}{C_2} \cdot \frac{H_{BP}}{\omega_o Q_o} \quad \text{......(3.11)}$$

$$R_2 = \frac{1}{C_2} \cdot \frac{1-H_{BP}}{\omega_o Q_o} \quad \text{......(3.12)}$$

$$R_1 = \frac{1}{C2} \cdot \frac{Q_o}{\omega_o (1-H_{BP})} \quad \text{......(3.13)}$$

Hence, $H_{BP} < 1$ for eq. (3.12) and (3.13) to take always positive values.

$$C_2 = \frac{1}{R_2+R_3} \cdot \frac{1}{\omega_o Q_o} \quad \text{......(3.14)}$$

$$C_1 = \frac{R_2+R_3}{R_1 \; R_2} \cdot \frac{Q_o}{\omega_o} \quad \text{......(3.15)}$$

$$C_T = C_1 + C_2 \quad \text{......(3.16)}$$

$$R_T = R_1 + R_2 + R_3 \quad \text{......(3.17)}$$

3.4 Sensitivity

The RC-active filter designer is concerned with the sensitivities of the resulting transfer function. The sensitivity performance of any active filter is best described in terms of its sensitivities with respect to variations of its active and passive elements.[7]

The sensitivities $S_x^{\omega_o}$ and $S_x^{Q_o}$, where x is any passive or active element are shown in Table - 3.

3.5 Stability

The second-order transfer function of the proposed band-pass filter can be written as:

$$\frac{Vo}{Vi}(s) = \frac{N(s)}{D(s)} = \frac{H_{BP}\frac{\omega_o}{Q_o}s}{s^2+\frac{\omega_o}{Q_o}s+\omega_o^2} \quad (3.18)$$

or:

$$\frac{Vo}{Vi}(s) = \frac{a_1 s}{b_2 s^2 b_1 s + bo} \quad (3.19)$$

The bi-coefficients of the i^{th} power in "S" determine whether the poles(S_p) are located in the LHP, in the RHP, or on the imaginary axis (jω). The last two pole-locations define the "critical stability" or the "oscillatory" condition of the filter. For stability, the b_i-coefficients for the transfer function of (3.19) must be real positive constants.

The denominator of the transfe function, eq. (3.4), will be examined in order to observe the importance of K of the amplifiers at the instant of power activation, and after activation. K is given by: $K = \frac{A_o}{A_o + 1}$. As A_o increases its values from zero, during activation, to infinity, during the steady-state period of the power (post activation), the gain K increases from zero to one, where it remains constant.

X	$S_x^{Q_o}$	$S_x^{\omega_o}$	Comments
R_1	$\frac{1}{2}$	$-\frac{1}{2}$	
R_2	$\frac{1}{2}\,\frac{R_3-R_2}{R_2+R_3}$	$-\frac{1}{2}$	$S_{R_2}^{Q_o} \leq \frac{1}{2}$
R_3	$-\frac{R_3}{R_2+R_3}$	0	$\left\lvert S_{R_3}^{Q_o} \right\rvert \leq 1$
C_1	$\frac{1}{2}$	$-\frac{1}{2}$	
C_2	$-\frac{1}{2}$	$-\frac{1}{2}$	
K_1	$\left.\frac{R_1C_1}{(R_2+R_3)C_2} - \frac{1}{2R_2}\right\rvert_{K_1=K_2=K=1}$	$\frac{1}{2}K_1K_2R_1C_1C_2$	$S_{K_1}^{Q_o} \approx \frac{R_1C_1}{(R_2+R_3)C_2}$, where $K_1 = K_2 = K = 1$ $S_{K_1}^{\omega_o} = \frac{1}{2}R_1C_1C_2$, where $K_1 = K_2 = K = 1$
K_2	$\left.\frac{R_1C_1}{(R_2+R_3)} - \frac{1}{2R_2}\right\rvert_{K_1=K_2=K=1}$	$\frac{1}{2}K_1K_2R_1C_1C_2$	$S_{K_2}^{Q_o}\ \frac{R_1C_1}{(R_2+R_3)C_2}$, where $K_1 = K_2 = 1$ $S_{K_2}^{\omega_o} \approx \frac{1}{2}R_1C_1C_2$, where $K_1 = K_2 = 1$

Table - 3 - Q_o and ω_o sensitivities with respect to the passive and active elements

3.5.1 Stability During Activation

For stability during activation, this is, right after power is switched on, the b_1-coefficient of the denominator should remain real and positive. For this circuit, the following conditions should hold:

1) $b_o = \omega_o^2 > 0$ where $\omega_o^2 = \dfrac{1}{R_1C_1C_2\ R_2+R_3(1-K^2)}$

Since

$$0 < K < 1,\ \omega_o^2 > 0$$

2) $b_2 > 0$. In this case, $b_2=1$. Therefore, b_2, the second-order coefficient, is always real positive.

3) $b_1 > 0$. For this filter, $b_1 = \dfrac{\omega_o}{Q_o}$

$$\text{or}\quad \frac{\omega_o}{Q_o} = \frac{R_1C_1+R_2C_2+R_3C_2-K_1K_2R_1C_1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]} = \frac{R_1C_1(1-K^2)+C_2(R_2+R_3)}{R_1C_1C_2\left[R_2+R_3(1-K^2)\right]}$$

It is obvious that $\dfrac{\omega_o}{Q_o}$ or b_1 is real positive, since $K^2 < 1$. From the above stability analysis, it can be concluded that the proposed configuration yields a stable filter.

Chapter Four

MINIMIZATION OF TOTAL CAPACITANCE (C_T)

AND TOTAL RESISTANCE (R_T)

4.1 General Concepts of Optimization (Non-linear Programming)[9]

In any optimization problem, there is a function $f(\bar{x})$ to be minimized, which satisfies some rules called constraints $g_i(\bar{x})$. The function to be minimized is called "objective function" The optimization process can be stated as: min $f(\bar{x})$, such that $g_i(\bar{x})=0$, $i=1,2,\ldots,m < n$, $h_j(\bar{x}) \geq 0$, $j=1,2,\ldots,r$ where $\bar{x} = [x_1, x_2, \ldots\ldots\ldots x_n]^T$, and all functions $f(\bar{x})$, $g_i(\bar{x})$ and $h_j(\bar{x})$ are differentiable.

With the given objective function, the m equality-constraints, and r inequality-constraints, it is possible to find a set (or sets, since the solution might not be unique) $[x_1^*, x_2^* \ldots\ldots\ldots x_n^*]$ which yields a minimum. The function $f(\bar{x})$ will be feasible for a solution if the dimension m in $g_i(\bar{x})$ does not exceed the number of variables in $f(\bar{x})$. Therefore, the inequality $m \leq n$ should hold. If $m \geq n$, the problem is termed "overconstrained." When $m < n$, the number of degrees of freedom, for optimizing, is n - m . The equality-constraints can be divided into two inequality-constraints: $g_i(\bar{x}) \geq 0$, i=1,2,.....,m

$g_i(\bar{x}) \geq 0$, i=1,2,.....,m

From the above definitions, the non-linear programming problem can be written as:

$$\min_x f(\bar{x}), \quad \text{such that} \quad \begin{bmatrix} g_i(\bar{x}) \\ -g_i(\bar{x}) \\ h_j(\bar{x}) \end{bmatrix} \geq 0, \quad \begin{matrix} i=1,2,\ldots\ldots,m < n \\ j=1,2,\ldots\ldots,r \end{matrix}$$

There are many minimization methods(or algorithms) available in literature; some of these are briefly described in Appendix C.

4.2 Total Capacitance (C_T) and Total Resistance(R_T)

For high volume production of active filters, hybrid integrated circuit realizations using thin-film RC-networks and silicon monolithic operational amplifiers have been a state of the art in recent filter technology and have very efficient production yields. To this end, however, due consideration must be given to the inherent properties of hybrid integrated circuits.

In a thin-film realization, a capacitor uses more space than a resistor, and the resistor uses more space than a transitor. It is estimated that if the area occupied by a transistor on an IC chip is taken to be one unit, then a resistor requires an area of two units and a capacitor occupies an area of three units.

Consequently, the aim of the designer should not only be to minimize the number of the passive components, but also to minimize C_T and R_T

In the context of the minimization procedure, the terms "total capacitance" or "total resistance" is interpreted in this report to mean a quantity that is directly proportioned to the sum of the individual areas of each capacitor or resistor, as the case may be. For the purposed active filter, minimization of the areas corresponding to C_T and/or R_T is the major topic of this report. Analysis deals with forty eight cases of minimizing the capacitance and/or resistance-areas of a thin-film substrate based on the propose filter component requirements and parameter (ω_0, Q_0 and H_{∞}) specifications. In some cases, minimization procedures have been given directly for the quantities C_T or R_T without considering corresponding areas.

The different optimization cases considered in this report are shown in Fig. 4.1. The expressions for C_T and R_T are defined in section 3.3 and are given in Table 5, 6 and 7.

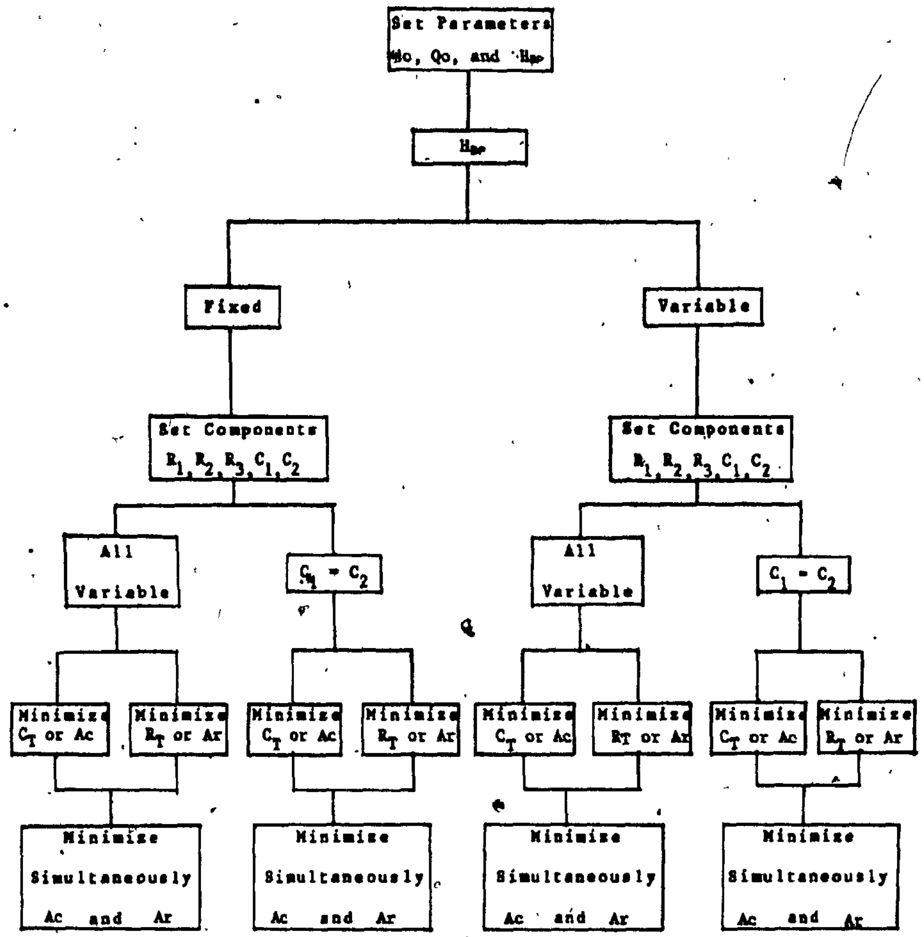


Figure 4.1 - Classification of minimization cases in terms of filter parameters and constraints

Chapter Five

SOME OPTIMAL DESIGNS FOR THE PROPOSED FILTER

5.1 Formulation of the problem

The filter design problem is viewed here as the determination of a set of "optimum" element values for a given network structure.

These values yield the minimum value of the objective function (ie. C_T , B_T , Ac , Ar) for the given filter specifications.

In applying the computer-aided analysis, proper formulation of the above objective function, selection of the constraints to be satisfied, together with the choice of suitable minimization algorithms, are the essential aspects of optimization problem.

The filter element-values are bounded in a feasible region, specified by the solid-state circuit manufacturer. These element-value bounds can be introduced in the computer program, either as variables in a range defined by "hard" limits (stop commands) or as minimization constraints. The constraints of the 48 objective functions are the filter parameters Wo and Qo and the component-requirement $C_1 = C_2$.

However, Wo and Qo are functions of the filter elements; in view of this dependence, their values in each iteration of the minimization algorithm, change throughout the algorithm until the "optimum" (minimum set $x^* = [x_1^*, x_2^*, \ldots\ldots, x_n^*]$) is achieved, in which instance, these constraints are satisfied, or until the parameters obtain their desired values.

5.2 The Optimal-Design Objective Function

The minimization problem can be stated as follows:
$\mathrm{Min}_x\ f(\bar{x})$, such that the equality-constraints $g_i(\bar{x}) = 0$, $i=1,2,..r$, hold, where $\bar{x} = [x_1, x_2, \ldots x_m]^T$.

The objective function $f(\bar{x})$, in this study, is determined by the specific requirements of the filter design to deliver the desired filter parameters at the end of the minimization process, where the physical size of C_T and R_T representing the corresponding areas Ac and Ar respectively, are minimized. This function is the "constrained" objective function to be minimized, without considering the penalty paid by the presence of the constraints; this penalty is the inability of the algorithm to reach the "global" (or sometimes "local") point when constraints ($g_i(\bar{x})$) are satisfied.

Computer-programs are compiled, in Fortran IV, utilizing two of the Computer-Library subroutines which minimize the specific five-dimensional twice-differentiable functions with some constraints, Figure 4.1 and Table - 4.

Quasi- Newton's algorithm is used to minimize $f(\bar{x})=C_T$ for four cases, each case pertaining to three sets of values in Wo and Qo, per Table -5,-6,-9, and -11.

Fletcher-Powell's algorithm solves the more feasible functions $f(\bar{x})$ given by: Ac, Ar and 2Ar+ 3Ac, where $Ac=A_1C_T, Ar=A_2R_T$, and A_1 and A_2 are constants defined by the electric and physical properties of the thin-film material used in this analysis. There are twelve cases for all three objective functions (f (x)), each case pertaining to three sets of values in ω_o and Q_o. Table -4, -7, -8, -10, and -12 show the various objective functions of this algorithm.

$F(\bar{x})$ is a two-dimensional constrained objective function since $\bar{x}=[x_1,x_2]^T$, where $x_1 = C_1$, $x_2 = C_2$, when $f(\bar{x})=C_T=C_1+C_2$ and three-dimensional ($\bar{x} = [x_1, x_2, x_3]^T$), where $x_1=R_1, x_2=R_3, x_3=R_3$, when $f(\bar{x}) = R_T = R_1 + R_2 + R_3$.

In a real situation technical problem, where the filter design has to meet certain parameter-specifications, besides minimizing the physical size of its components, constraint-functions $g_i(\bar{x})$ are present.

Table - 4 INDEX OF MINIMIZATION AND "PLOT" PROGRAMS

a) fo=500 HZ, Qo=50   b) fo=500 HZ, Qo = 10   c) fo=1000 HZ, Qo = 10

Program No	Program Name	Case	Description
1		1a	Miminize C_T using Newton's method
2	MINCT	1b	when H_{BP} is floating and all
3		1c	elements are floating $\left(H_{BP} = \frac{R_3}{R_2+R_3}\right)$
4		2a	Minimize C_T using Newton's method
5	$MINCT_1$	2b	when H_{BP} is floating and $C_1=C_2 = C$
6		2c	
7		3a	Minimize C_T using Newton's method
8	$MINCT_2$	3b	when H_{BP} is constant $(R_3=KR_2; H_{BP}=\frac{K}{K+1})$
9		3c	and C_1 , C_2 , R_1 , R_2 are floating
10		4a	Minimize C_T using Newton's method
11	$MINCT_3$	4b	when H_{BP} is constant and $C_1 = C_2 = C$
12		4c	
13		1a	Minimize area "Ac" of C_T using
14	C_1MIN	1b	Fletcher's method when H_{BP} is float
15		1c	-ing and all elements are floating
16.		2a	Minimize area "Ac" of C_T using
17	C_2MIN	2b	Fletcher's method when H_{BP} is
18		2c	floating and $C_1 = C_2 = C$
19		3a	Minimize area "Ac" of C_T using
20	C_3MIN	3b	Fletcher's method when H_{BP} is
21		3c	constant $(H_{BP} = \frac{K}{K+1}$; $R_3 = KR_2)$
22		4a	Minimize area "Ac" of C_T using
23	C_4MIN	4b	Fletcher's method when H_{BP} is
24		4c	constant and $C_1 = C_2 = C$

INDEX CONTINUED

Program No	Program Name	Case	Description
25		5a	Miminize area "Ar" of R_T using
26	R_1MIN	5b	Fletcher's method when H_{BP} and all
27		5c	elements are floating .
28		6a	Minimize area "Ar" of R_T using
29	R_2MIN	6b	Fletcher's method when H_{BP} is
30		6c	floating and $C_1=C_2=C$
31		7a	Minimize area "Ar" of R_T using
32	R_3MIN	7b	Fletcher's method when H_{BP} is
33		7c	constant ($H_{BP}=\frac{K}{K+1}$; $R_3=KR_2$)
34		8a	Minimize area "Ar" of R_T using
35	R_4MIN	8b	Fletcher's method when H_{BP} is
36		8c	constant and $C_1=C_2$
37		9a	Miminize area of 3Ac+2Ar using
38	RCMIN$_1$	9b	Fletcher's method when H_{BP} is float
39		9c	-ing and all elements are floating
40		10a	Minimize area of 3Ac + 2Ar using
41	RCMIN$_2$	10b	Fletcher's method when H_{BP} is
42		10c	floating and $C_1=C_2$
43		11a	Minimize area of 3Ac + 2Ar using
44	RCMIN$_3$	11b	Fletcher's method when H_{BP} is
45		11c	constant ($H_{BP}=\frac{K}{K+1}$; $R_3=KR_2$)
46		12a	Minimize area of 3Ac + 2Ar using
47	RCMIN$_4$	12b	Fletcher's method when H_{BP} is
48		12c	constant and $C_1=C_2$

INDEX CONTINUED

Program No	Program Name	Case	Description
49 50 51	Paris2 " "	fo=500HZ, Qo=50, H_{BP}=.909 fo=500HZ, Qo=50, H_{BP}=.75 fo=500HZ, Qo=10, H_{BP}=.75	Plot the Amplitude and Phase Response with Ideal OAs in the Unity-Gain Mode
52 53 54	Paris " "	fo=500HZ, Qo=50, H_{BP}=.909 fo=500HZ, Qo=10, H_{BP}=.909 fo=1000HZ, Qo=10, H_{BP}=.909	Plot the Amplitude and Phase Response with Non-Ideal OAs in the Unity-Gain Mode. B=100MHZ
55 56 57	Paris1 " "	fo=500HZ, Qo=50, H_{BP}=.909 Ao=150000, Ko=1000 fo=500HZ, Qo=50, H_{BP}=.909 Ao=150000, Ko=10 fo=500HZ, Qo=50, H_{BP}=.909 Ao=150000, Ko=1	Plot the Amplitude and Phase Response with Non-Ideal OAs in the Non Unity-Gain Mode
58 through 69	Paris	Optimal-element values of Quasi-Newton minim. programs (Program nos: 1 - 12)	Plot the Amplitude and Phase Response with Non-Ideal OAs in the Unity-Gain Mode. B=100MHZ
70 through 105	Paris	Optimal-element values of Fletcher-Powell's minim. programs (program nos: 13 - 48)	"

TABLE - 5 EXPRESSIONS OF ELEMENTS AND PARAMETERS - GENERAL

CASE	DESCRIPTION	R_1	R_2	R_3	C_1	C_2	H	OBJECTIVE FUNCTION C_T OR R_T	Wo	Qo
1a	minimize C_T when H_{sp} and all elements are floating	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	$\frac{1}{QoWo}\frac{1}{R_2+R_3}$	$\frac{R_3}{R_2+R_3}$	C_1+C_2	$\frac{1}{\sqrt{C_1C_2R_1R_2}}$	$\frac{R_2}{R_2+R_3}\sqrt{\frac{C_1}{C_2}\frac{R_1}{R_2}}$
1b	minimize C_T when H_{sp} is floating and $C_1=C_2=C$	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	C_1	$\frac{R_3}{R_2+R_3}$	$2C_1=2C$	$\frac{1}{C\sqrt{R_1R_2}}$	$\frac{R_2}{R_2+R_3}\sqrt{\frac{R_1}{R_2}}$
1c	minimize C_T when H_{sp} is constant ($R_3=kR_2$) and C_1,C_2,R_1,R_2 are floating	FLOATING	FLOATING	KR_2	$\frac{K+1}{R_1}\frac{Qo}{Wo}$	$\frac{1}{(K+1)QoWo}\frac{1}{R_2}$	$\frac{k}{K+1}$	C_1+C_2	$\frac{1}{\sqrt{C_1C_2R_1R_2}}$	$\frac{1}{K+1}\sqrt{\frac{C_1R_1}{C_2R_2}}$
1d	minimize C_T when H_{sp} is constant and $C_1=C_2$	FLOATING	FLOATING	KR_2	$\frac{K+1}{R_1}\frac{Qo}{Wo}$	C_1	$\frac{k}{K+1}$	$2C_1=2C$	$\frac{1}{C\sqrt{R_1R_2}}$	$\frac{1}{K+1}\sqrt{\frac{R_1}{R_2}}$
2a	minimize R_T when H_{sp} and all elements are floating	$\frac{1}{C_1(1-H_{sp})}\frac{Qo}{Wo}$	$\frac{1-H_{sp}}{C_2WoQo}$	$\frac{H_{sp}}{C_2WoQo}$	FLOATING	FLOATING	$\frac{R_3}{R_2+R_3}$	$R_1+R_2+R_3$	$\frac{1}{\sqrt{C_1C_2R_1}}$	$\frac{R_2}{R_2+R_3}\sqrt{\frac{C_1R_1}{C_2R_2}}$
2b	minimize R_T when H_{sp} is floating and $C_1=C_2=C$	$\frac{1}{C(1-H_{sp})}\frac{Qo}{Wo}$	$\frac{1-H_{sp}}{CWoQo}$	$\frac{H_{sp}}{CWoQo}$	FLOATING	C_1	$\frac{R_3}{R_2+R_3}$	$R_1+R_2+R_3$	$\frac{1}{C\sqrt{R_1R_2}}$	$\frac{R_2}{R_2+R_3}\sqrt{\frac{R_1}{R_2}}$
2c	minimize R_T when H_{sp} is constant ($R_3=KR_2$) and C_1,C_2,R_1,R_2 are floating	$\frac{1}{C_1(1-H_{sp})}\frac{Q}{Wo}$	$\frac{1-H_{sp}}{C_2WoQo}$	KR_2	$\frac{K+1}{R_1}\frac{Qo}{Wo}$	$\frac{1}{(K+1)QoWo}\frac{1}{R_2}$	$\frac{k}{K+1}$	$R_1+R_2(K+1)$	$\frac{1}{\sqrt{C_1C_2R_1R_2}}$	$\frac{1}{K+1}\sqrt{\frac{C_1R_1}{C_2R_2}}$
2d	minimize R_T when H is constant and $C_1=C_2$	$\frac{1}{C_1(1-H_{sp})}\frac{Q}{Wo}$	$\frac{1-H_{sp}}{CWoQo}$	KR_2	FLOATING	C_1	$\frac{k}{K+1}$	$R_1+R_2+R_3$	$\frac{1}{C\sqrt{R_1R_2}}$	$\frac{1}{K+1}\sqrt{\frac{R_1}{R_2}}$

TABLE - 6 EXPRESSIONS OF ELEMENTS AND PARAMETERS USED IN THE MINIMIZATION PROGRAMS (NEWTON'S METHOD)

Program Name	R_1	R_2	R_3	C_1	C_2	Constrain 1	Constrain 2	Constrain 3	C_T	R_T
MIN CT (1to3)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2} \frac{Qo}{Wo}$	$\frac{1}{WoQo} \frac{1}{R_2+R_3}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	N/A	C_1+C_2	$R_1+R_2+R_3$
MIN C_{T1} (4to6)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2} \frac{Qo}{Wo}$	$\frac{1}{WoQo} \frac{1}{R_2+R_3}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	C_1+C_2	$R_1+R_2+R_3$
MIN C_{T2} (7to9)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo} \frac{K+1}{R_1}$	$\frac{1}{WoQo} \frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (K+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	N/A	C_1+C_2	$R_1+R_2+R_3$
MIN C_{T3} (10to12)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo} \frac{K+1}{R_1}$	$\frac{1}{WoQo} \frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (K+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	C_1+C_2	$R_1+R_2+R_3$

TABLE - 7 EXPRESSIONS OF ELEMENTS AND PARAMETERS USED IN THE MINIMIZATION PROGRAMS (FLETCHER-POWELL'S METHOD)

PROGRAM NAME AND NUMBER	ELEMENT CALCULATIONS					CONSTRAINS		OBJECTIVE FUNCTION					
	R_1	R_2	R_3	C_1	C_2	Constrain 1	Constrain 2	Constrain 3	C_T	R_T	A_C	A_R	$2A_R + 3A_C$
C_1 MIN (13to15)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	NONE	C_1+C_2	-	x	-	-
C_2 MIN (16to18)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	C_1+C_2	-	x	-	-
C_3 MIN (19to21)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{K+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(k+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	NONE	C_1+C_2	-	x	-	-
C_4 MIN (22to24)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{K+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	C_1+C_2	-	x	-	-
R_1 MIN (25to27)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	NONE	-	$R_1+R_2+R_3$	-	x	-
R_2 MIN (28to30)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1 \cdot R_2}\frac{Qo}{Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	-	$R_1+R_2+R_3$	-	x	-
R_3 MIN (31to33)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{K+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	NONE	-	$R_1 \pm (k+1) R_2$	-	x	-
R_4 MIN (34to36)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{k+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(k+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	$\frac{C_1}{C_2} - 1 = 0$	-	$R_1+(k+1) R_2$	-	x	-

TABLE - 7 EXPRESSIONS OF ELEMENTS AND PARAMETERS USED IN THE MINIMIZATION PROGRAMS (FLETCHER-POWELL'S METHOD) CONT.

PROGRAM NAME AND NUMBER	ELEMENT CALCULATIONS					CONSTRAINS			OBJECTIVE FUNCTION				
	R_1	R_2	R_3	C_1	C_2	Constrain 1	Constrain 2	Constrain 3	C_T	R_T	A_C^*	A_R^*	$2A_R^* + 3A_C^*$
RC MIN 1 (37to39)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1}\frac{Qo}{R_2 Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	NONE	C_1+C_2	$R_1+R_2+R_3$	x	x	x
RC MIN 2 (40to42)	FLOATING	FLOATING	FLOATING	$\frac{R_2+R_3}{R_1}\frac{Qo}{R_2 Wo}$	$\frac{1}{R_2+R_3}\frac{1}{QoWo}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (R_2+R_3)^2 \frac{C_2}{C_1 R_1 R_2} - 1 = 0$	$\frac{C_2}{C_1} - 1 = 0$	C_1+C_2	$R_1+R_2+R_3$	x	x	x
RC MIN 3 (43to45)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{K+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	NONE	C_1+C_2	$R_1+(k+1)R_2$	x	x	x
RC MIN 4 (46to48)	FLOATING	FLOATING	KR_2	$\frac{Qo}{Wo}\frac{K+1}{R_1}$	$\frac{1}{WoQo}\frac{1}{R_2(K+1)}$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Qo^2 (k+1)^2 \frac{C_2 R_2}{C_1 R_1} - 1 = 0$	$\frac{C_2}{C_1} - 1 = 0$	C_1+C_2	$R_1+(k+1)R_2$	x	x	x

$Ac^* = A_1 C_T$, where $A_1 = \frac{2}{3} \cdot \frac{V}{EoErE}$, and V = Breaking Voltage of the dielective material

Eo = 8.85 x exp(-14), is the permittivity of the free space ($\frac{\text{Farads}}{\text{cm}}$)

Er = dielective constant relative to that of free space

E = dielective strength of the thin-film ($\frac{\text{Volts}}{\text{cm}}$).

$A_R^* = A_2 R_T$, where $A_2 = \frac{W^2}{Rs}$, and W = width of the thin-film resistive strip (cm)

Rs = sheet resistance of the resistive strip (ohms)

TABLE – 8 CALCULATED GRADIENTS OF FLETCHER-POWELL'S MINIMIZATION ALGORITHM

	C_1MIN	C_2MIN	C_3MIN
PENALTY MULTIPLIER			
K_1	1000	500	
K_2	1000	100000000	
K_3		10000	
CONSTRAINT:			
h_1	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	$Wo^2 R_1 C_1 R_2 C_2 - 1 = 0$	
h_2	$Qo^2 (R_2+R_3)^2 C_2/(C_1 R_1 R_2) - 1 = 0$	$Qo^2 (R_2+R_3)^2 C_2/(C_1 R_1 R_2) - 1 = 0$	
h_3		$C_1/C_2 - 1 = 0$	
VARIABLE : xi (NORMALIZED)			
x1	* $A_1 C_1$	$A_1 C_1$	$A_1 C_1$
x2	$A_1 C_2$	$A_1 C_2$	$A_1 C_2$
x3	$A_2 R_1$	$A_2 R_1$	$A_2 R_1$
x4	$A_2 R_2$	$A_2 R_2$	$A_2 R_2$
x5	$A_2 R_3$	$A_2 R_3$	$A_2 R_3 = k A_2 R_2$
UNCONSTRAINED FUNCTION: F(xi)	$A_1 (C_1 + C_2)$	$A_1 (C_1 + C_2)$	$A_1 (C_1 + C_2)$
CONSTRAINED FUNCTION: F(xi)	$A_1 (C_1+C_2) + k_1 h_1^2 + k_2 h_2^2$	$A_1 (C_1+C_2) + k_1 h_1^2 + k_2 h_2^2 + k_3 h_3^2$	$A_1 (C_1+C_2) + k_1 h_1^2 + k_2 h_2^2$
GRADIENT G(i) $\frac{\Delta F}{\Delta xi}$ =			
G(1)	$1 + \frac{2}{C_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1))$	$1 + \frac{2}{C_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1)) + k_3 h_3 (h_3+1))$	$1 + \frac{2}{C_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1))$
G(2)	$1 + \frac{2}{C_2} (k_1 h_1 (h_1+1) + k_2 h_2 (h_2+1))$	$1 + \frac{2}{C_2} (k_1 h_1 (h_1+1) + k_2 h_2 (h_2+1) - k_3 h_3 (h_3+1))$	$1 + \frac{2}{C_2} (k_1 h_1 (h_1+1) + k_2 h_2 (h_2+1))$
G(3)	$\frac{2}{R_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1))$	$\frac{2}{R_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1))$	$\frac{2}{R_1} (k_1 h_1 (h_1+1) - k_2 h_2 (h_2+1))$
G(4)	$\frac{2}{R_2} (k_1 h_1 (h_1+1) + \frac{R_2-R_3}{R_2+R_3} k_2 h_2 (h_2+1))$	$\frac{2}{R_2} (k_1 h_1 (h_1+1) + (\frac{R_2-R_3}{R_2+R_3}) k_2 h_2 (h_2+1))$	$\frac{2}{R_2} (k_1 h_1 (h_1+1) + k_2 h_2 (h_2+1))$
G(5)	$(\frac{4}{R_2+R_3}) k_2 h_2 (h_2+1)$	$(\frac{4}{R_2+R_3}) (k_2 h_2 (h+1))$	$\frac{4}{R_2+R_3} k_2 h_2 (h_2+1)$

* $A_1 = \frac{2}{3} \frac{V}{EoErE}$ AND $A_2 = \frac{W^2}{Rs}$ (SEE TABLE – 7)

TABLE - 8 CONTINUED

PENALTY MULTIPLIERS	C_4MIN	R_1MIN	R_2MIN
K_1	100000	500	1000
K_2	1000	500	100000
K_3	10000		50000
CONSTRAINT :			
h_1	$Wo^2 R_1C_1R_2C_2-1=0$	$Wo^2 R_1C_2R_2C_2-1=0$	$Wo^2 R_1C_1R_2C_2 - 1 = 0$
h_2	$Qo^2 (1+K)^2 C_2R_2/(C_1R_1)-1=0$	$Qo^2 (R_2+R_3)^2 / (C_1R_1R_2)- 1 = 0$	$Qo^2 (R_2+R_3)^2 C_2 /(C_1R_1R2) - 1 = 0$
h_3	$C_1/C_2 - 1 = 0$		$\frac{C_2}{C_1} - 1 = 0$
VARIABLE : xi (normalized)			
x_1	A_1C_1	A_1C_1	A_1C_1
x_2	A_1C_1	A_1C_2	A_1C_2
x_3	A_2R_1	A_2R_1	A_2R_1
x_4	A_2R_2	A_2R_2	A_2R_2
x_5	A_2R_3	A_2R_3	A_2R_3
UNCONSTRAINED FUNCTION: P(xi)	$A_1 (C_1 + C_2)$	$A2 (R1 + R_2 + R_3)$	$A2 (R1 - R2 + R3)$
CONSTRAINED FUNCTION:P(xi)	$A_1 (C_1+C_2) + K_1h_1^2 + K_2h_2^2 + K_3h_3^2$	$A_2 (R1+R2+R3) + K_1h_1^2 + K_2h_2^2$	$R_2(R_1+R_2+R_3) + K_1h_1^2 + K_2h_2^2 + K_3h_3^2$
GRADIENT $G(i) = \frac{\nabla P}{\nabla xi}$:			
G(1)	$1+\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1)+K_3h_3(h_3+1))$	$\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$\frac{2}{C_1}(K_1h_1(h_1+1)-K2h_2(h_2+1)-K_3h_3(h_3+1))$
G(2)	$1+\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)-K_3h_3(h_3+1))$	$\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1))$	$\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)+K_3h_3(h_3+1))$
G(3)	$\frac{2}{K_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$1+\frac{2}{R_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$1+\frac{2}{R_1}(K_1h_1(h_1+1)-K_2h_2(h2+1))$
G(4)	$\frac{2}{R_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1))$	$1+\frac{2}{R_2}(K_1h_1(h_1+1)+(\frac{R2-R3}{R2+R3})K_2h_2(h_2+1))$	$1+\frac{2}{R_2}(K_1h_1(h_1+1)+\frac{R2-R3}{R2+R3}K_2h_2(h_2+1))$
G(5)	$(\frac{4}{R_2+R_3}) K_2h_2(h_2+1)$	$1+(\frac{4}{R_2+R_3})K_2h_2(h_2+1)$	$1+\frac{4}{R_2+R_3}K_2h_2(h_2+1)$

TABLE - 8 CONTINUED

PENALTY MULTIPLIER	R_3MIN	R_4MIN	$RCMIN_1$
K_1	1200	5000	100
K_2	500	1000	500
K_3		5000	
CONSTRAINT:			
h_1	$Wo^2 R_1C_1R2C_2-1=0$	$Wo^2 R_1C_1R_2C_2-1=0$	$Wo^2 R_1C_1R2C_2-1=0$
h_2	$Qo^2 (K+1)^2 R_2C2 /(R_1C_1)-1=0$	$Qo^2 (K+1)^2 R_2C_2/(R1C_1)-1=0$	$Qo^2 (R2+R_3)^2 C_2/(C_1R_1R_2)-1=0$
h_3		$C_1/C_2 - 1 = 0$	
VARIABLE: xi (normalized)			
x1	A_1C_1	A_1C_1	A_1C_1
x2	A_1C_2	A_1C2	A_1C2
x3	A_2R_1	A_2R_1	$A2R1$
x4	A_2R_2	A_2R_2	A_2d2
x5	$A_2R_3=KA_2R_2$	$A_2R_3=KA_2R_2$	A_2R_3
UNCONSTRAINED FUNCTION: P(xi)	A_2 , $R_1+(K+1)R_2$	$A2(R_1+(K+1)R_2)$	$3(A_1(C_1+C_2))+2(A_2(R_1+R_2+R_3))A_{RC}$
CONSTRAINED FUNCTION: P(xi)	$A_2 \quad R_1+(K+1)R_2 \quad +K_1h_1^2+K_2h_2^2$	$A_2(R_1+(K+1)R_2)+K_1h_1^2+K_2h_2^2+k_2h_3^2$	$A_{RC}+K_1h_1^2+K_2h_2^2$
GRADIENT $G(i)= \frac{\nabla P}{\nabla xi}$:			
G(1)	$\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h2+1))$	$\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1)+K_3h_3(h_3+1))$	$3+\frac{2}{C_1}(K_1H_1(h_1+1)-K_2h_2(h_2+1))$
G(2)	$\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1))$	$\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)-K_3h_3(h_3+1))$	$3+\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1))$
G(3)	$1+\frac{2}{R_1}\ K_1h_1(h_1+1)-K_2h_2(h_2+1)$	$1+\frac{2}{R_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$2+\frac{2}{R_1}(K_1h_1(h1+1)-K_2h_2(h_2+1))$
G(4)	$K+1+\frac{2}{R_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)$	$K+1+\frac{2}{R_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1))$	$2+\frac{2}{R_2}(K_1h_1(h_1+1)+\frac{R_2-R_3}{R_2+R_3}K_2h_2(h_2+1))$
G(5)	$(\frac{4}{R_2+R_3})K_2h2(h_2+1)$	$(\frac{4}{R_2+R_3})K_2h2(h_2+1)$	$2+(\frac{4}{R2+R_3})\ K_2h2(h_2+1)$

TABLE - 8 CONTINUED

PENALTY MULTIPLIER	$RCMIN_2$	$RCMIN_3$	$RCMIN_4$
K_1 K_2 K_3	100 500 1000	2000 2000	3200 6400 3200
CONSTRAIN: h_1 h_2 h_3	$Wo^2R_1C_1R_2C_2-1=0$ $Qo^2(R_2+R_3)^2C_2/(C_1R_1R_2)-1=0$ $C_2/C_1-1=0$	$Wo^2R_1C_1R_2C_2-1=0$ $Qo^2(K+1)^2R_2C_2/(R_1C_1)-1=0$	$Wo^2R_1C_1R_2C_2-1=0$ $Qo^2(K+1)^2R_2C_2/(R_1C_1)-1=0$ $C_2/C_1-1=0$
VARIABLE: xi (normalized) x_1 x_2 x_3 x_4 x_5	A_1C_1 A_1C_2 A_2R_1 A_2R_2 A_2R_3	A_1C_1 A_1C_2 A_2R_1 A_2R_2 $A_2R_3 = KA_2R_2$	A_1C_1 A_1C_2 A_2R_1 A_2R_2 $A_2R_3 = KA_2R_2$
UNCONSTRAINED FUNCTION: P(xi)	$3(A_1(C_1+C_2))+2(A_2(R_1+R_2+R_3)) = A_{RC}$	$3(A_1(C_1+C_2))+2(A_2(R_1+(K+1)R_2)) = A_{RC}$	$3(A_1(C_1+C_2))+2(A_2(R_1+(K+1)R_2))= A_{RC}$
CONSTRAINED FUNCTION: P(xi)	$A_{RC} + K_1h_1^2+K_2h_2^2+K_3h_3^2$	$A_{RC} + K_1h_1^2+K_2h_2^2$	$A_{RC} + K_1h_1^2+K_2h_2+K_3h_3^2$
GRADIENT $G(i) = \frac{\nabla P}{\nabla xi}$:			
G(1)	$3+\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1)-K_3h_3(h_3+1))$	$3+\frac{2}{C_1}(k_1h_1(h_1+1)-K_2h_2(h_2+i)$	$3+\frac{2}{C_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1)- K_3h_3(h_3+1))$
G(2)	$3+\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)+K_3h_3(h_3+1))$	$3+\frac{2}{C_2}(K_1h_1(h_1+1)+K_2h_2(h_2+1)$	$3+\frac{2}{C_2}(K_1h_1(h1+1)+K_2h_2(h_2+1)+ K_3h_3(h_3+1))$
G(3)	$2+\frac{2}{R_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$2+\frac{2}{R_1}(K_1h_1(h_1+1)-K_2h_2(h_2+1))$	$2+\frac{2}{R_1}(K_1h_1(H_1+1)-K_2h_2(h_2+1))$
G(4)	$2+\frac{2}{R_2}(K_1h_1(h_1+1)+(\frac{R_2-R_3}{R_2+R_3})\ K_2h_2(h_2+1)$	$2(K+1)+\frac{2}{R_2}\ K_1h_1(h_1+1)+K_2h_2(h_2+1))$	$2+(K+1)+\frac{2}{R_2}\ K_1h_1(h_1+1)+K_2h_2(h_2+1))$
G(5)	$2+(\frac{4}{R_2+R_3})\ K_2h_2(h_2+1)$	$(\frac{4}{R_2+R_3})\ K_2h_2(h_2+1)$	$(\frac{4}{R_2+R_3})K_2h_2(h_2+1)$

To take into account the presence of these constraints, the penalty-function[9,10] is introduced, where the constrained function (i.e. $\min_x f(\bar{x})$, such that $g_i(\bar{x})=0, i=1,2,\ldots r$) is converted into the new unconstrained function $P(\bar{x};k_i)$ where $P(\bar{x};k_i) = f(\bar{x}) + \sum_{i=1}^{r} k_i \; g_i(\bar{x})^2$ ....(5.1)

Here, k_i is the penalty-function multiplier, which is arbitrary, but a very important real positive constant.

The dimension of $f(\bar{x})$ is m, but that of $P(\bar{x};k_i)$ is n ; $n>m$. So $\bar{x} = \left[x_1, x_2, \ldots x_n\right]^T$, for all the unconstrained objective functions $P(\bar{x};k_i)$ and for both algorithms.

5.3 The Optimal-Design Constraints

In order to maintain the specific parameters ω_o and Q_o within close limits of their desired values, constraint-functions g_1 and g_2, respectively, must be specified in the main programs. For example, the parameters ω_o and Q_o can retain their values, at 10 and 50 KHZ, respectively, within .1 percent accuracy. The parameter H_{BP} can also be assigned a value within a range of real positive values. For example, $0 < H_{BP} < 1$ where $H_{BP} = \frac{R_3}{R_2+R_3}$, and R_2 and R_3 take real positive values.

In order to achieve inequality condition in H_{BP}, two constraint-functions g_3 and g_4 should be specified, where $g_3 = H_{BP}$, when $H_{BP} > 0$, and $g_4 = H_{BP}$, when $H_{BP} < 1$. Note that H_{BP} is not allowed to take any of the two limit values in the inequality-constraints g_3 and g_4.

If it did, both values would violate the feasible region of values in the transfer function $T(s)$, which is a function of C_1, C_2, R_1, R_2, and R_3.

The equality $H_{BP} = \frac{R_3}{R_2+R_3}$ can be specified as another constraint-function, g_5, where $g_5 = H_{BP} - \frac{R_3}{R_2+R_3} = 0$.

The variables xi, $i=1,2,....5$, must be real positive $(o < xi < \epsilon)$, where "ϵ" is the maximum component-value achieved by solid-state techniques. Ten inequality-constraint functions g_6 through g_{15} are required for the five variables xi. Finally, the constraint-function g_{16} will determine the required case: $C_1 = C_2$. Here, $g_{16} = \frac{C_1}{C_2} - 1 = o$. A more careful observation, for this technical problem to be feasible, shows that constraints g_2 and g_5 are inter-dependent, thus, they cannot be satisfied independently, and hence simultaneously. In one case, H_{BP} is required to be constant. This can be achieved by letting $R_3 = KR_2$, where K is a constant. Constraints g_3, g_4 and g_5 can be eliminated, allowing constraint g_2 to be satisfied. Constraints g_6 through g_{15} can be eliminated, being redundant since all elements xi are real positive and bounded by upper and lower limits.

The remaining three constraint-functions are g_1, g_2, and g_{16} which will be called g_1, g_2 and g_3, respectively. Given the three specifications $\omega_o = \frac{1}{\sqrt{R_1R_2C_1C_2}}$, $Q_o = \frac{1}{R_2+R_3}\sqrt{\frac{C_1R_1R_2}{C_2}}$ and $C_1 = C_2$, the corresponding constraints are:

$$g_1 = \omega_o^2 \; R_1R_2C_1C_2 - 1 = 0 \qquad (5.2)$$

$$g_2 = Q_o^2 \; (R_2+R_3)^2 \frac{C_2}{C_1R_1R_2} - 1 = 0 \qquad (5.3a)$$

when R_2 is independent of R_3, or

$$g_2 = Q\sigma^2 (k+1)^2 \frac{C_2R_2}{C_1R_1} - 1 = 0 \quad (5.3b)$$

where, $R_3 = KR_2$ ......(5.3c)

$$g_3 = \frac{C_1}{C_2} - 1 = 0 \quad (5.4)$$

5.4 The Objective-Function Gradients

Quasi-Newton's and Fletcher-Powell's optimization algorithms compute the gradients $\nabla f(\bar{x})$ of the objective function $f(\bar{x})$ which are required in the respective recurrence formulae:

$$\bar{x}_{i+1} = \bar{x}_i - H^{-1}(\bar{x}_i)\, \nabla f(\bar{x}_i) \quad (5.5)$$

[9]

and $\bar{x}_{i+1} = \bar{x}_i - \lambda_n H_i \nabla f(\bar{x}_i)$ ......(5.6)

Here, λn is the step-size of the gradient change, during the "descent" from one iteration to the next, and H^{-1} and H_i are the inverse Hessian matrices of the objective function $f(\bar{x})$. Subscript "i" denotes the iteration number. In this study, given the above constraints, the objective function $f(\bar{x})$ is replaced by the new objective function $P(\bar{x}; K_i)$ that includes the penalty functin. Similarly $\nabla f(\bar{x})$ is replaced by $\nabla P(\bar{x}, K_i)$,

where: $P(\bar{x}; K_i) = f(\bar{x}) + \sum_{i=1}^{r} K_i f(\bar{x})^2$ ......(5.7)

$$\text{and} \quad \nabla P(\bar{x}; K_i) = \begin{bmatrix} \frac{\partial P}{\partial x_1} \\ \frac{\partial P}{\partial x_2} \\ \frac{\partial P}{\partial x_3} \\ \frac{\partial P}{\partial x_4} \\ \frac{\partial P}{\partial x_5} \end{bmatrix} = \begin{bmatrix} G(1) \\ G(2) \\ G(3) \\ G(4) \\ G(5) \end{bmatrix} \quad (5.8)$$

For local minimum, $\nabla P(\bar{x};K_i) = 0$ ....(5.9)

The computer-subroutines corresponding to the Quasi-Newton's and Fletcher-Powell's algorithms are "ZXMIN" and FMFM", respectively. Both subroutines ure the gradient-vector $\nabla P(\bar{x};Ki)$ For illustration purposes, the gradient vector of the objective function C_T in case 1a(Table - 4) is derived in Appendix D. The gradient-vectors of all cases in the Fletcher-Powell algorithm are presented in Table-8.

5.5 Determination of Ac and Ar

5.5.1 Thin-Film Components(11,12,13)

5.5.1.1 Capacitors

In the IC fabrication, the two basic types of capacitors are: "thin-film" and "junction" capacitors. Both types consist of two (or more) low-resistance layers of eletrodes; the bottom electrode is called "base electrode" and the top electrode is called "counterelectrode".

The plates (electrodes) of thin-film capacitors are formed by depositing a true metal (Al, Au and Ta), and the carrier-free region is formed by a dielectric material(S_iO , T_aO_5, and M_nO_2). A typical group of these metals and dielectrics is demonstrated in Table - 13.

In the case of "junction" capacitors, both plates are formed by diffused low-resistance layers of opposite dopant types, and the space-charge layer results from the depletion of charges at the pn-junction.

The capacitance is given by:

$$C = \frac{\epsilon_r \epsilon_o A}{d} \text{ Farads} \quad \text{......(5.10)}$$

The capacitance-desity is given by: $\frac{C}{A} = \frac{\epsilon_r \epsilon_o}{d}$ ....(5.11)

If Ac is the total thin-film area occupied by the total capacitance C_T , then, it can be shown that: $\frac{C_T}{Ac} = K$......(5.12)

where, $K = \frac{3}{2} \epsilon_o (\epsilon_r / V_{BK})$ ......(5.13)

It is estimated that $V_{BK} \approx \frac{2}{3} Va$, Eq. (5.12) can be written as:

$$Ac = \frac{1}{K} C_T = nA_i = nw^2 \quad \text{......(5.14)}$$

where the length "l" of the unit-square and the width "w" of the thin-film are equal (l = w) and n is the number of unit-squares required. From eq.(5.14), it can be seen that the total area Ac is directly related to the total capacitance C_T . Therefore, minimization of Ac implies corresponding reduction of C_T , since K is a constant multiplier.

Detailed analysis for calculating Ac is presented in Appendix E.

5.5.1.2 Resistors

Integrated resistors are of two types: "diffused" and "deposition" (thin-or thick-film) resistors.
Even though diffused resistors can be found simultaneously with transistors, diodes, and diffused capacitors, they exhibit large TCR and their range of resistor values is limited.

Thin-and thick-film resistors require additional steps of processing, but they offer much wider range of resistance, together with reduced TCR and narrower tolerances. Table - 14 identifies some thin-film materials suitable for integrated resistors. From Table-14 it is clear that tantalum is a preferred material.
In the integrated-circuit technology, a thin-film exhibits total resistance given by:

$$R_T = \frac{\rho[\text{ohm-cm}]}{d\,[\text{cm}]} \cdot \frac{l\,[\text{cm}]}{w\,[\text{cm}]} = \frac{\rho}{d} \cdot \frac{l}{w} \text{ ohms} \quad \text{......(5.15)}$$

The ratio($\frac{l}{w}$) is called "aspect ratio" and the ratio ($\frac{\rho}{d}$) is called "sheet resistance" Rs. When $l = w$, then eq. (5.15) becomes:

$$R_T = \frac{\rho}{d} = Rs \text{ ohms}/\square \quad \text{......(5.16)}$$

When $l = nw$, where n is an integer number,

$$R_T = n\frac{\rho}{d} = nRs \text{ ohms} \quad \text{......(5.17)}$$

The resistance-density is given by

From eq. (5.15) $\frac{R_T}{A_R} = \frac{Rs}{W^2}$ ......(5.18)

and $A_R = \frac{W^2}{Rs} \cdot R_T$, cm^2 ......(5.19)

Note that eq. (5.18) was derived by assuming:

$$nA_i = n\,(\,l \times w\,) = nw^2 \quad \text{......(5.20)}$$

Derivation of eq. (5.19) is presented in Appendix E.

From eq. (5.19 and (5.20), A_T can be minimized (i.e. the number of resistance squares can be reduced) by minimizing the total resistance R_T through minimization algorithms.

5.5.2 Range of the Passive Component Values

The range of resistance per substrate, using tantalum thin-film material, is limited at the high and low ends, the upper limit being 10,000Rs, where is in the range of 10 - 100 ohms/□. This limit is due to the maximum number of squares attained in a given resistor pattern, compatible with an acceptable yield in production. The lower limit is ½ Rs, due to the tolerance of the minimum film-square and the specific resistance (ρ)of the material.

Recently, tantalum thin-film resistor values are available in the range of 1 to 5 megohms per substrate. The range of capacitor values, available with TM capacitors, is determined at the upper-end by the acceptable yield, and at the low-end by the acceptable capacitor tolerances. It is not the number of capacitors, nor the value of any one capacitor, that is important, but rather the total capacitance per substrate, since a defect in the area of any one capacitor will cause a defective device.

The range of values of capacitors is 100pF to .08μ F for TM capacitors and 10pF to 5μ F for TMM capacitors.

Chapter Six

PROBLEM SOLVING WITH COMPUTER PROGRAMMING

6.1 Computer-Program Considerations

6.1.1 Minimization Programs

Computer programming is a powerful tool to handle the minimization problems in this study. It is time-effective for: solving the sets of simultaneous equations, manipulating matrices, and computing the feasible points of the "descending" path on which the "minimum" point is located.[14]

The amount of work involved in minimizing the given non-linear functions is dictated by the size of the variable-vector $\bar{x}_i$, the complexity of the functions in the minimization subroutines ZXMIN and FMFP, and the choice of the initial values $\bar{x}_0$, as well as the penalty-function coefficients K_i.

The accuracy of computations is determined by the number of decimal-point digits.

If the accuracy is not adequate, "round-off" errors will result. These errors, when compared with the magnitude of any of the variables, make it difficult for the algorithm to determine the next vector x_{i+1} in each iteration, because the least-significance decimal digits will be truncated, and the vector $\bar{x}_i$ will remain unchanged. Therefore, the algorithm will be "zig-zagging"(or oscillating) in a region far from the "feasible" region which contains the "minimum" point-vector $\bar{x}^*$.

Consequently, scaling of the variables (usually normalized to unity) before entering the subroutine ZXMIN or FMFP is a safe approach. In general, when correct input data are specified, fast computations will occur, which otherwise would be lengthy. The computer time must be taken into consideration when dealing with a complex problem. In view of the above considerations, fast convergence, and hence computer-time and costs, will be minimized, if proper algorithms are employed.

Since high accuracy of the final values of the constraints specified (ω_o , $Q_{O.}$, and H_{BP}) causes slower convergence, and adversely more computer time, compromize between high accuracy and expensive computer time must be accepted.

Finally, small step-size (high penalty-function multipliers) is a must, in order to achieve convergence along the descending path of the function to be minimized. This requirement will cause relatively slow convergence but will ensure satisfactory parameter-values. In order to minimize the volume of the output "printout" paper, a command is necessary to print only one in every desired number of iterations.

6.1.2 Amplitude and Phase Response Programs

The "optimized" filter components and parameters can be further used in a second class of programs, the "plot-programs", which depict, in tabular and graphic form, the amplitude and phase versus frequency responses.

These programs verify the fact that the minimization algorithms not only achieve minimization of the total capacitance and the total resistance of the filter, but also they preserve the amplitude and phase responses, as specified. In order to show the steep slope of the graphs around the center frequency, the plotted points in this region must be increased.

Chapter Seven

CONCLUSIONS AND COMMENTS

In this report, a new RC-active band-pass filter using unity-gain amplifiers has been proposed. The circuit has been shown to be stable and to possess low sensitivity properities. Initial design equations have also been given. Computer algorithms have been developed to yield a variety of design procedures yielding minimum total resistance or minimum total capacitance while meeting the required specifications.

Optimization procedure is also described that simultaneously minimizes the total resistance and the total capacitance in the circuit.

Assuming that all the necessary considerations have been taken into account, in applying computer programming to solve the minimization problems, together with proper input data, the expected program-results were retrieved in "hard copy" form and were properly tabulated.

The volume of computer-programs is divided into three major groups. Each group is also divided into four cases; each case is further divided into three sets of data on ω_0 and Q_0.

In the first group, the total capacitance is minimized, and in the second group, the total areas A_C, A_r, and $(2A_r+3A_c)$ are minimized, as they were described in sections 5.2 and 5.5 In the third group, the minimized passive components of group one and two, in addition to a group with general component values, are fed in the "plot" programs.

In the first group, the computer programs are summarized in Table - 4 (programs 1 through 12) and the other relevant data required for the programs are shown in Table - 5 and - 6. Table - 9 shows the original values of the components, as input, and the minimized values as output. Table - 11 shows the effect of the minimized components on H_{BP} .

The second group minimizes the area A_r or A_c which corresponds to the thin-film total areas occupied by the total resistance and by the total capacitance, respectively, and their combined area $2A_r+3A_c$. Since the purpose of the problem in this report is to minimize the physical size of the passive components of the proposed RC-active filter, the above areas are minimized with the Fletcher-Powell's algorithm. This algorithm is more effective than the Quasi-Newton's algorithm.(9) The solutions of the above minimization problems are obtained by executing several programs divided in 12 cases, each case being solved for 3 sets of values in f_o and Q_o . There are 36 programs (program no. 13 through 48), per Table - 4, and the relevant data required for the programs are shown in Table - 7 and - 8. Table - 10 shows the input original values and the output minimized values of the passive components. Table - 12 shows the effect of the optimized passive elements on the insertion loss (H_{BP}) of the transfer function.

The third group of 57 programs plots the magnitude and phase responses of the proposed filter versus frequency divided into three subgroups, per Table - 4. The first subgroup, consisting of nine programs (program no. 49 through 57) utilizes either one of the OA mode (unity-or non-unity amplifier and the condition of the OA (ideal or practical OA).

The second subgroup, consisting of 12 programs (program no. 58 through 69), per Table - 4, uses the optimal results of the Quasi-Newton's algorithm, with unity-gain, amplifiers (non-ideal OAs).

The third subgroup consists of 36 programs (program no. 70 through 105), per Table - 4, that utilizes the Flethcer-Powell's optimal results, with unity-gain amplifiers (non-ideal OAs).

The summary results of both minimization algorithms, extracted from the "computer-printouts", are shown in Table-9 and - 10 which demonstrate and verify the expected minimized total capacitance and total areas (A_C and A_R) of both algorithms. Table - 11 and - 12 show the percentage-reduction of the objective functions and its effects over the filter insertion loss (H_{BP}).

Due to the excessive volume of the computer-program package, only sample-printouts with corresponding sample flow-charts are presented in this report, Appendix F.

Study of Table - 9 and - 10 shows the original and the final values of the passive elements of the filter. Indeed, the total capacitance, total resistance, and the corresponding thin-film areas are reduced. Furthermore, these values satisfy the desired values of the parameters f_o, Q_o and H_{BP} (i.e. H_{BP} can be specified as "fixed" at the beginning of the algorithm or it can be left floating).

An important feature of the minimization algorithms is that not only do they minimize the passive element values, but also, they solve the filter-design equations for the required component value, simultaneously. In the conventional case, for example, given five elements to determine their values, and three known parameters (i.e. ω_o, Q_o, and H_{BP}), at least two element values have to be specified, before any computation. In the minimization case, however, there is no need for arbitrary element-values; all five elements can be floating. The element-values are determined through the algorithm operations to determine the minimum point of the objective function, especially whenever the constraints are satisfied. As it was mentioned in previous chapters, the Flethcer-Powell's algorithm is faster than the Quasi-Newton's algorithm. Table - 11 and - 12 show the number of iterations in each algorithm, for the same minimization case. It can be seen that Fletcher-Powell's algorithm requires fewer iterations.

The speed of convergence depends not only on the penalty function multiplier, but also, on how close to the local minimum point the original point is located.

The percentage-reduction of the objective functions in both algorithms, shown in Table - 11 and - 12, shows that the more reduction attained the more insertion loss (i.e. the smaller H_{BP}) is allowed in the filter amplitude response, especially for low center-frequency. It is worth noticing that there is no difference in the amount of reduction produced when comparing both algorithms, assuming identical input data. The percentage reduction of an objective function, regardless of the algorithm, depends, mainly, on the starting point (i.e. how far it is from the final minimum point) of the convergence path and on the number of the constraints.

These constraints force the algorithm to follow a lesser steep path along the boundary of the constraint functions, so that the "forced" minimum point is higher than that achieved without constraint-functions. This argument can be verified by observing the difference in "minimum" points obtained between heavily constrained functions (i.e. in the case where $C_1 = C_2$, $H_{BP} = G = \frac{K}{K+1}$)and less constrained functions (i.e., in cases where C_1 , C_2 and H_{BP} are floating.)

Both algorithms, in their process to reduce C_T, R_T, A_c , and A_F show that, while C_T or A_c is reduced (i.e. C_1 and C_2 are minimized), the resistors R_1 through R_3 increase in a complex manner, dictated by different factors, such as location of the variable-descending point, constraints, etc. For example, when the constraint-function that is determined by the specification $\omega_o^2 = \frac{1}{(C_1R_1)(C_2R_2)}$ is forced to be kept constant, along the iteration process, the resistors R_1 and R_2 have to increase disproportionally, while C_1 and C_2 decrease, which is the case of minimizing C_T or A_C. The reverse process takes place when R_T or A_r is minimized. These arguments can be verified by observing the results in Table - 9

The above observations explain the reason why the objective function (3Ac + 2Ar) is very "shallow", in the sense that its gradient-slopes are not steep and the final (minimum) point is not far from the initial point. This can be considered as a "conflict" between two senses of optimization; the capacitor decreases while the resistor increases, the net effect being a small decrease (if not at all). Table - 4, and Table - 12 (program no. 37 through 48) verify these arguments.

In both minimization algorithms, the computer-programs have a "stopping" command which is used whenever any of the five variables reaches its design-limit, imposed by the manufacturers, regardless of whether the minimum point was reached.

Finally, the plots of the amplitude and phase responses show that this filter configuration is feasible only with unity-gain amplifiers. Comparison of the amplitude and phase responses, where non-optimal versus optimal components were used, shows that they are identical, for the same values of the parameters ω_o, Q_o and H_{∞}.

This, once again, proves that the transfer-function is independent of the minimization process, provided that the parameters ω_o, Q_0 and H_{BP} remain unchanged.

Fig 6.1 and 6.2 show the amplitude and phase responses of the Band-Pass Filter configured with unity-gain amplifiers. The three graphs verify the dependence of the insertion loss on H_{BP} and the shape (or bandwidth) on Qo of its transfer function.

The transfer function of the present filter is unaffected by the non-idealness of the unity-gain model of OAs, provided that fo is significantly smaller than B, as it is demonstrated in fig. 6.3, 6.4, 6.5 and 6.6.

When the d.c. gain of the amplifiers is non-unity ($K_{1,2} \neq 1$) the transfer function is non-feasible, as it can be seen from the amplitude and phase responses, fig 6.7, 6.8, and 6.9.

Provided that the unity-gain model of the OAs is employed, the amplitude and phase responses of the transfer function, using "optimized" passive components (from Newton's and Fletcher-Powell's minimization algorithms) are identical to those using non-optimal passive components, fig 6.10 to 6.18.

TABLE - 9 OPTIMIZED COMPONENT VALUES USING NEWTON'S METHOD

Program No	ORIGINAL VALUES						FINAL VALUES					
	R_1 (MΩ)	R_2 (KΩ)	R_3 (KΩ)	C_1 (nF)	C_2 (nF)	C_T (nF)	R_1 (MΩ)	R_2 (KΩ)	R_3 (KΩ)	C_1 (nF)	C_2 (nF)	C_T (nF)
1	0.1	1	1	318.31	3.1831	321.493	4.90394	4.85175	.335591	3.22246	.132088	3.35454
2	0.1	1	1	63.662	15.9155	79.5775	4.86053	5.01807	2.81786	.617958	.671953	1.2899
3	0.1	1	1	31.831	7.95775	39.7887	4.86053	5.01807	2.81786	.308979	.335976	.644955
4	0.1	0.1	0.1	318.31	31.831	350.141	4.90095	.727451	.466471	5.3302	5.33068	10.6609
5	1	0.1	1	35.0141	28.9373	63.9514	4.8242	.226882	3.08095	9.61617	9.61678	19.233
6	1	0.1	1	17.507	14.4686	31.9757	4.8242	.226882	3.08095	4.80809	4.80839	9.61648
7	1	1	3	63.662	1.59155	65.253	5.0119	1.51847	4.5554	12.6962	1.04808	13.7443
8	1	1	3	12.7324	7.95775	20.6901	4.9404	1.54738	4.64214	2.57677	5.14263	7.7194
9	1	1	3	6.3662	3.97887	10.3457	5.00159	1.49508	4.48747	1.27245	2.65987	3.93232
10	1	1	3	636.62	1.59155	638.211	4.92382	0.12312	0.369359	12.9267	12.9269	25.8535
11	0.1	1	3	127.324	7.95775	135.282	4.98984	3.11848	9.35543	2.55161	2.55164	5.10325
12	0.1	1	3	63.662	3.97887	67.6409	4.93091	3.08182	9.24545	1.29106	1.29107	2.58213

TABLE -10 OPTIMIZED COMPONENT VALUES USING FLETCHER'S METHOD

Program No	ORIGINAL VALUES						FINAL VALUES					
	R_1 (MΩ)	R_2 (KΩ)	R_3 (KΩ)	C_1 (nF)	C_2 (nF)	*A(cm²)	R_1 (MΩ)	R_2 (KΩ)	R_3 (KΩ)	C_1 (nF)	C_2 (nF)	*A(cm²)
13	1	1	1	31.831	3.1831	.26376	4.9385	5.1082	4.5252	6.0727	.66043	.50572
14	1	1	1	6.3662	15.915	.16785	4.8755	4.9933	4.4037	1.2287	3.3848	.034754
15	1	1	1	3.1831	7.9577	.083924	4.8755	4.9933	4.4037	.61437	1.6924	.017377
16	1	1	1	31.831	3.1831	.26376	4.7135	1.5236	0.17375	3.7486	3.7378	.056345
17	1	1	1	6.3662	15.915	.16785	4.749	7.6806	1.1425	1.6677	1.6664	.025116
18	1	1	1	3.1831	7.9577	.083924	4.749	7.6806	1.1425	.83387	.83321	.012558
19	0.5	5	15	126.32	.31831	.96152	1.4833	1.5149	4.5447	42.84	.10491	.32350
20	0.5	5	15	35.465	1.5195	.20381	5.0347	5.1093	153.28	2.5274	.15571	.020212
21	0.5	5	15	12.732	.79577	.10191	3.7935	38.519	11.556	1.6767	.10324	.01348
22	0.05	100	300	1273.2	.15915	9.5925	5.2603	0.1311	0.39354	12.102	12.101	.18232
23	0.05	10	30	254.65	.79577	1.9242	5.0963	3.185	9.5551	2.4987	2.4984	.037643
24	0.05	10	30	127.32	.39789	.96212	5.0963	3.185	9.5551	1.2494	1.2494	0.01882

* A : AREA OF "AC" OR "AR" OR "3AC + 2AR" ASSOCIATED WITH THE EQUIVALENT PROGRAM

TABLE -10 CONTINUED

Program No	ORIGINAL VALUES						FINAL VALUES					
	R_1(MΩ)	R_2(KΩ)	R_3(KΩ)	C_1(nF)	C_2(nF)	A(cm²)	R_1(MΩ)	R_2(KΩ)	R_3(KΩ)	C_1(nF)	C_2(nF)	A(cm²)
25	40	0.5	1	11.937	4.2441	2.0008	0.30999	0.073388	0.038723	78.447	56.737	0.15505
26	4	0.5	1	2.3873	2.1221	2.0008	0.96595	0.25055	0.017138	5.5087	75.304	0.485
27	4	0.5	1	1.1937	10.610	2.008	0.54588	0.13191	0.077223	4.6224	75.908	0.27306
28	1	1	10	175.07	0.57875	0.50550	206.6	0.079054	0.001773	78.702	78.702	.10334
29	0.5	0.5	1	19.099	21.221	0.25075	0.11656	0.13691	0.2623	79.790	79.799	0.058477
30	0.5	0.5	1	9.5493	10.610	0.25075	0.075362	0.053968	0.14772	78.909	78.895	.037782
31	4	1	3	15.915	1.5915	2.0022	0.83149	0.07806	0.23418	76.510	20.388	0.41590
32	4	1	3	3.183	7.9577	2.002	1.0056	0.10098	0.30294	12.615	78.907	0.50349
33	4	1	3	1.5195	3.9789	2.002	0.59478	0.050552	0.15166	10.674	78.814	0.29747
34	1	1	3	6.3662	1.5915	0.50200	0.81130	0.020282	0.060847	78.444	78.467	0.40569
35	1	1	3	12.732	7.9577	0.50200	0.16256	0.10159	0.30476	78.292	78.294	0.081483
36	1	1	3	6.3662	3.9789	0.50200	0.080437	0.050264	0.15079	79.155	79.15819	0.040319
37	4	1	10	43.768	0.57875	5.0132	4.0894	1.1359	7.5744	29.830	73.052	4.7887

TABLE -10 CONTINUED

Program No	ORIGINAL VALUES						FINAL VALUES					
	R_1(MΩ)	R_2(KΩ)	R_3(KΩ)	C_1(nF)	C_2(nF)	A(cm²)	R_1(MΩ)	R_2(KΩ)	R_3(KΩ)	C_1(nF)	C_2(nF)	A(cm²)
38	4	·1	10	8.7535	2.8937	4.2742	4.0894	1.1359	7.5744	5.9661	3.6526	4.3155
39	4	1	10	4.3768	1.4469	4.1426	4.0894	1.1359	7.5744	2.9830	1.8263	4.2068
40	10	0.01	0.1	175.07	57.875	6.2644	1.111	0.012345	0.061723	85.912	85.910	4.9941
41	10	0.01	0.1	35.014	289.37	8.3309	0.92695	0.010299	0.29862	102.93	102.95	5.5799
42	10	0.01	0.1	17.507	144.69	4.6655	0.92695	0.010299	0.29862	51.464	51.475	3.2336
43	1	1	3	63.662	1.5915	2.4787	1.2247	0.61236	1.8371	51.979	2.599	2.4606
44	1	1	3	12.732	7.9577	1.4716	1.2247	0.61236	1.8371	10.396	12.995	1.7588
45	1	1	3	6.3662	3.9789	1.2378	1.2247	0.61236	1.8371	5.1979	6.4974	1.4915
46	1	·1	3	6.3662	1.5915	2.4787	7.4764	0.18694	0.56083	8.5145	8.5133	7.862
47	1	1	3	12.732	7.9577	1.4716	1.0556	0.65974	1.9792	12.062	12.062	1.6034
48	1	1	3	6.3662	3.9789	1.2378	1.0556	0.65974	1.9792	6.0308	6.0309	1.3308

TABLE -11 MINIMIZATION EFFECTS ON FILTER INSERTION LOSS ($H_{vp} = \frac{R_3}{R_2 + R_3}$) NEWTON'S METHOD

Program No	Initial Values		Final Values		% of Capacitance Reduction	Number of Iterations	Minimum Obtained	Comments
	H_{vp}	Loss(dB)	H_{vp}	Loss(dB)				
1	0.500	6.02	$.686938 \times 10^{-2}$	43.2616	99	2380	NO	R_1 reached max. value
2	0.500	6.02	$.531685 \times 10^{-1}$	25.487	98	2200	NO	"
3	0.500	6.02	$.531685 \times 10^{-1}$	25.487	98	2200	NO	"
4	0.500	6.02	.390705	8.163	97	3120	NO	"
5	0.90907	0.828	.931411	0.617	70	830	NO	"
6	0.90907	0.828	.931411	0.617	70	830	NO	"
7	0.750	2.498	.75	2.498	79	1160	NO	"
8	0.750	2.498	.75	2.498	63	1120	NO	"
9	0.750	2.498	.75	2.498	62	1350	NO	"
10	0.750	2.498	.75	2.498	96	1080	NO	"
11	0.750	2.498	.75	2.498	96	3600	NO	"
12	0.750	2.498	.75	2.498	96	5000	NO	"

TABLE -12 MINIMIZATION EFFECTS ON FILTER INSERTION LOSS ($H_{\infty} = \frac{R_3}{R_2 + R_3}$) FLETCHER'S METHOD

Program No	Initial Values		Final Values		% of Area(A_c,A_r) Reduction	Number of Iterations	Minimum Obtained	Comments
	H_{∞}	Loss (dB)	H_{∞}	Loss (dB)				
13	0.500	6.028	0.469741	6.5636	81	454	NO	R_1 reached max. value
14	0.500	6.028	0.468630	6.583	79	494	NO	"
15	0.500	6.028	0.468630	6.583	79	494	NO	"
16	0.500	6.028	0.102366	19.79688	79	214	NO	"
17	0.500	6.028	0.598001	4.466	85	514	NO	"
18	0.500	6.028	0.598001	4.466	85	514	NO	"
19	0.75	6.028	0.75	2.498	66	274	NO	"
20	0.75	2.498	0.75	2.498	90	894	NO	"
21	0.75	2.498	0.75	2.498	87	734	NO	"
22	0.75	2.498	0.75	2.498	98	274	NO	"
23	0.75	2.498	0.75	2.498	98	634	NO	"
24	0.75	2.498	0.75	2.498	98	634	NO	"
25	0.6666	3.522	.3454	9.23355	92	674	NO	"

TABLE - 12 CONTINUED

Program No	Initial Values		Final Values		% of Area (A_c,Ar) Reduction	Number of Iterations	Minimum Obtained	Comments
	H_{sp}	Loss (dB)	H_{sp}	Loss (dB)				
26	0.6666	3.522	0.4062	7.8256	75	214	NO	C_2 reached its max. value
27	0.6666	3.522	0.36925	8.6536	86	394	NO	C_2 reached its max. value
28	0.9090	0.8278	0.02193	33.18	80	1574	NO	C_1 and C_2 reached their max. values
29	0.6666	3.522	0.65788	3.637	77	714	NO	" " "
30	0.6666	3.522	0.7324	2.7048	85	1354	NO	" " "
31	0.75	2.498	0.75	2.498	79	514	NO	C_1 reached its max. value
32	0.75	2.498	0.75	2.498	75	434	NO	C_2 reached its max. value
33	0.75	2.498	0.75	2.498	85	674	NO	C_2 reached its max. value
34	0.75	2.498	0.75	2.498	19	1234	NO	C_2 reached its max. value
35	0.75	2.498	0.75	2.498	84	1294	NO	C_1 and C_2 reached their max. values
36	0.75	2.498	0.75	2.498	92	1854	NO	" " "
37	0.909	0.8278	0.8695	1.213	4	185	YES	No component limits
38	0.909	0.8278	0.8695	1.213	1(increase)	185	YES	No component limits

TABLE - 12 CONTINUED

Program No	Initial Values		Final Values		% of Area (A_c,Ar) Reduction	Number of Iterations	Minimum Obtained	Comments
	R_{op}	Loss (dB)	R_{op}	Loss (dB)				
39	0.909	0.8278	0.8695	1.213	2 (increase)	182	YES	No component limit
40	0.909	0.8278	0.8333	1.583	20	295	YES	C_1 and C_2 reached their limits
41	0.909	0.8278	0.9666	0.2945	33	473	YES	" " "
42	0.909	0.8278	0.9666	0.2945	30	473	YES	" " "
43	0.75	2.498	0.75	2.498	1	501	YES	" " "
44	0.75	2.498	0.75	2.498	19 (increase)	501	YES	" " "
45	0.75	2.498	0.75	2.498	20 (increase)	501	YES	" " "
46	0.75	2.498	0.75	2.498	300 (increase)	1290	YES	" " "
47	0.75	2.498	0.75	2.498	9 (increase)	226	YES	" " "
48	0.75	2,498	0.75	2.498	7 (increase)	226	YES	" " "

Table 13 - Process compatible with various types of thin-film materials

	DEPOSITION PROCESS	MATERIAL
METALS	Vacuum Evaporation Cathode Sputtering Vapor Plating	Nichrome, aluminum chromium, gold, nickel Tantalum Copper, gold, nickel tin, oxide
DIELECTRICS	Vacuum Evaporation Anodization Vapor Plating	Silicon monoxide silicon dioxide Tantalum oxide Silica, alumina, glass

Table 14 - Characteristics of some important thin-film materials for resistors

MATERIALS	SUITABLE PROCESS	ohms/sq. range	TEMPERATURE COEFFIC	CHARACTERISTICS
Nickel-chromium (Nichrome)	Vacuum Evaporation	50-400	$\pm$ 50-100	Good temperature coefficient, good adhesion
Tin-Oxide	Vapor-plating	100-5000	$\pm$ 100-300	High sheet resistance, good adhesion.
Tantalum	Sputtering	50-500	+ 100-200	Good process control and temperature coefficient, good adhesion, high stability
Cermets	Silk Screen	10-100000	$\pm$ 100-300	Wide range of resistivity process not suitable for close tolerances

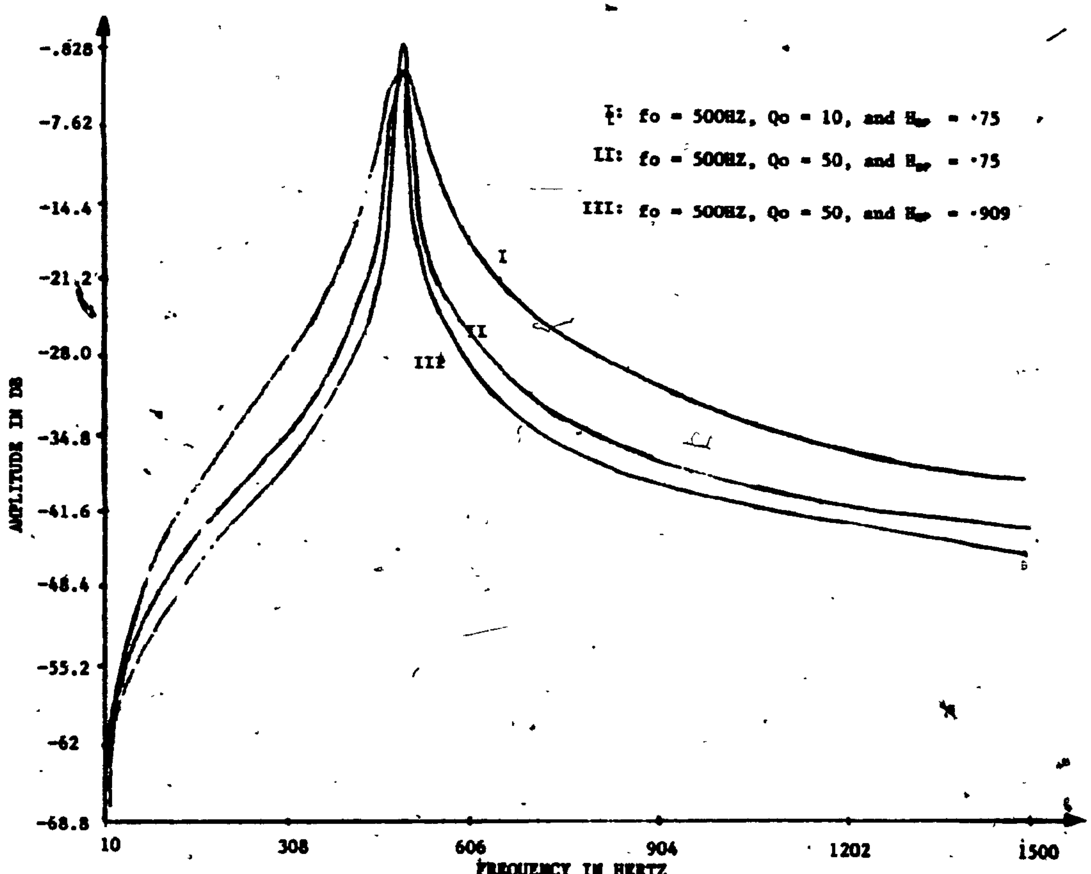


Fig. 6.1 - Amplitude v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and general component values.

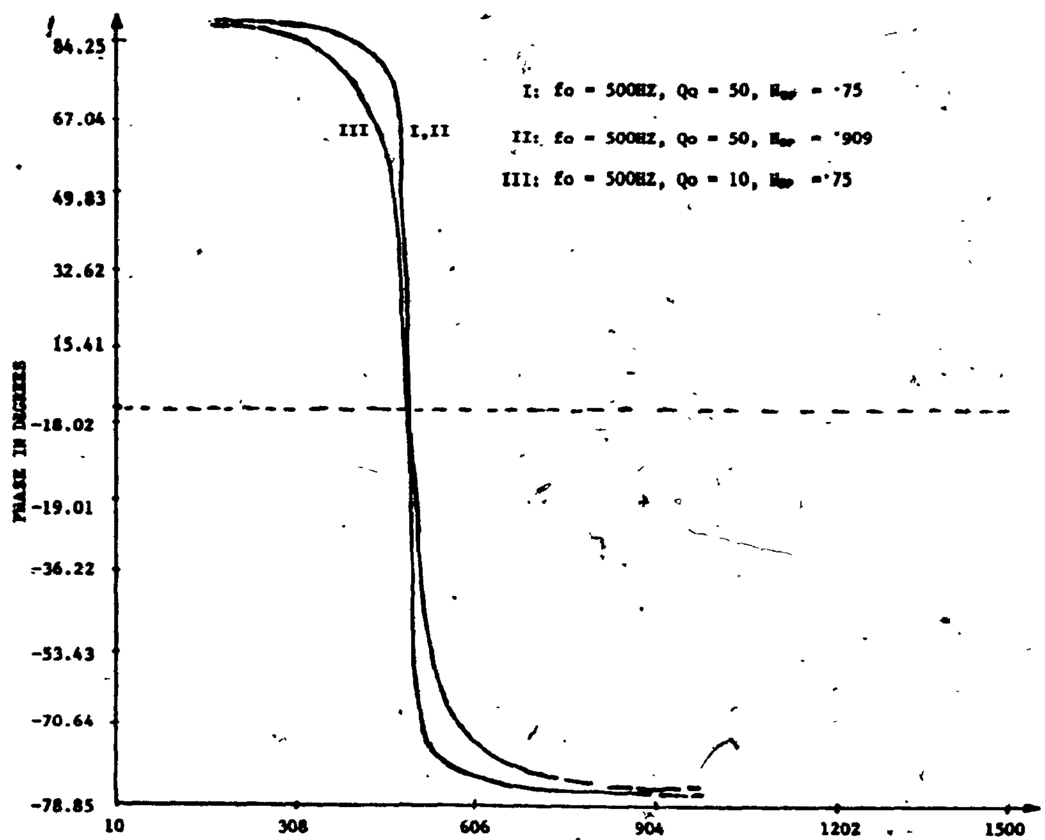


Fig. 6.2 - Phase v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and general component values.

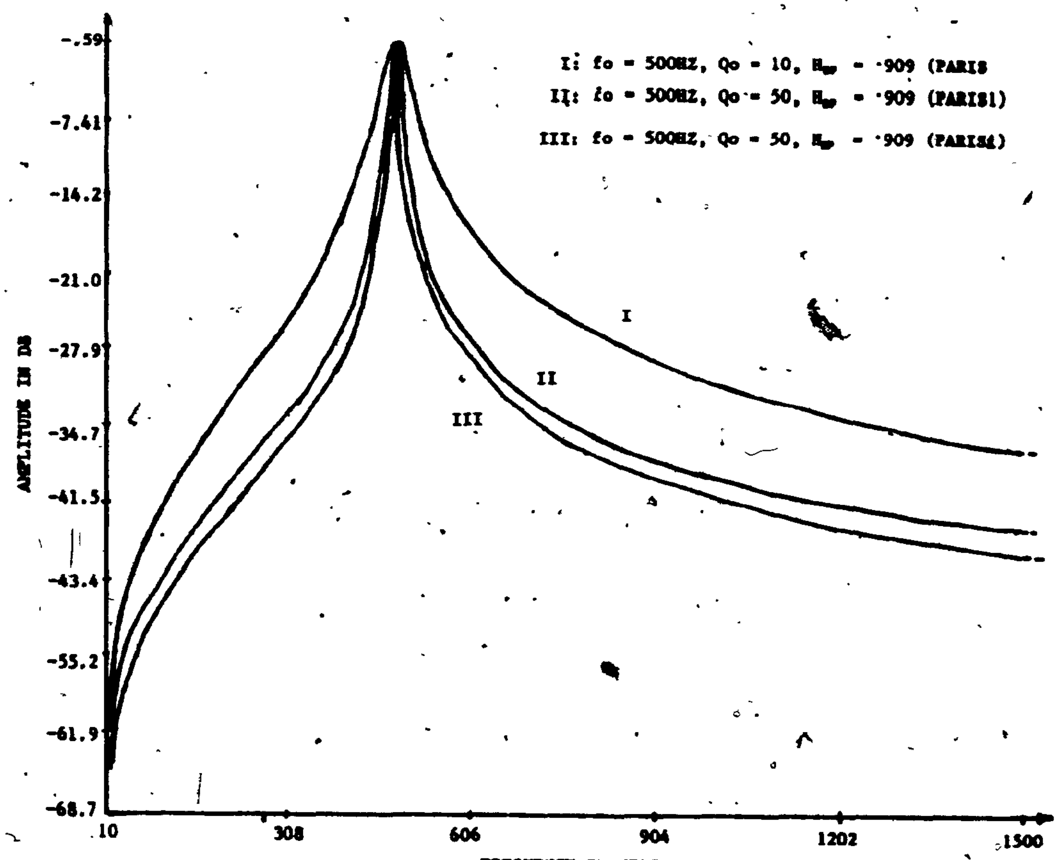


Fig. 6.3 - Amplitude v.s. frequency response of the RC-active filter assuming non-ideal OAs in unity-gain mode and general component values.

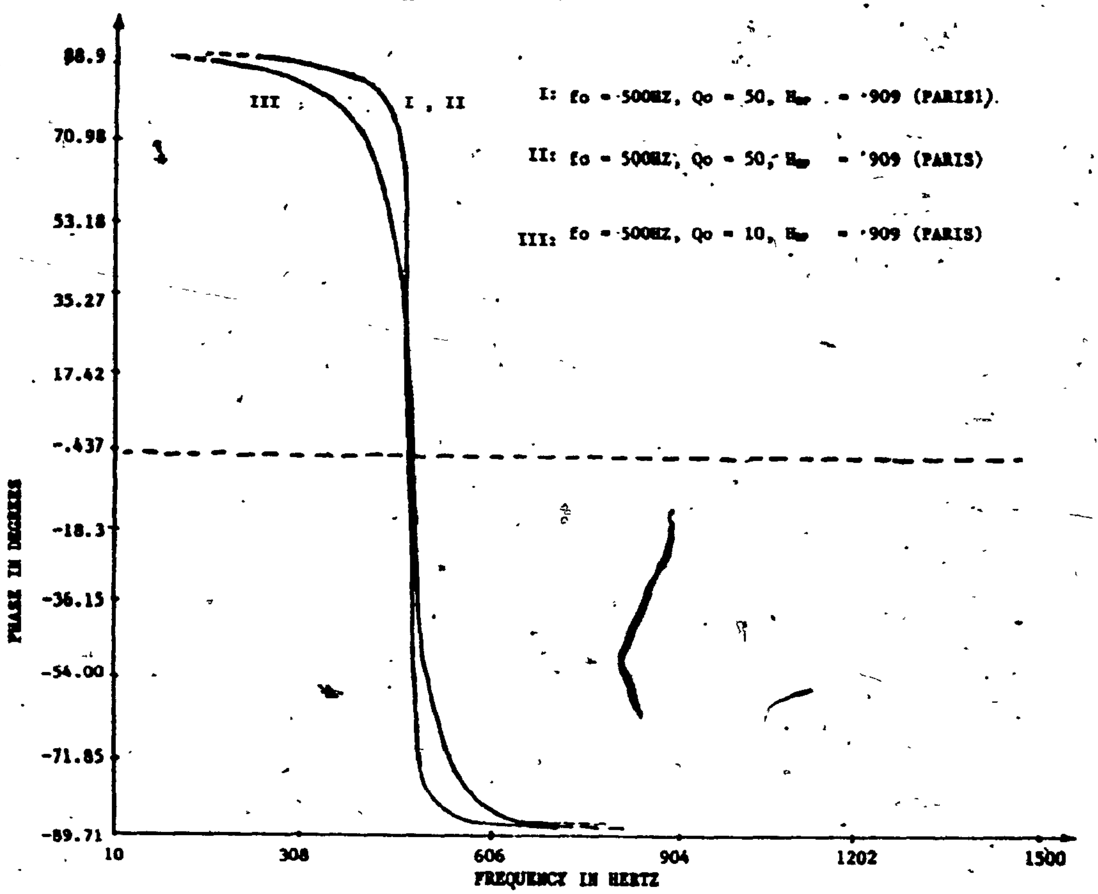


Fig. 6.4 - Phase v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in unity-gain mode and general component values.

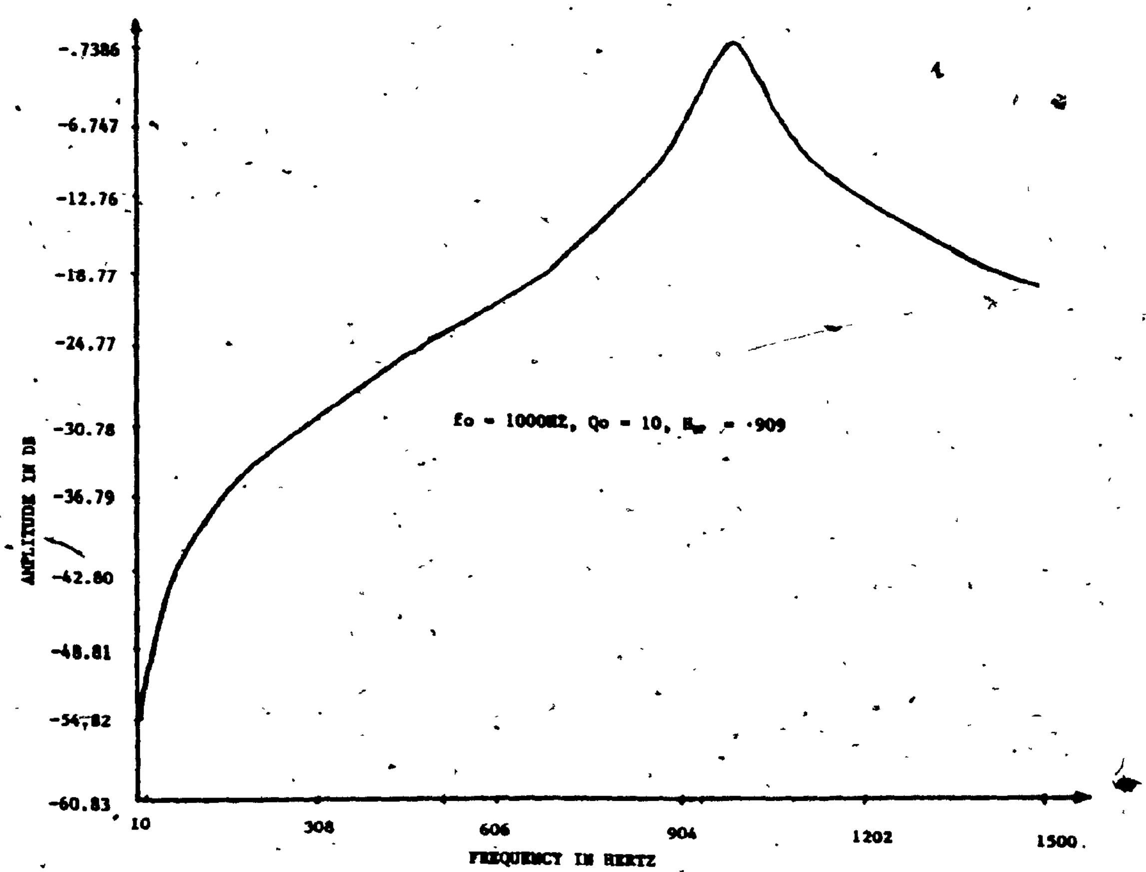


Fig. 6.5 - Amplitude v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in unity-gain mode and general component values.

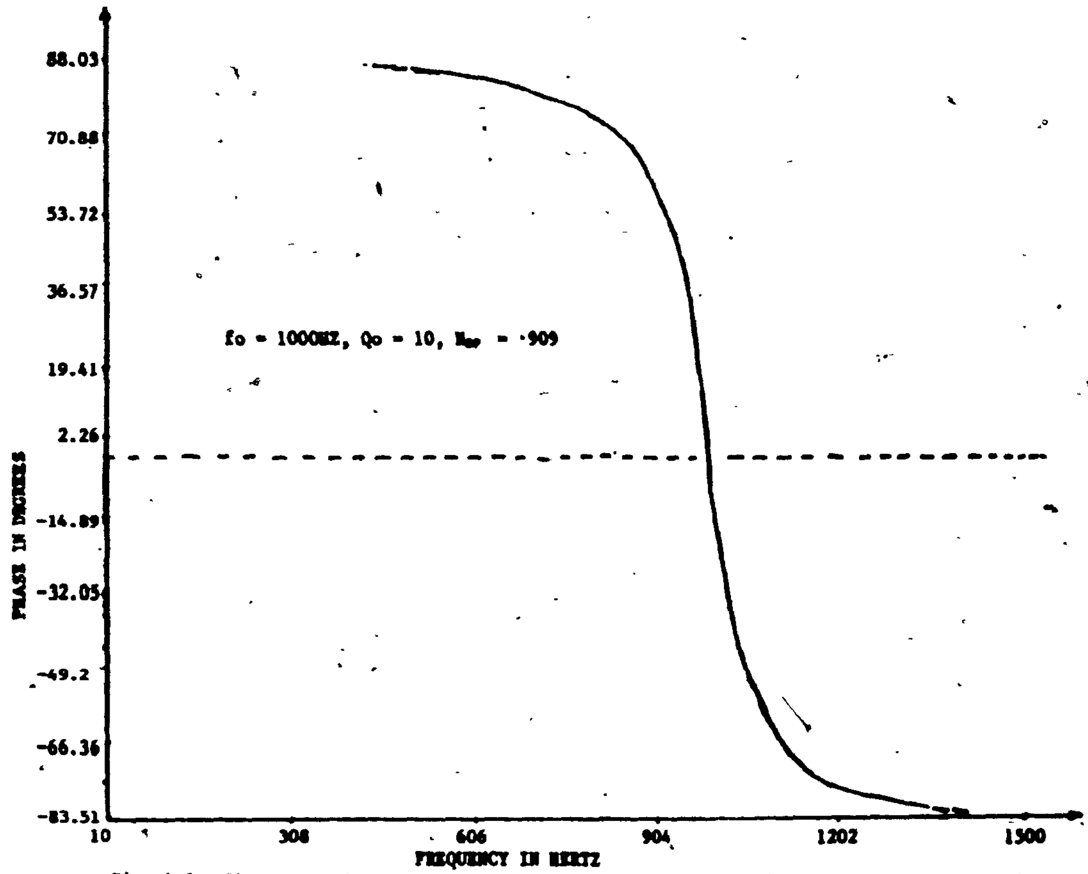


Fig. 6.6 - Phase v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in unity-gain mode and general component values.

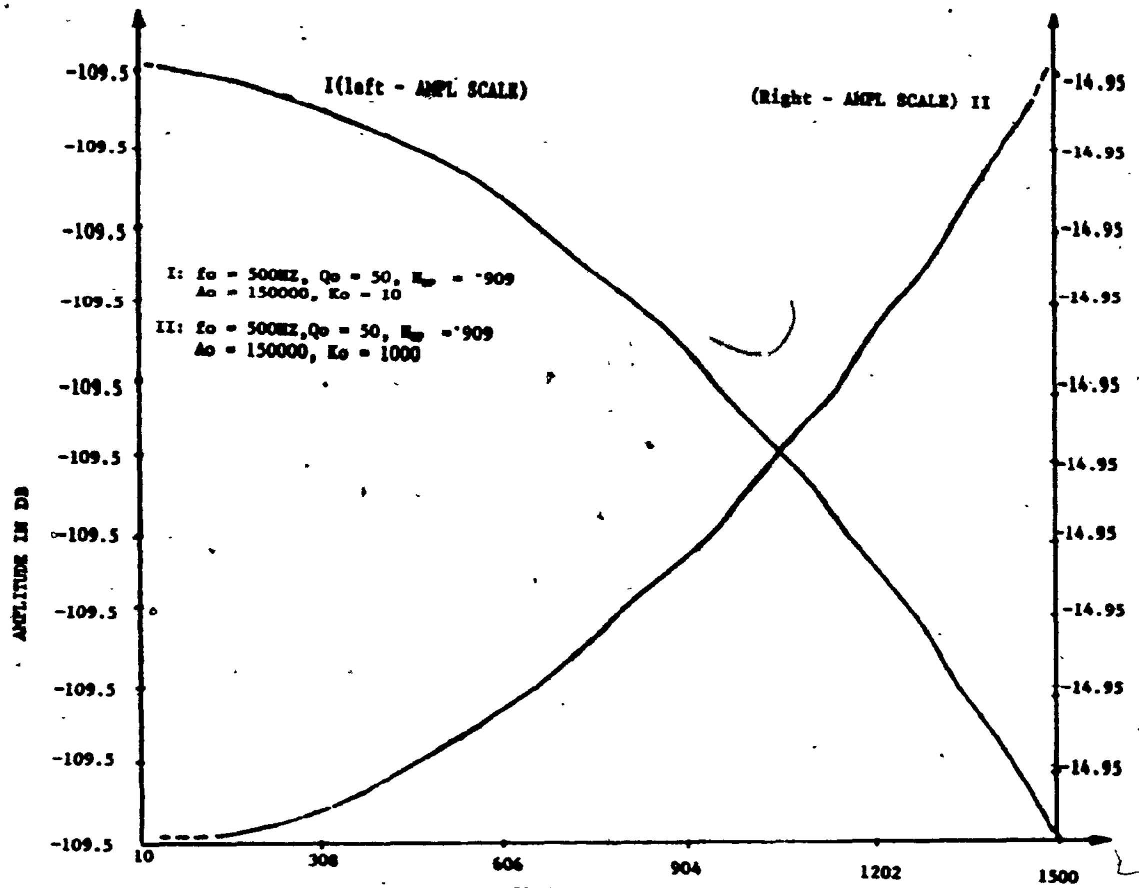


Fig. 6.7 - Amplitude v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in non-unity-gain mode and general component values.

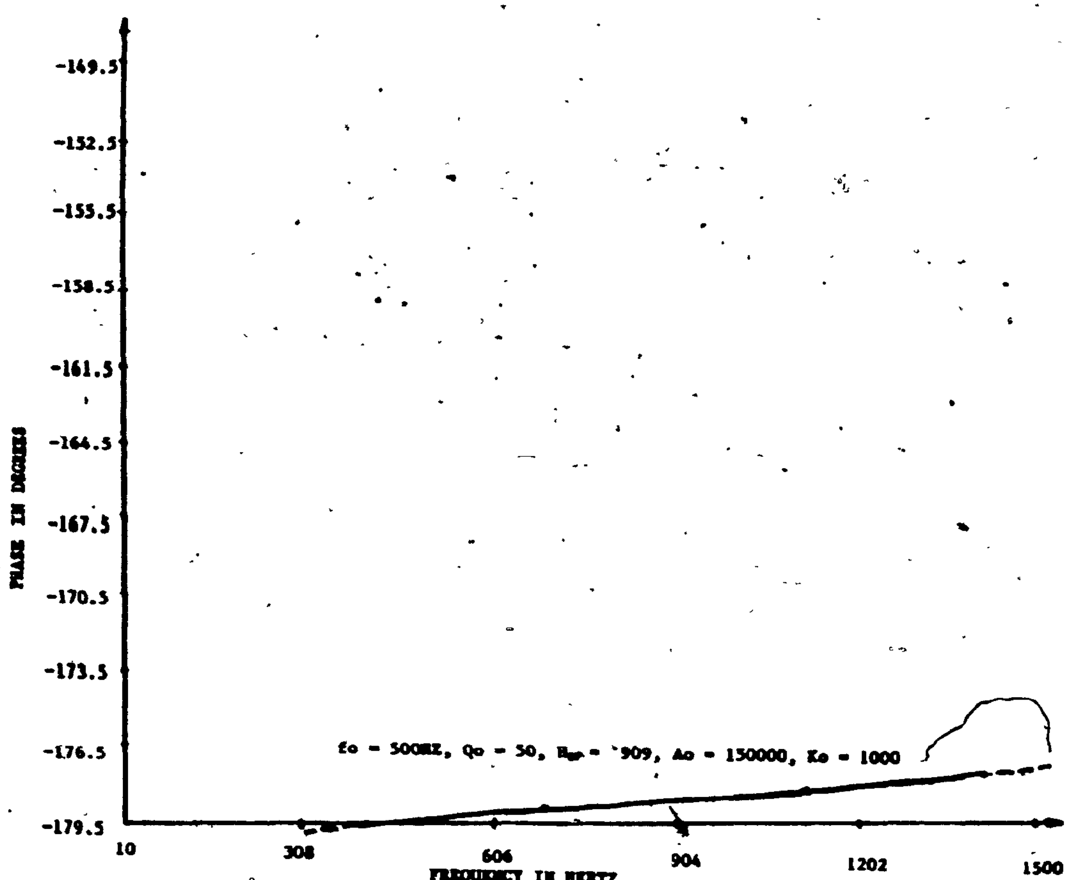


Fig. 6.8 – Phase v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in non-unity-gain mode and general component values.

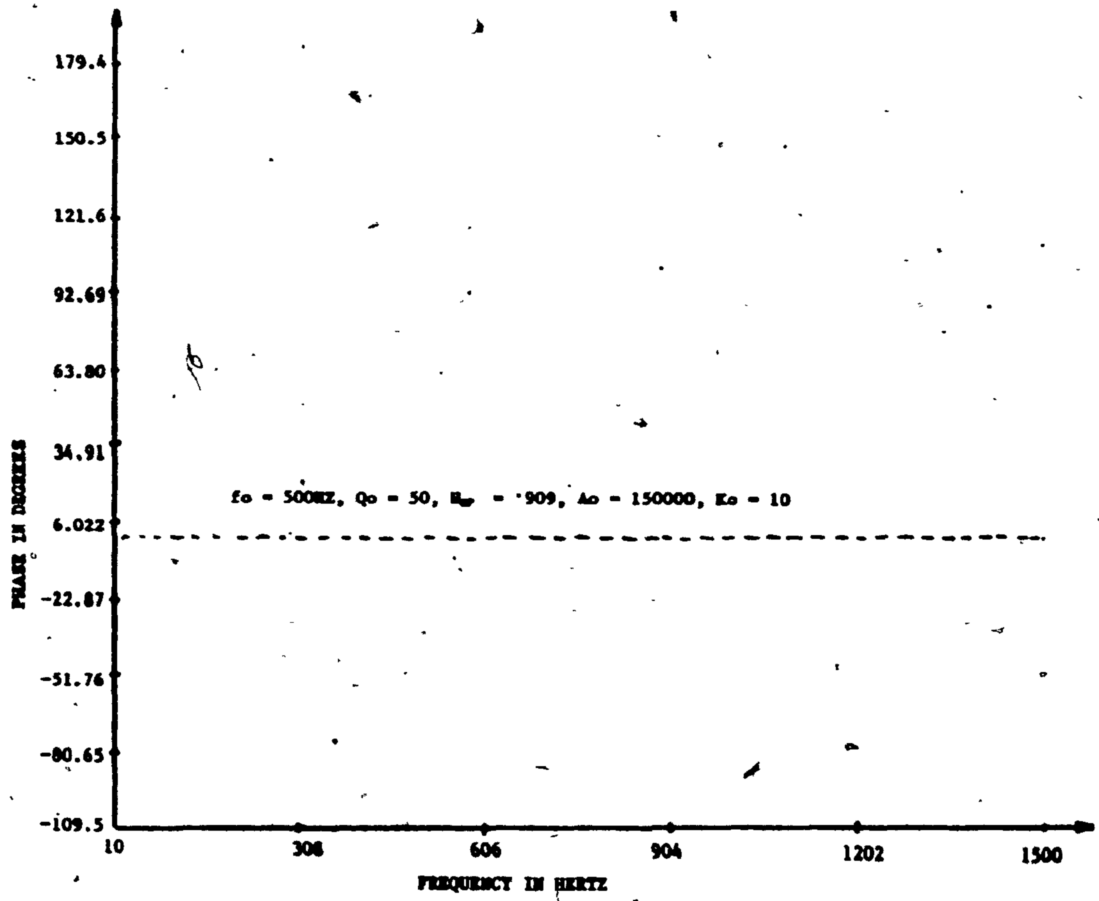


Fig. 6.9 - Phase v.s. frequency response of the proposed RC-active filter assuming non-ideal OAs in non-unity gain mode and general component values.

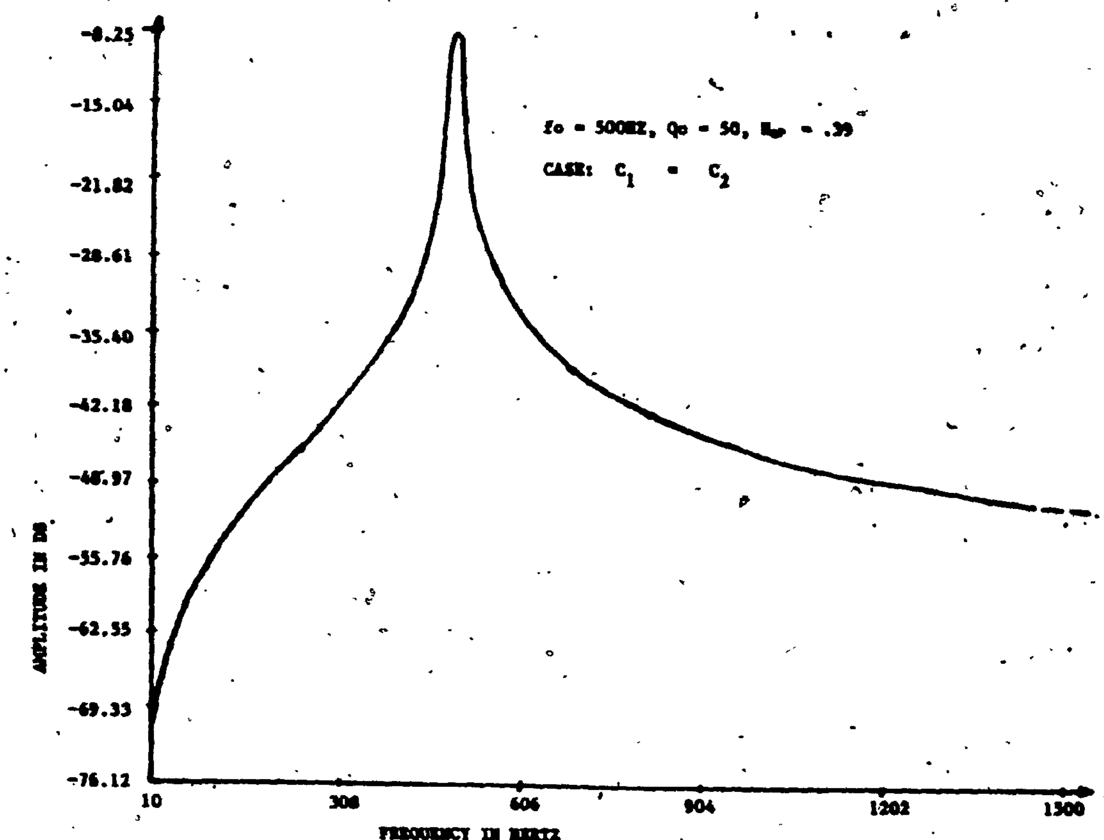


Fig. 6.10 - Amplitude v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Newton's minimization algorithm.

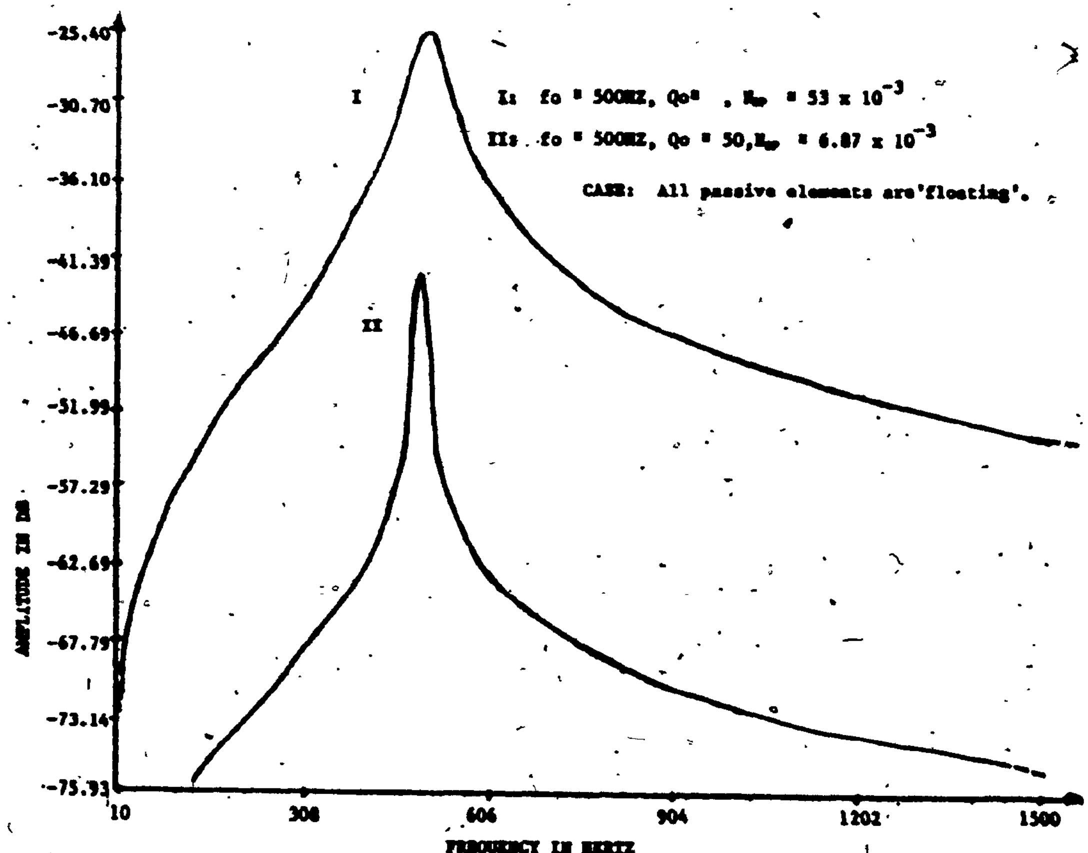


Fig. 6.11 - Amplitude v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Newton's minimization algorithm.

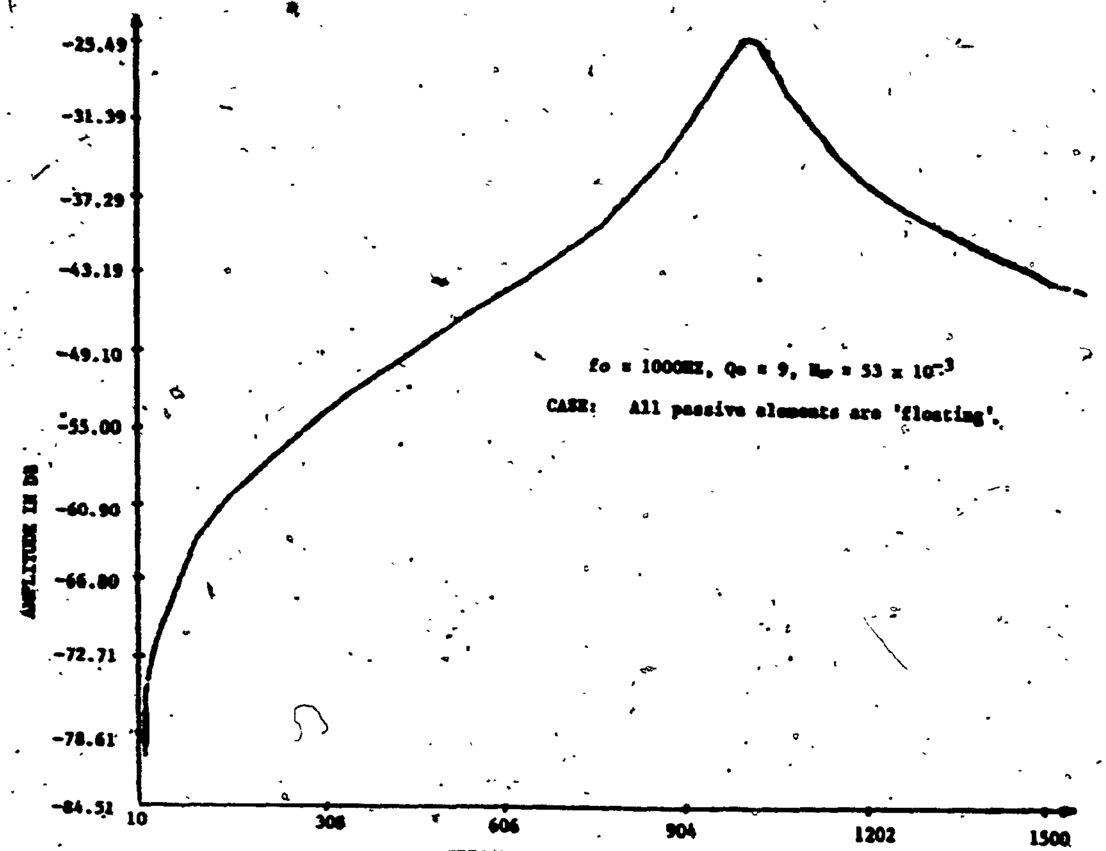


Fig. 6.12 - Amplitude v.s. frequency response of the proposed RC-acive filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Newton's minimization algorithm.

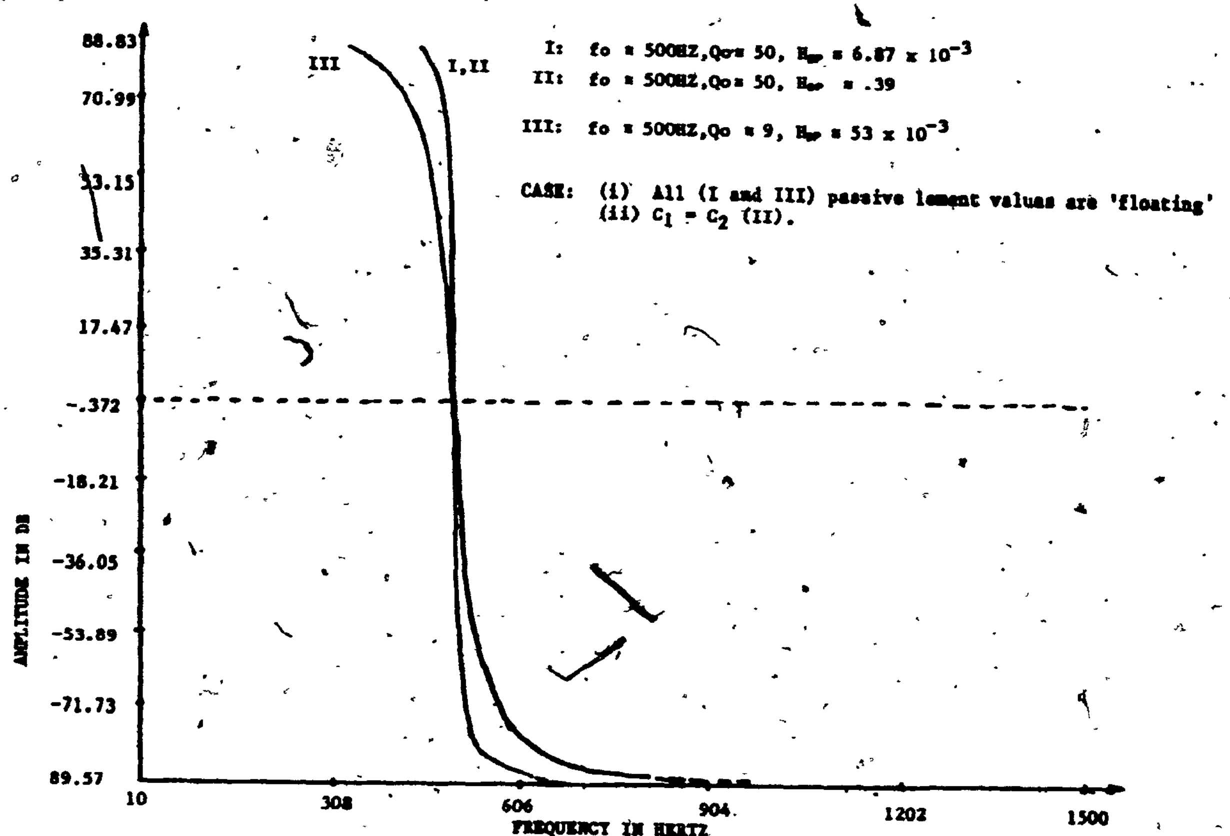


Fig. 6.13 - Phase v.s. frequency response of the proposed Rc-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Newton's optimization algorithm.

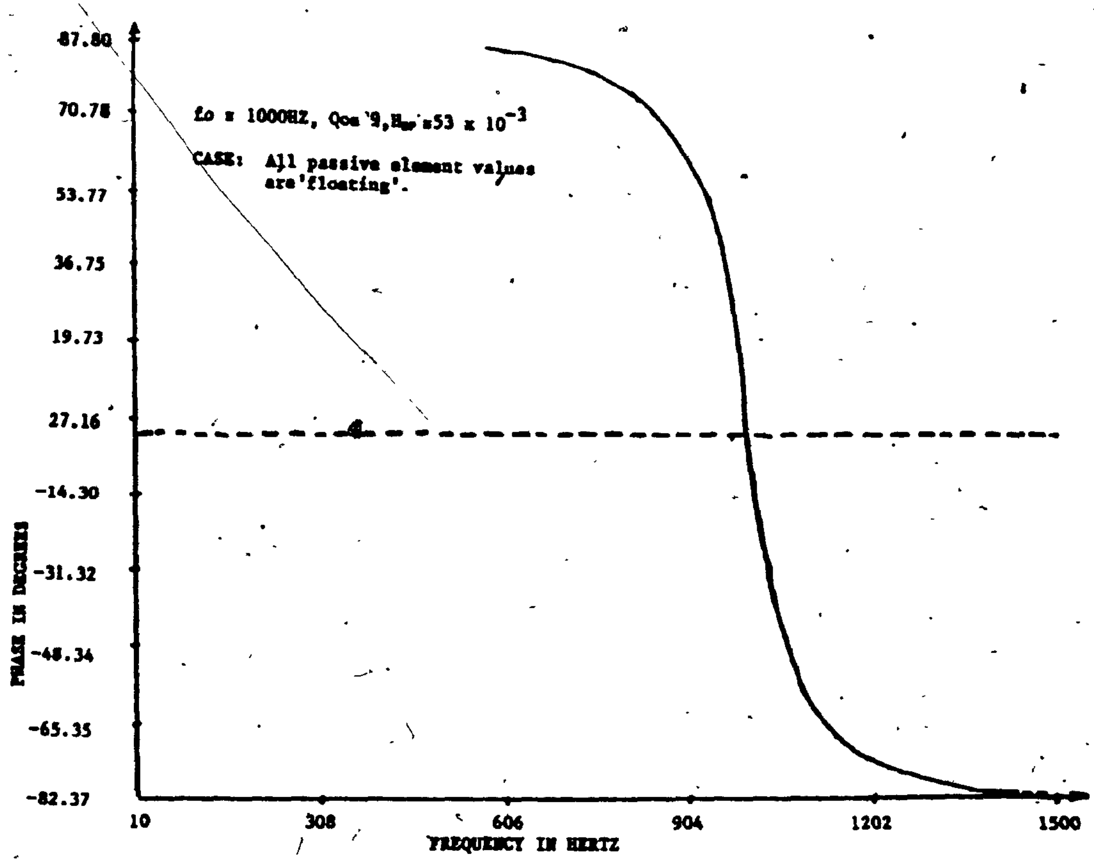


Fig. 6.14 - Phase v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Newton's minimization algorithm.

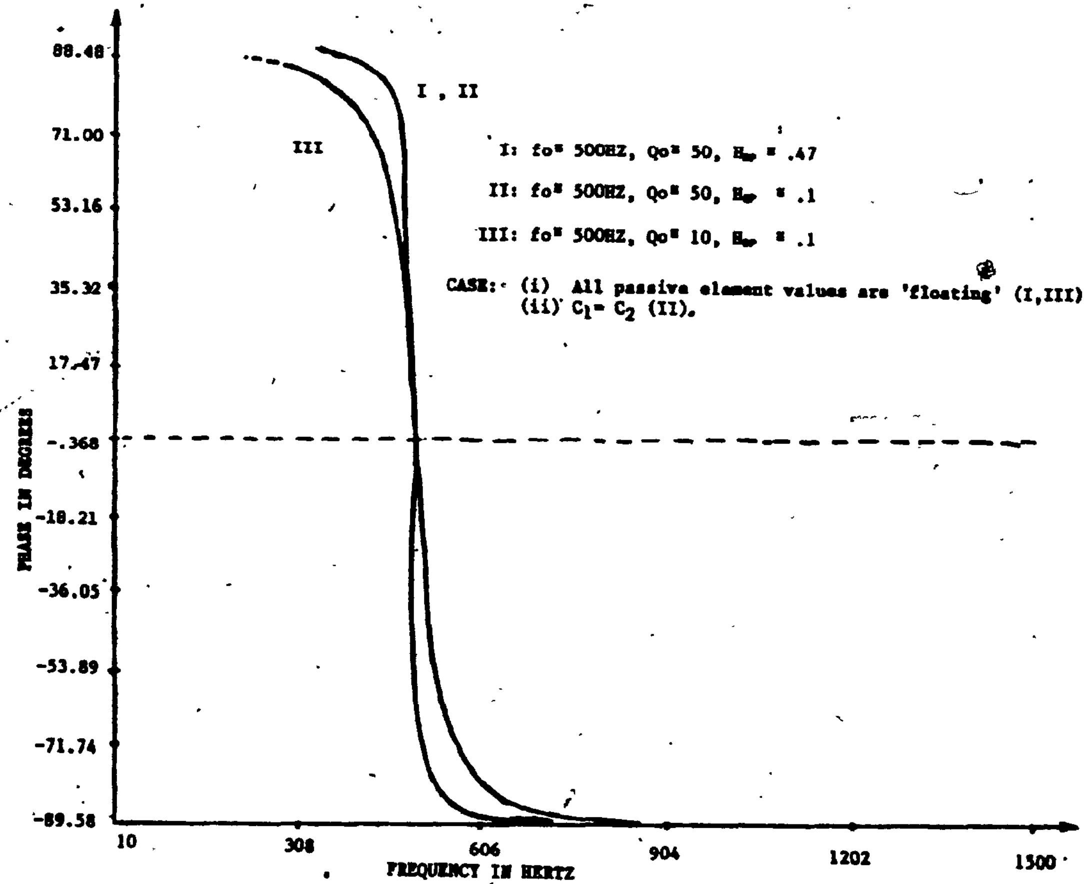


Fig. 6.15 - Phase v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Fletcher-Powell's optimization algorithm.

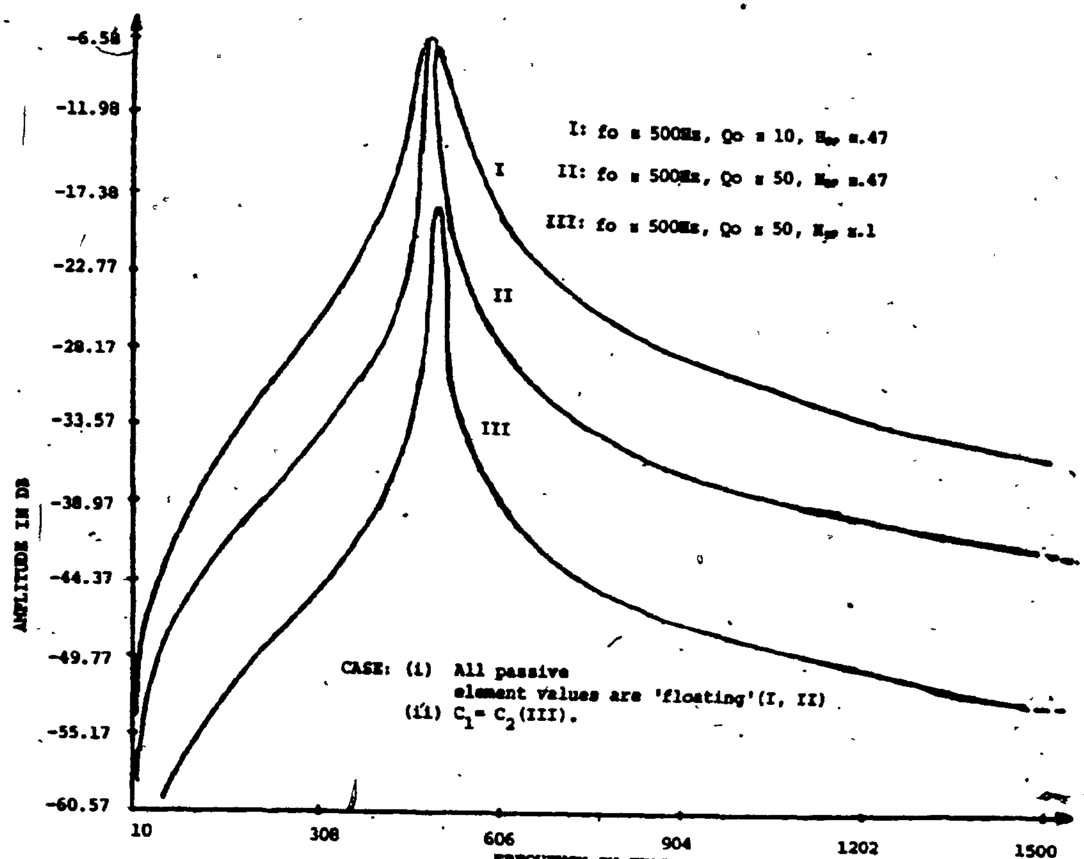


Fig. 6.16 - Amplitude v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Fletcher-Powell's optimization algorithm.

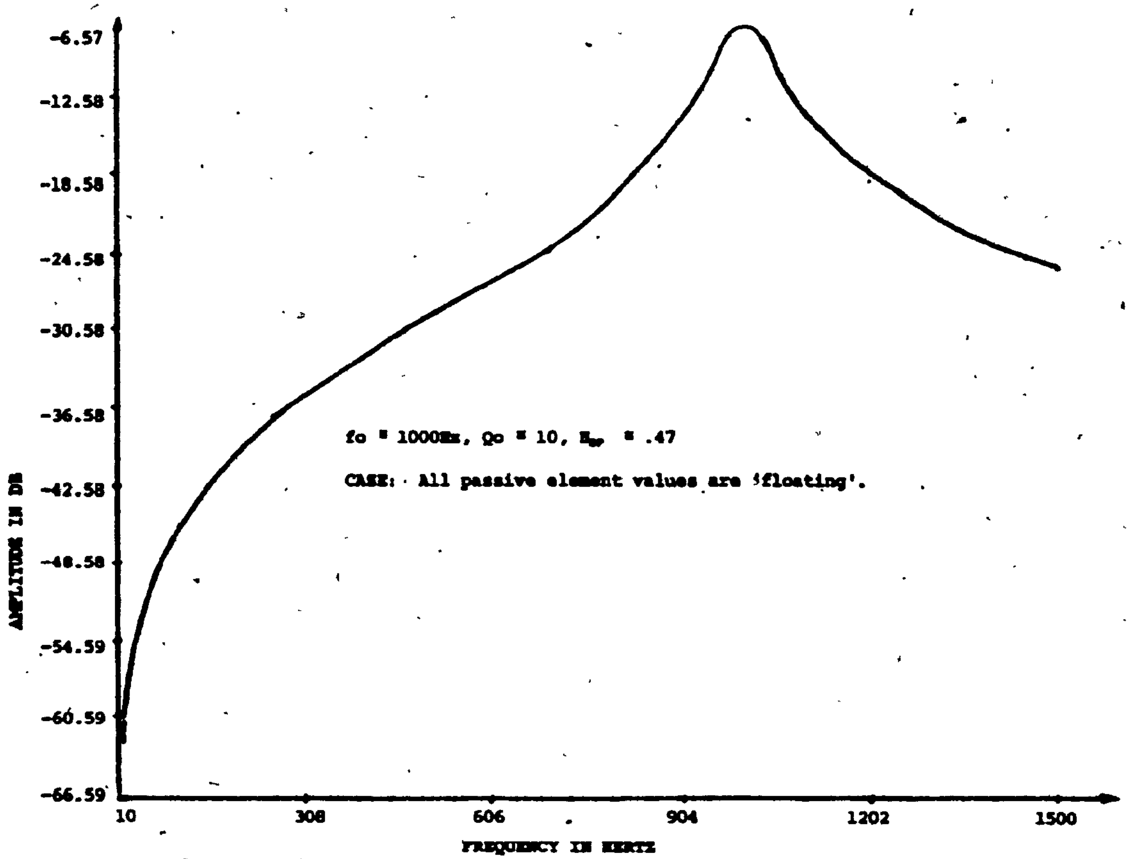


Fig. 6.17 - Amplitude v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Fletcher-Powell's minimization algorithm.

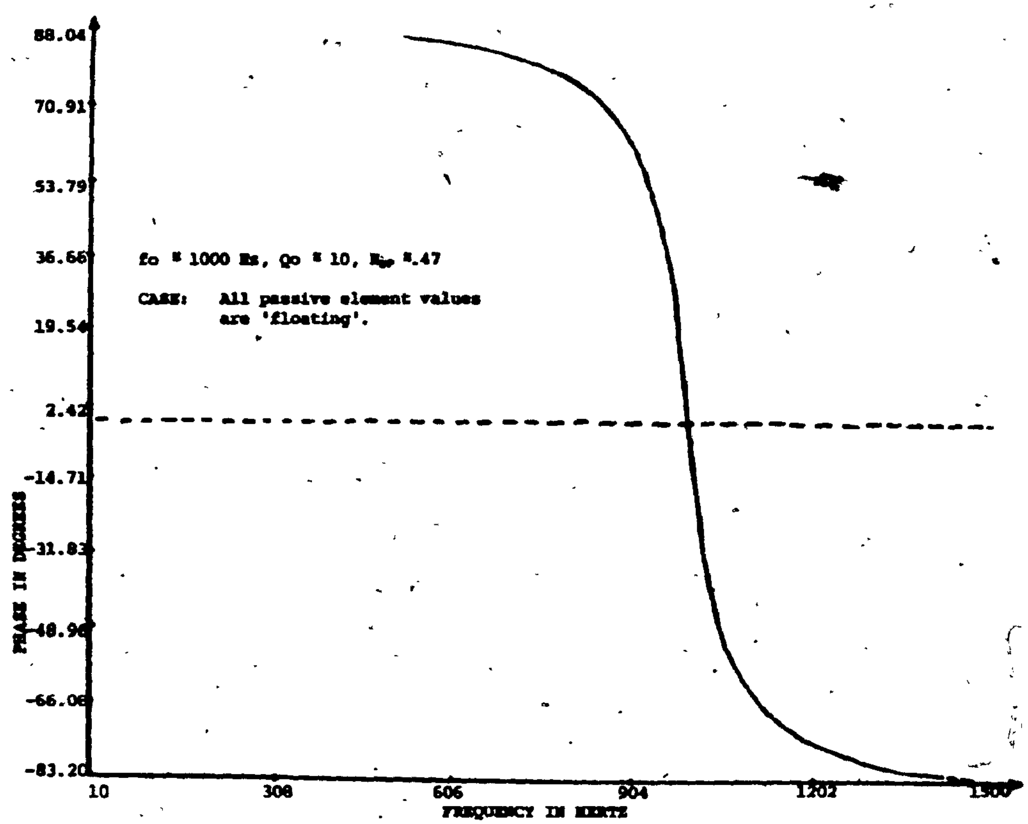


Figure 6.18 - Phase v.s. frequency response of the proposed RC-active filter assuming ideal OAs in unity-gain mode and 'optimized' passive element values using Fletcher-Powell's minimisation algorithm.

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APPENDIX A

DERIVATION OF THE TRANSFER FUNCTIONS OF EQUATION 3.2 AND 3.2

In this section, the voltage transfer functions of the proposed filter are derived. For convenience, the filter configuration of figure -3.3 will be repeated.

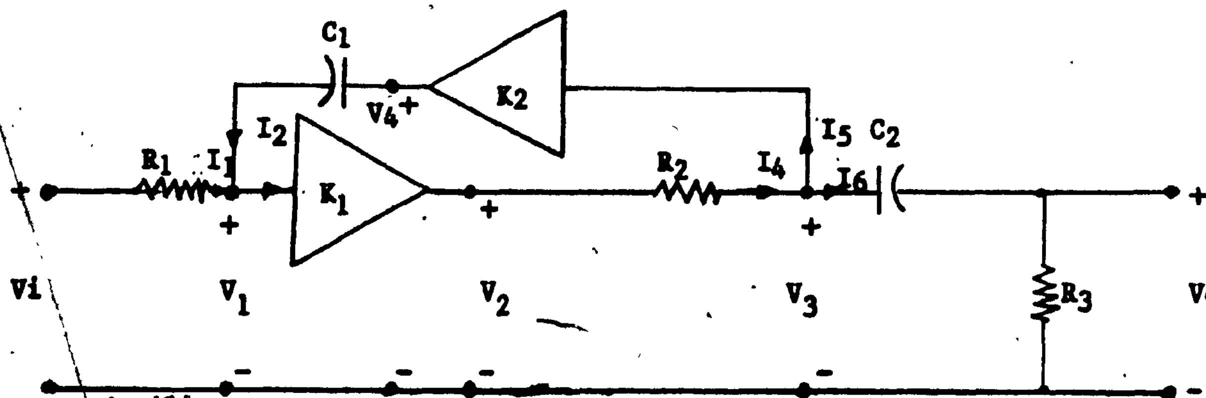


Figure A1- Band-Pass RC-active filter with OAs of non-unity-gain mode (Proposed filter, figure 3,3)

Observing the branch-voltages and branch-currents of figure A , the KCL and KVL analysis follows:

$I_3 = I_1 + I_2 = 0$ ....(A -1)

$I_1 = -I_2$ ....(A -2)

$$V_1 = \frac{V_2}{K_1} \quad \text{.......} (A_1-3)$$

$$V_4 = K_2V_3 \quad \text{.......} (A_1-4)$$

$$V_i = I_1R_1 + V_1 \quad \text{.......} (A_1-5)$$

Substituting eq. (A_1 -2) and eq. (A_1 -3) into eq. (A_1 -5), then

$$V_i = -I_2R_1 + \frac{V_2}{K_1} \quad \text{.......} (A_1-6)$$

$$I_2 = (V_4 - V_1)C_1S \quad \text{.......} (A_1-7)$$

Substituting eq. (A_1 -3) and (A_1-4) into eq. (A_1 -7), then

$$I_2 = K_2V_3C_1S - \frac{V_2}{K_1} C_1S \quad \text{.......} (A_1-8)$$

Substituting eq. (A_1 -7) into eq. (A_1-6), the latter becomes

$$V_i = -KV_3R_1C_1S + \frac{V_2}{K_1} R_1C_1S + \frac{V_2}{K_1} \quad \text{.......} (A_1-9)$$

Also, from the same configuration,

$$V_2 = I_4R_2 + V_3 \quad \text{.......} (A_1-10)$$

and $I_4 = I_5 + I_6 = I_6$ .... (A_1-11)

where $I_5 = 0$

Eq. (A_1-10) becomes $V_2 = I_6R_2 + V_3$ .... (A_1-12)

Also, by observing the filter configuration,

$$I_6 = (V_3 - V_0)\, C_2S \quad \text{.......} (A_1-13)$$

Substituting eq. (A_1-13) into eq. (A_1-12), then

$$V_2 = V_3\,(1 + R_2C_2S) - V_o R_2C_2S \quad \text{.......} (A_1-14)$$

Substituting eq. (A_1-14) into eq. (A_1 -9), the latter becomes:

$$V_i = V_3\left[\frac{1}{K_1}R_1C_1(R_2C_2s+1)s + \frac{1}{K_1}(R_2C_2s+1) - K_2R_1C_1s - \frac{V_o}{K_1}\left[R_1R_2C_1C_2s^2 + R_2C_2s\right]\right. \quad \text{..}(A_1-15)$$

By observation, $V_o = \dfrac{V_3R_3C_2s}{R_3C_2s+1}$ ....(A$_1$ -16)

From eq. (A_1-16), $V_3 = V_o \dfrac{(R_3C_2s+1)}{R_3C_2s}$......................(A$_1$ -17)

Substituting eq. (A_1-17) into eq. (A_1-15) and solving for $\dfrac{V_o}{V_i}$ after some calculations, then

$$\frac{V_o}{V_i} = \frac{\dfrac{K_1R_3}{R_1C_1\left[R_2+R_3(1-K_1K_2)\right]}s}{s^2 + \dfrac{R_1C_1+R_2C_2+R_3C_2-K_1K_2R_1C_1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]}s + \dfrac{1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]}} \quad \text{......}(A_1-18)$$

Letting $K_1 = K_2 = K$, then

$$\frac{V_o}{V_i} = \frac{\dfrac{K_1R_3}{R_1C_1\left[R_2+R_3(1-K^2)\right]}}{s^2 + \dfrac{R_1C_1+R_2C_2+R_3C_2-K^2R_1C_1}{R_1C_1C_2\left[R_2+R_3(1-K^2)\right]}s + \dfrac{1}{R_1C_1C_2\left[R_2+R_3(1-K^2)\right]}} \quad \text{....}(A_1-19)$$

Finally, setting K=1, then

$$\frac{V_o}{V_i} = \frac{\dfrac{R_3}{R_1R_2C_1}}{s^2 + \dfrac{R_2+R_3}{R_1R_2C_1} + \dfrac{1}{R_1R_2C_1C_2}} \quad \text{.........................}(A_1-20)$$

APPENDIX B

FILTER DESIGN EQUATIONS

The filter design-equations are analyzed in this section. In this analysis, the transfer-functions, eq. (3.2) and (3.3), are considered, which are repeated for convenience.

Case 1. Ideal OA of unity-gain mode (see figure 3.1)

(A) Parameter-equations (ω_o, Q_o and H_{BP})

For convenience, eq. (3.2) is repeated here:

$$\frac{V_o}{V_i} = \frac{\frac{R_3}{R_1 R_2 C_1} s}{s^2 + \frac{R_2+R_3}{R_1 R_2 C_1} s + \frac{1}{R_1 R_2 C_1 C_2}} \quad \text{.......(B1-1)}$$

or $$\frac{V_o}{V_i} = \frac{H_{BP} \frac{\omega_o}{Q_o} s}{s^2 + \frac{\omega_o}{Q_o} s + \omega_o^2} \quad \text{.......(B1-2)}$$

From eq. (B1-1) and (B1-2) $$\frac{\omega_o}{Q_o} = \frac{R_2+R_3}{R_1 R_2 C_1} = \frac{1}{R_1 C_1}\left(1+\frac{R_3}{R_2}\right) \quad \text{.......(B1-3)}$$

$$\omega_o^2 = \frac{1}{R_1 R_2 C_1 C_2} \quad \text{.......(B1-4)}$$

and $$H_{BP} \cdot \frac{\omega_o}{Q_o} = \frac{R_3}{C_1 R_1 R_2} \quad \text{.......(B1-5)}$$

From eq. (B1-4), $$\hat{\omega}_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}} \quad \text{.......(B1-6)}$$

Substituting eq. (B1-6) into eq. (B1-3) and solving for Qo, then, $Q_o = \frac{1}{R_2+R_3} \cdot \sqrt{\frac{R_1 R_2 C_1}{C_2}}$ ....(B1-7)

Substituting eq. (B1-3) into eq. (B1-5) and solving for H_{BP}

then $H_{BP} = \frac{R_3}{R_2+R_3}$ ....(B1-8)

(B) Element-Equations (Resistors)

Multiplying eq. (B1-6) by eq. (B1-7) and replacing the term $(R_2 + R_3)$ in eq. (B1-8) by $R_2 + R_3 = \frac{R_3}{H_{BP}}$ ....(B2-1)

then $\omega_o Q_o = \frac{H_{BP}}{R_3} \cdot \frac{1}{C_2}$ ....(B2-1)

Solving eq. (B2-1) for R_3, then $R_3 = \frac{1}{C_2} \cdot \frac{H_{BP}}{\omega_o Q_o}$ ....(B1-3)

Solving eq. (B1-8) for R_2 and replacing R_3 from eq. (B1-3),

then $R_2 = \frac{1}{C_2} \cdot \frac{1 - H_{BP}}{\omega_o Q_o}$ ....(B1-4)

Solving eq. (B1-6) for R_1 and replacing R_2, from eq. (B1-4),

then $R_1 = \frac{1}{C_1} \cdot \frac{Q_o}{\omega_o (1-H_{BP})}$ ....(B1-5)

(C) Element-equations (Capacitors)

Solving eq. (B1-3) for C_2, then $C_2 = \frac{1}{R_3} \cdot \frac{H_{BP}}{\omega_o Q_o}$ ......(B2-1a)

or multiplying eq. (B1-6) by eq (B1-7) and solving for C_2,

then $C_2 = \frac{1}{R_2+R_3} \cdot \frac{1}{\omega_o Q_o}$ ....(B2-1b)

Solving eq. (B1-3) for C_1, then $C_1 = \frac{R_2+R_3}{R_1R_2} \cdot \frac{Q_o}{\omega_o}$ .....(B2-1c)

Case 2 Ideal amplifiers (non-unity-gain mode)

In this case, only the parameter-equations will be analysed which are used in the sensitivity and stability sections, 3.4 and 3.5 respectively.

Eq. (3.3) is repeated for convenience:

$$\frac{V_o}{V_i}(s) = \frac{\frac{K_1R_3}{R_1C_1\left[R_3+R_2(1-K_1K_2)\right]}s}{s^2+\frac{R_1C_1+R_2C_2+R_3C_2-K_1K_2R_1C_1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]}s+\frac{1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]}} \quad \text{....(B3-1)}$$

From eq. (B1-2) and (B3-1),

$$\omega_o^2 = \frac{1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]} \quad \text{....(B3-2)}$$

$$\frac{\omega_o}{Q_o} = \frac{R_1C_1+R_2C_2+R_3C_2-K_1K_2R_1C_1}{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]} \quad \text{....(B3-3)}$$

and $H_{BP}\frac{\omega_o}{Q_o} = \frac{K_1R_3}{R_1C_1\left[R_2+R_3(1-K_1K_2)\right]}$ ....(B3-4)

From eq. (B3-2), $\omega_o = \frac{1}{\sqrt{R_1C_1C_2\left[R_2+R_3(1-K_1K_2)\right]}}$ ....(B3-5)

Replacing Wo from eq. (B3-5) in eq. (B3-3) and solving for Qo, then

$$Q_o = \frac{\sqrt{R_1C_1C_2[R_2+R_3(1-K_1K_2)]}}{R_1C_1(1-K_1K_2)+C_2(R_2+R_3)} \quad \text{..................(B3-6)}$$

Substituting eq. (B3-3) in eq. (B3-4) and solving for H_{SP}, then

$$H_{SP} = \frac{K_1R_3C_2}{R_1C_1(1-K_1K_2)+C_2(R_2+R_3)} \quad \text{........................(B3-7)}$$

APPENDIX C

MINIMIZATION METHODS

C1 Unconstrained Problems

In this class of minimization problems, the function $f(\bar{x})$ is twice differentiable with $\bar{x} = [x, y]^T$. Letting $x = x_o + h$ and $y = y_o + k$, then $\min_x f(\bar{x})$ is found by Taylor series expansion and a strong local point "x_o, y_o" is sought, so that $f(x_o+h, y_o+k) >$ $f(x_o, y_o)$ for all h and k.

For minimization,

$$hf_x(x_o, y_o) + kf_y(x_o, y_o) + \frac{1}{2}\begin{bmatrix} h, k \end{bmatrix} H(x_o, y_o) \begin{bmatrix} h \\ k \end{bmatrix} + o\,(h^3, k^3) > 0,$$

where $H(x_o, y_o)$ is the Hessian matrix evaluated at "x_o, y_o" and $f_x(x_o, y_o) = 0$, $f_y(x_o, y_o) = 0$

C2 Newton's method for minimization

For one-dimensional cases, the roots of a function $f(x) = 0$ are sought by, first, approximating it with its tangent at some point "x_o", and, then by solving for its next value at "x_1" when the tangent crosses the x-axis. The process is repeated at subsequent points $x_2, x_3, \ldots x_n$, by the recurrence formula:

$$x_{n+1} = x_n - \frac{f(x)}{f'(x)} \quad \text{.....................................(C2-1)}$$

until the algorithm converges. The closer the initial point is to the actual solution "x^*" the faster the convergence.

For multi-dimensional problem, where "x" is replaced by the vector $\bar{x} = [x_1, x_2 \ldots x_n]^T$, the corresponding recurrence formula in eq. (C2-1) is replaced by:

$$\nabla f(x_{n+1}) = \nabla f(x_n) + \nabla \nabla^T f(x_n) \cdot (x_{n+1} - x_n) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (C2-2)$$

Substituting $\nabla\nabla^T f(x_n)$ with the hessian matrix $H(x_n)$ and solving for x_{n+1}, then: $\bar{x}_{n+1} = \bar{x}_n - H^{-1}(\bar{x}_n) \nabla f(\bar{x}_n)$ ....(C2-3)

This is one of a few algorithms under the Quasi-Newton's method, and it converges fast if a suitable value "$\bar{x}_o$" is chosen. The only drawback of this algorithm is that it requires second partial derivative of $f(\bar{x})$ at each iteration. In view of this, H^{-1} will assume new values at each iteration.

In order to alleviate this problem, this algorithm is replaced by other algorithms wherever the hessian matrix H is required. However, when the function is of the quadratic form, $f(\bar{x}) = \frac{1}{2} \bar{x}^T A\bar{x} + \bar{b}^T \bar{x} + c$, then H^{-1} is constant. For this reason, non-linear functions are often approximated by quadratic forms which can be conveniently used in the Penalty-function minimization algorithms.

One recommended type of the Quasi-Newton's algorithms is the following:

Step 0. Select $\bar{x}^{o}$; also, select a real positive constant β ($.5 < \beta < .8$) and set $i = 0$.

Step 1. Compute $\nabla f(\bar{x}^{i})$.

Step 2. If $\nabla f(\bar{x}^{i})=0$, stop; else, go to step 3.

Step 3. Compute $H(\bar{x}^{i})^{-1}$ if it exists, and go to step 5; else, set $h(\bar{x}^{i}) = -\nabla f(\bar{x}^{i})$ and go to step 5

Step 4. Select step-size k_i (i.e. $k_i=k=1$, or $k_i=k\beta$) from known algorithms.

Step 5. Set $\bar{x}^{i+1}=\bar{x}^{i}+k_i\, h(\bar{x}^{i})$, set $i=i+1$ and go the step 1.

C3 Constrained problems

These problems may be stated as follows: $\min_x f(\bar{x})$, such that $g_i(\bar{x}) = 0$, $i=1,2,...,m$..(C3-1)
where $m < n$. Using the Lagrangian multipliers "λ" these constrained problems can be converted into unconstrained ones by the relation: $L(\bar{x};\lambda_i)=f(\bar{x})+\sum_{i=1}^{m}\lambda_i\, g_i(\bar{x})$..................(C3-2)
where $\lambda_i = \lambda_2, \lambda_3, ..., \lambda\ m$ are the Lagrangian multipliers.
Necessary conditions for "stationary" (maximum or minimum) point are:

$$\frac{\partial L}{\partial x_j} = \frac{\partial f(\bar{x})}{\partial x_j} + \sum_{i=1}^{m} \lambda_i \frac{\partial g_i}{\partial x_j} = 0, \quad j=1,2,....n, \quad i=1,2,....m \qquad \text{(C3-3)}$$

Using the gradient notation "∇" the expression in eq. (C3-3) can be re-written in the compact form:

$$\nabla_x f(\bar{x}) + \left[\frac{\partial g_i}{\partial \bar{x}}\right] = 0 \quad \text{(C3-4)}$$

C3.1 Computational methods

The Lagrangian computational problem leads to m + n simultaneous equations in m+n unknown variables by using the necessary convergence conditions at "x *" and "λ *", namely:

$$\nabla_x L(x^*, \lambda^*) = 0 \quad \text{(C3.5)}$$

and $\nabla L_\lambda(x^*, \lambda^*) = 0$ .... (C3.6)

Newton-Raphson's method is numerically straight-forward, but often inadequate, especially when (m+n) increases. Necessary convergence condition at "z*" is:

$$\nabla_x L(Z^*) = 0 \quad \text{(C3.7)}$$

where $Z = \left[\frac{\bar{x}}{\lambda}\right]$ .... (C3.8)

The recurrence formula is:

$$Z_{n+1} = Z_n - H^{-1}(Z_n)\, \nabla_z L(Z_n) \quad \text{(C3.9)}$$

where H(z) is the hessian matrix of $f(\bar{x},\bar{\lambda})$ given by:

$$H(Z_n) = \begin{bmatrix} \nabla_{xx}L & \nabla_{x\lambda}L \\ \nabla_{\lambda x}L & \nabla_{\lambda\lambda}L \end{bmatrix} \quad \text{and} \quad \nabla_z L(Z_n) = \begin{bmatrix} \nabla_x L \\ \nabla_\lambda L \end{bmatrix} \quad \text{(C3.10)}$$

C3.2 Kuhn and Tucker convergence conditions

Kuhn-Tucker theorem refers to Langrangian-type functions using inequality constraints and converting to unconstrained functions with the stationary convergence conditions:

$$
\begin{aligned}
&\nabla_{\bar{x}} L(\bar{x}^*, \bar{\lambda}^*) = 0 \\
&\nabla_{\bar{\lambda}} L(\bar{x}^*, \bar{\lambda}^*) \leq 0 \\
&(\bar{\lambda}^*)^T \cdot \bar{g}(\bar{x}^*) = 0 \\
&\bar{\lambda}^* \geq 0
\end{aligned}
\qquad \text{(C3.11)}
$$

C3.3 One-dimensional search techniques

If $f(\bar{x})$ is a real-valued one-dimensional function then x^* is its "minimum" in an interval $[a^o, b^o]$ after the nth iteration, and after this interval is reduced to a smaller one $[a^n, b^n]$ by using different search techniques.

Some search techniques are: dichotomous search, equal-interval search, Fibonacci search, Golden-section search, and quadratic interpolation search, each being exhibiting merits and (or) drawbacks from the other. A distinct feature of these techniques is that there is no need for derivatives in $f(x)$.

C4 Gradient techniques

C4.1 Unconstrained algorithms

In this class of gradient techniques, multi-dimensional problems are solved using "direct methods". The "gradient-direction" vector, $\nabla f(\bar{x}) = \left[\frac{\partial f(\bar{x})}{\partial x_1}, \frac{\partial f(\bar{x})}{\partial x_2}, \ldots, \frac{\partial f(\bar{x})}{\partial x_n}\right]^T$.(C4.1)

is used in the algorithms.

This vector is also called "direction of steepest descent" for minimizing $f(\bar{x})$ and "direction of steepest ascent" for maximizing $f(\bar{x})$.

For example, for steepest descent, the difference relation: $f(\bar{x}_0)-f(\bar{x}_0+d\bar{x})$ is maximized, where the vector $d\bar{x}$ describes an incremental distance ds along the path of steepest descent:

$$ds^2 = \sum_{i=1}^{n} (dx_i)^2 \quad \text{or} \quad 1 - \sum_{i=1}^{n} \left(\frac{dx_i}{ds}\right)^2 = 0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (C4.2)$$

where $\frac{dx_i}{ds}$ are the direction cosines.

The Langrangian-multiplier function $\left(L\left(\frac{dx_i}{ds}, \lambda\right)\right)$ and its necessary convergence conditions are used. The recurrence relation (discrete algorithm) is $x^{p+1} = x^p + k\nabla f(x^p)$.........(C4.3)

where k is the step-size of the gradient change, on the descent-path (i.e., $k<0$ for convergence). With small k, the discrete algorithm will follow the gradient path very closely but the convergence rate will be slow. On the other hand, with large k, the convergence will be fast, but the optimum point $\bar{x}^*$ might be missed, causing "oscillations" around $\bar{x}^*$. One way to avoid this situation is to reduce the number of steps by increasing the number of computations at each step.

C4.2 Constrained algorithms

In this class of gradient techniques, "boundary-following" and "penalty-function" problems are solved. In the "boundary-following" problems, linear quadratic and non-linear multi-dimensional problems can be optimized using linear or non-linear programming algorithms.
In the non-linear function case, gradient-type (such as feasible direction and projection methods) algorithms are employed.

The gradient techniques using equality-constraints ($g_i(\bar{x}) = 0$) are similar to those using inequality-constraints, except that the iterative path must lie on the boundary at all times.

C4.3 Penalty-function method

Direct and Lagrangian multiplier-methods are used to solve these converted (from constrained into unconstrained) objective functions.

C4.3.1 Equality-constrained problems

In this category, a problem can be formulated as follows: $\text{Min}_x f(\bar{x})$, such that $g_i(\bar{x}) = 0,\ i=1,2,\ldots m$.........(C4.4)

Here, $f(\bar{x})$ is the constrained objective function. The above objective function is converted into the new unconstrained function:

$$P(\bar{x};k_i) = f(\bar{x}) + \sum_{i=1}^{m} k_i (g_i(\bar{x}))^2 \quad \text{......................(C4.5)}$$

where $\bar{k} = [k_1, k_2, \ldots k_m]^T$....................................(C4.6)

is a positive real-valued vector, which is a specified weighting factor, depending on how much the constraint-functions is to be satisfied. As ki increases from zero-value to infinity, the constraint-functions are satisfied more closely to their desired values. Thus, these added "weighting" terms (i.e. the second term of the right hand side of eq. (C4.5) of the objective function represent "penalties" for closeness to the constraint boundaries. This penalty, implies more effort and longer process in order to reach optimum solution.

C4.3.2 Inequality-constraints

In this category, the problem is stated as follows:

$$\min_x f(\bar{x}), \text{ such that } g_i(\bar{x}) \leq 0, \; i=1,2,\ldots,r \quad \ldots\ldots\ldots\ldots\ldots \text{(C4.7)}$$

The new unconstrained function is:

$$P(\bar{x};k = f(\bar{x}) + \sum_{i=1}^{r} k_i [g_i(\bar{x})]^2 U_i (g_i) \quad \ldots\ldots\ldots\ldots\ldots \text{(C4.8)}$$

$$\text{where } U_i(g_i) = \begin{cases} 0 & \text{if } g_i(\bar{x}) \leq 0 \\ 1 & \text{if } g_i(\bar{x}) > 0 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots \text{(C4.9)}$$

and $\bar{k} > 0$. $U_i(g_i)$ is a step-function served to ignore the constraint, whenever "$\bar{x}$" is inside the feasible region and allows the existence of the equality-constraint, $g_i(\bar{x}) = 0$ whenever "$\bar{x}$" is outside the feasible region.

C4.4 Variable-metric algorithms

The variable-metric algorithms, as part of the quadratically convergent algorithms, optimize the convergence direction near the optimum "$\bar{x}^*$", by determining the vector difference $(\bar{x}^* - \bar{x}^o)$ from $\nabla f(\bar{x}^o)$ where $f(\bar{x}^o)$ is approximated by a sequence of quadratic functions near "$\bar{x}^*$".

Using first-order Taylor series expansion of $\nabla f(\bar{x})$ and assuming that $f(\bar{x})$ is twice-differentiable, that "$\bar{x}^*$" and "$\bar{x}^o$"

are its minimum and close-to-minimum points respectively, and $H(\bar{x})$ is its Hessian matrix at "$\bar{x}^*$", then $\nabla f(\bar{x}^*)=0$ and $H(\bar{x})^*$ is positive definite.

The respective recurrence formulae for a general function $f(\bar{x})$ described above and for a quadratic function $f(\bar{x}) = c+[\bar{b}]^T \bar{x} + \frac{1}{2} [\bar{x}]^T A\bar{x}$) are:

$\bar{x}^* = \bar{x}^o - H[\bar{x}^*]^{-1} . \nabla f(\bar{x}^o)$ ....(C4.10)

and $\bar{x}^* = \bar{x}^o - A^{-1} . \nabla f(\bar{x}^o)$ ....(C4.11)

where $\nabla f(\bar{x}^o) = A\bar{x}^o + \bar{b}$ ....(C4.12)

and $\bar{x}^* = -A^{-1}\bar{b}$ ....(C4.13)

C4.5 Fletcher-Powell variable-metric algorithm

Let $\bar{x}^i$ and H_i denote the approximations to $\bar{x}^*$ and the inverse of the Hessian matrix, respectively. Let $\bar{g}_i = \nabla f(\bar{x}^i)$ The Fetcher-Powell algorithm consists of the following four basic steps:

1. Choose $\bar{x}^o$ and H_o
2. For $i = 0,1,\ldots,n-1$, define:

   $\bar{x}^{i+1} = \bar{x}^i + \lambda_i \bar{v}^i$....................................(C4.14)

where $\bar{v}^i = -H_i \bar{g}_i$ ....(C4.15)

and λ_i minimizes $f(\bar{x}^i + \lambda\bar{v}^i)$ with respect to λi

3. For $i=0,1,\ldots n-1$, let $\bar{u}^i = \lambda_i \bar{v}^i$ ....(C4.16)

and $\bar{y}^i = \bar{g}^{(i+1)} - \bar{g}^i$ ....(C4.17)

Define $H_{i+1} = H_i + A_i + B_i$ ....(C4.18)

where $A_i = \dfrac{\bar{u}^i(\bar{u}^i)^T}{(\bar{u}^i)^T(\bar{y}^i)}$ and $B_i = -\dfrac{H_i\bar{y}^i(H_i\bar{y}^i)^T}{(\bar{y}^i)\cdot(H_i\bar{y}^i)^T}$ (C4.19)

4. If the "stopping" criteria are not satisfied, then let $\bar{x}^o = x^n$ and go to step 2.

The starting point $\bar{x}^o$ is arbitrary but can be suitably chosen by methods available in the literature.
H_o is any symmetric positive-definite matrix, as initial approximation to the inverse of the Hessian matrix; the simplest H_i is the diagonal matrix with positive scalars along the main diagonal.

Stopping rules are available in the literature. In many computer-program minimization techniques, such as the variable-metric algorithm, the convergence point "$\bar{x}*$" may be missed when "round-off" errors occur in the matrix and gradient computations. In order to minimize this effect, a good approach is to discard H_n after n iterations and start with new approximation.

APPENDIX D

GRADIENT-VECTOR $G(\bar{x})$

In this section, the elements G(i), i=1,2,...,5 are calculated for a five-dimensional gradient-vector, $G(\bar{x}) = \nabla P(\bar{x};ki)$, per equation (5.9). As an example, the gradient-vector $\nabla P(\bar{x}; ki)$, will be derived (minimization case 1a), where $P(\bar{x};k_i) = C_T + K_1 g_1{}^2 + K_2 g_2{}^2$ ....(D-1)

and $C_T = C_1 + C_2$ ....(D-2)

$g_1 = \omega_o{}^2 R_1 R_2 C_1 C_2 - 1 = 0$ ....(D-3)

$g_2 = Q_o{}^2 (R_2 + R_3)^2 \dfrac{C_2}{R_1 R_2 C_1} - 1 = 0$ ....(D-4)

Also $x_1 = C_1$, $X_2 = C_2$, $X_3 = R_1$, $x_4 = R_2$, $X_5 = R_3$ ....(D-5)

$$G(1) = G(x_1) = \frac{\partial P(\bar{x};K_i)}{\partial x_1} = \frac{\partial P(\bar{x};K_i)}{\partial C_1} \qquad \text{(D-6)}$$

$$\text{or } G(1) = \frac{\partial C_T}{\partial C_1} + K_1 \frac{\partial}{\partial C_1}(g_1{}^2) + K_2 \frac{\partial (g_2{}^2)}{\partial C_1} \qquad \text{(D-7)}$$

$$\frac{\partial C_T}{\partial C_1} = 1 \qquad \text{(D-8)}$$

$$k_1 \frac{\partial (g_1{}^2)}{\partial C_1} = 2k_1(\omega_o{}^2 R_1 R_2 C_1 C_2 - 1)\, \omega_o{}^2 R_1 R_2 C_2$$

$$= \frac{2k_1}{C_1}(\omega_o{}^2 R_1 R_2 C_1 C_2 - 1) \cdot (\omega_o{}^2 R_1 R_2 C_1 C_2) \qquad \text{(D-9)}$$

$$= \frac{2k_1}{C_1} g_1 (g_1 + 1) \qquad \text{(D-10)}$$

where eq. (C-3) was used in eq. (D-8).

$$K_2 \frac{\partial(g_2{}^2)}{\partial C_1} = - \frac{2K_2}{C_1} \left[Q_o^2 (R_2 + R_3)^2 \frac{C_2}{R_1R_2C_1} - 1\right] \cdot \left[Q_o^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1}\right] \quad \text{(D-11)}$$

$$= - \frac{2k_2}{C_1} g_2 (g_2+1) \quad \text{(D-12)}$$

Substituting eq. (D-8), (D-10), and (D-12) in eq. (D-7),

then $G(1) = 1+ \frac{2}{C_1}\left[K_1g_1(g_1+1) - K_2g_2 (g_2+1)\right]$ ....(D-13)

Similarly, $G(2) = \frac{\partial C_T}{\partial C_2} + K_1 \frac{\partial}{\partial C_2} (g_1{}^2) + K_2 \frac{\partial (g_2{}^2)}{\partial C_2}$ ....(D-14)

where, $\frac{\partial C_T}{\partial C_2} = 1$ ....(D-15)

$$K_1 \frac{\partial}{\partial C_2} (g_1{}^2) = \frac{2k_1}{C_2}(\omega_o{}^2R_1R_2C_1C_2-1) (\omega_o{}^2R_1R_2C_1C_2) \quad \text{(D-16)}$$

$$= \frac{2k_1}{C_2} g_1 (g_1 + 1) \quad \text{(D-17)}$$

$$K_2 \frac{\partial}{\partial C_2} (g_2{}^2) = \frac{2k_2}{C_2}\left[Q_o{}^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1} - 1\right] \cdot \left[Q_o{}^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1}\right] \quad \text{(D-18)}$$

$$= \frac{2k_2}{C_2} g_2 (g_2 + 1) \quad \text{(D-19)}$$

Substituting eq. (D-15), (D-17), and (D-19) in eq. (D-14),

$$G(2) = 1+ \frac{2}{C_2}\left[K_1g_1(g_1+1) + K_2g_2(g_2+1)\right] \quad \text{(D-20)}$$

$$G(3) = \frac{\partial C_T}{\partial R_1} + K_1 \frac{\partial (g_1{}^2)}{\partial R_1} + K_2 \frac{\partial (g_2{}^2)}{\partial R_1} \quad \text{(D-21)}$$

where $\frac{\partial C_T}{\partial R_1} = 0$ ....(D-22)

$$K_1 \frac{\partial (g_1{}^2)}{\partial R_1} = \frac{2K_1}{R_1} (R_1R_2C_1C_2-1) (R_1R_2C_1C_2) \quad \text{(D-23)}$$

$$= \frac{2K_1}{R_1} g_1 (g_1 + 1) \quad \text{(D-24)}$$

$$K_2 \frac{\partial (g_2{}^2)}{\partial R_1} = - \frac{2k_2}{R_1}\left[Q_o{}^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1} - 1\right] \cdot \left[Q_o{}^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1}\right] \quad \text{(D-25)}$$

$$= -\frac{2k_2}{R_1} g_2 (g_2 + 1) \quad \text{(D-26)}$$

Substituting eq. (D-22), (D-24), and (D-26) in eq. (D-21)

then, $G(3) = \frac{2}{R_1}\left[K_1 g_1(g_1+1) - K_2 g_2(g_2 + 1)\right]$ ....(D-27)

$$G(4) = \frac{\partial C_T}{\partial R_2} + k_1 \frac{\partial(g_1^2)}{\partial R_2} + K_2 \frac{\partial(g_2^2)}{\partial R_2} \quad \text{(D-28)}$$

where $\frac{\partial C_T}{\partial R_2} = 0$ ....(D-29)

$$K_1 \frac{\partial (g_1^2)}{\partial R_2} = \frac{2}{R_2} K_1(R_1R_2C_1C_2-1) (R_1R_2C_1C_2) \quad \text{(D-30)}$$

$$= \frac{2K_1}{R_2} g_1 (g_1+1) \quad \text{(D-31)}$$

$$K_2 \frac{\partial(g_2^2)}{\partial R_2} = \frac{2(R_2-R_3)}{R_2(R_2+R_3)} K_2\left[Q_o^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1} - 1\right] \cdot \left[Q_o^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1}\right] \quad \text{(D-32)}$$

$$= \frac{2(R_2-R_3)}{R_2(R_2+R_3)} k_2 g_2(g_2 + 1) \quad \text{(D-33)}$$

Substituting eq. (D-29), (D-31), and (D-33) in eq. (D-28),

then $G(4) = \frac{2}{R_2}\left[K_1 g_1(G_1+1) + \frac{R_2-R_3}{R_2+R_3} K_2 g_2(g_2+1)\right]$ ....(D-34)

Finally, $G(5) = \frac{\partial C_T}{\partial R_3} + K_1 \frac{\partial (g_1^2)}{\partial R_3} + k_2 \frac{\partial (g_2^2)}{\partial R_3}$ ....(D-35)

where, $\frac{\partial C_T}{\partial R_3} = 0$ ....(D-36)

$$K_1 \frac{\partial(g_1^2)}{\partial R_3} = K_1 \frac{\partial}{R_3} (R_1R_2C_1C_2-1) = 0 \quad \text{(D-37)}$$

$$K_2 \frac{\partial (g_2^2)}{\partial R_3} = \frac{4}{R_2+R_3} K_2\left[Q_o^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1} - 1\right] \cdot \left[Q_o^2 (R_2+R_3)^2 \frac{C_2}{R_1R_2C_1}\right] \quad \text{(D-38)}$$

$$= \frac{4}{R_2+R_3} K_2 g_2 (g_2 + 1) \quad \text{(D-39)}$$

Substituting eq. (D-36), D(-37), and (D-39) in eq. (D-35),

the latter becomes: $G(5) = \frac{4}{R_2+R_3} k_2 g_2 (g_2+1)$ ....(D-40)

APPENDIX E

Thin-film area: Ac and Ar

I) Calculation of Ac

As an example, the tantal metal (TM) capacitor is considered, which consists of a tantalum pentoxide dielectric, a tantalum base electrode, and a counterelectrode of evaporated gold, aluminum, or other metal, as shown in figure E.1

Electric field $\mathcal{E}$(volts/cm) is developed between the plates, separated by distance d(cm) and sustaining potential V, which represents the anodizing voltage Va during deposition of the dielectric film. It is estimated, by general acceptance, that the relation between the anodization voltage Va and the breakdown voltage V_{BR} is:

$V_{BR} \cong (\frac{2}{3})$ Va ....(E 1-1)

Since thickness "d" is a function of the applied voltage and the electric field $\mathcal{E}$, then d = f($\mathcal{E}$,Va) or $\mathcal{E} = \frac{Va}{d}$, and $d = \frac{Va}{\mathcal{E}}$(cm) ....(E 1-2)

The capacitance density $\frac{C}{A}$ (Farads/cm²) is given by: $\frac{C}{A} = \frac{\varepsilon_r \varepsilon_o}{d}$....(E 1-3)

where ε_r and ε_o were defined in section 5.5.1.1

After substituting eq. (E1-2) in eq. (E1-3),

$$\frac{C}{A} = \varepsilon_r \varepsilon_o \frac{\mathcal{E}}{V_a} = \varepsilon_o(\varepsilon_r\ \mathcal{E}/V_a) \qquad \text{(E1-4)}$$

Substituting eq. (E1-1) in eq.(E1-4), then the latter becomes:

$$\frac{C}{A} = \frac{3\varepsilon_o}{2}\,(\varepsilon_r \mathcal{E} V_{BR}) \qquad \text{(E1-5)}$$

Eq. (E1-5) can be written as: $\frac{C}{A} = k$ .... (E1-6)

where $k = \frac{3}{2}\varepsilon_o\,(\varepsilon_r \mathcal{E}/V_{BR})$ .... (E1-7)

So, k is a constant number; it defines the thin-film material and the anodization characteristics, during deposition process.

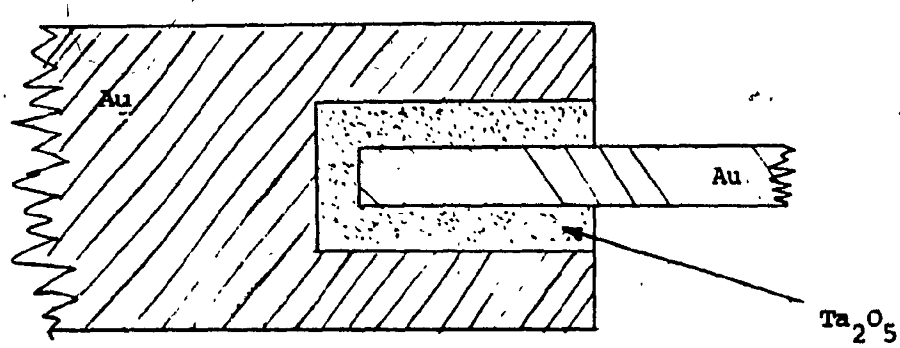
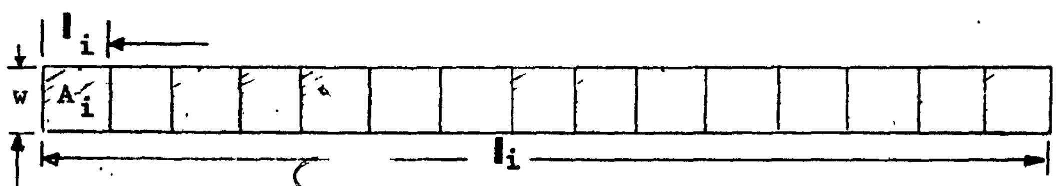


Figure E.1 Thin-film capacitor pattern

The capacitance area A can be thought of the summation of small unit-squares A_i, such that $A_i = w \times l_i$, as shown in a simple geometry of the capacitance pattern below.



The width "w" is uniform, and the unit length "l_i" can be estimated to be equal to the width "w". Therefore, $l_i = w$, and the unit-square is $A_i = w \times l_i = w^2$

Table E.1 shows typical values of capacitance per unit-area (F/□), for different dielectric films, and some characteristics, such as quality factor Q, TCC and accuracy before trimming.

The total area A_T (or Ac) is $Ac = \sum_{i=1}^{n} A = \sum_{i=1}^{n} W_i^2 = nw^2$, ...(E1-8)
since $w_1 = w_2 = , \ldots , w_n = w$

The total capacitance density $\frac{C}{A}$ is given by: $\frac{C_T}{Ac} = k$.
Conversely, the total area required for the total capacitance C_T is: $Ac = \frac{1}{k} C_T$ ....(E1-9)

or $Ac = \frac{2}{3} \cdot \frac{V}{\varepsilon_o \varepsilon_r \mathcal{E}} \cdot C_T$ ....(E1-10)

where $Ac = nA_i = nw^2$

For example, from Table E.2, for dielectric film Ta_2O_5 $\varepsilon_r = 25$, $\varepsilon_o = 8.85 \times 10^{-14}$ [F/cm], $\mathcal{E} = 4 \times 10^6$ [Volts/cm]
and $V_{BR} = 100$ [volts],

$$Ac = \frac{2}{3} \cdot \frac{100}{8.85 \times 10^{-14} \times 25 \times 4 \times 10^6} = (7.533 \times 10^7)\, C_T \left[cm^2\right]$$

Table E.1 - Some Dielectric materials
and typical characteristics that can be achieved

Dielectric	Deposition process	Capacitance per □	Q_o at 10 MHZ	Temper coeff/pm/°c	Accuracy before trimming
Silicon	vacuum evaporation	0.013 pf/mil² at 6 v	200	200 - 250	±15%
Alumina	vapor plating	0.3 pf/mil² at 30 v	10 - 100	150 - 400	±10%
Tantalum	Anodic oxidation	1.55 pf/mil² at 12 v	good	150 - 350	±20%
Silicon Dioxide	vapor oxidation	0.25-0.4 pf/mil² at 12 v	10 - 100	100	±15%

Table E.2 - Properties of typical thin-film materials

Dielectric film Material	Dielectric constant (ϵr)	Dissipation factor ($\tan\delta$)	TCC (ppm/°c)	Breaking voltage V_{BR} (v)	Electric field $\mathcal{E}$ (v/cmx10 6)	Capacitance Density C/A (μF/cm 2)	Dieletric film Thickness (Å)
SiO	5-7	.01-.03	150-400	5-100	1 - 2	.001-.015	3000-40000
SiO_2	3-4	.004-.04	100	50-200	3	.002-.02	800-10000
Ta_2O_5	20-27	.002-.006	180-220	30-150	3 - 4	.03-.2	1000-6000
TiO_2	30-100	.01-1.0	200-800	25-90	.3 - 1	.1-1.0	1000-2000
Al_2O_3	8-100	.2-.24	200-300	25-120	2 - 4	.03-.25	400-2500

II) Calculation of Ar

A thin-film resistor is considered. A simplified top and cross-sectional view of a thin-film resistor is shown in figure E.2.

The resistance of a complete film, with resistivity , uniform width "w", length "l", and thickness "d" is given by:

$$R = \frac{\rho\,[\text{ohms-cm}]}{d\,[\text{cm}]} \cdot \frac{l\,[\text{cm}]}{w\,[\text{cm}]}\ , \quad \text{or} \quad R = \frac{\rho}{d} \cdot \frac{l}{w} \quad \text{ohms} \qquad \text{.....................(E2-1)}$$

The ratio $(\frac{l}{w})$ is called "aspect ratio" and the ratio $(\frac{\rho}{d})$ is called the "sheet resistance" Rs.

when $l = w$, then $R = \frac{\rho}{d} = Rs$ ohms/□ ....(E2-2)

when $l = w$, then $R = n\frac{\rho}{d} = nRs$ ....(E2-3)

where n is the number of square-units or the number of sheet squares.

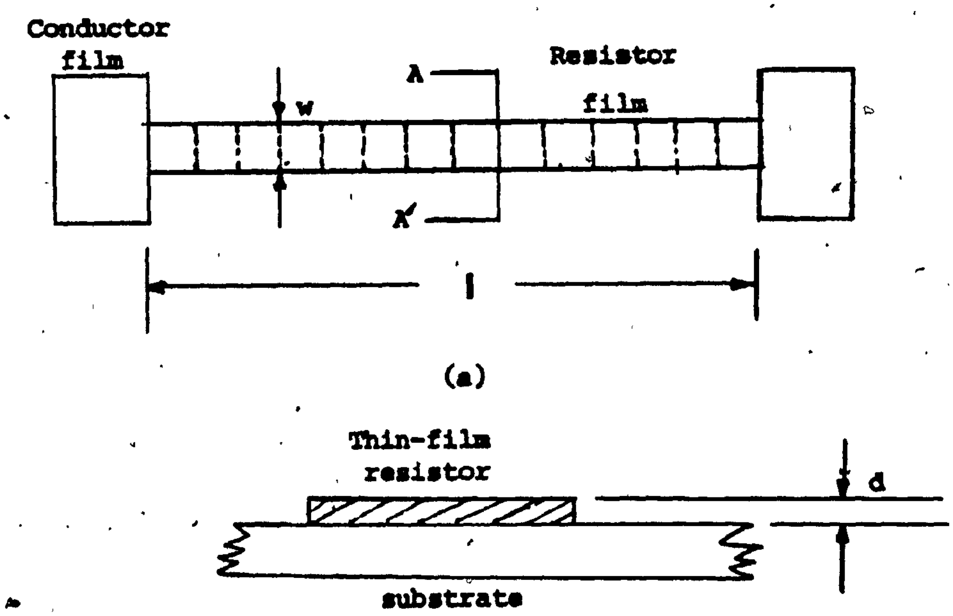


Fig. E.2 - A thin-film resistor pattern.
(a) Top view, (b) cross-section A-A'

The sheet resistance "Rs" characterizes the specific resistivity of a given resistor film whose thickness "d" is constant. It also corresponds to the resistance of a single square of material. The amount of resistivity depends on the impurity-type of dopant used. The thickness of the film "d" depends on the impurity-carrier diffusion and the diffusion coefficient D, by the relation:

$$N(x,t) = No \left[\text{Erfc} \left(\frac{x}{2 \quad Dt} \right) \right] \quad \text{(E2-4)}$$

So, by defining the amount N(x,t),(which in turn determines the amount of resistivity ρ) the coefficient "D", and the time duration "t", the thickness "d" is determined from error function (erfc) tables or graphs.

Table E.3 illustrates the relation between tolerances (and yields) and the geometry of resistor films, while Table E.4 illustrates the specific resistivity "ρ" obtained for different tantalum films.

Multiplying both numerator and denominator of the expression in eq. (E2-1) by w, then $R = \frac{\rho}{d} \cdot \frac{lw}{w^2}$ .... (E2-5)

or $R = \frac{\rho}{d} \quad \frac{A}{w^2}$ .... (E2-6)

and the resistance density is given by:

$$\frac{R}{A} = \frac{\rho}{d} \frac{1}{W^2} \quad \text{(E2-7)}$$

or $\frac{R}{A} = Rs \frac{1}{W^2}$ .... (E2-8)

The total area A_T (or A_r) is the summation of unit-squares Ai or the product n x A_1, where n is the total number of unit-squares. Hence, $A_r = \sum_{i=1}^{n} A_i = nA_1$ where A_1 is the first unit-square. Also, $A_r = nA_1 = nw^2$ ....(E2-9)

and $R_T = \frac{Rs}{W^2} \cdot A_r = \frac{Rs}{W^2} (A_1 + A_2 + \ldots + A_n)$........................(E2-10)

or $R_T = \frac{nRs}{W^2} A_1$........................(E2-11)

since, $A_1 = A_2 =, \ldots, A_n$

Finally, from eq. (E2-10)

$A_r = \left(\frac{w^2}{Rs}\right) R_T$ mils² ....(E2-12)

where A_T is given by eq. (E2-9).

For example, from Table E.3, for w = .5mils

Rs = 4000 ohms/□ , and R_T = 40,000 ohms, A_r = 50 (mils)².

Table E.3 - Tradeoffs involved in reduction of width to increase resistance. The following are assumed:

ρ_s = 4000 ohms / sq., A= 50 mils^2

w [mils]	l [mils]	R [ohms]	Resistor tolerance %	Representative overall yield %
2.5	10.0	1600	9	98
2.0	12.5	2500	10	95
1.0	25.0	10000	15	90
0.5	50.0	40000	25	80
0.25	100.0	160000	45	60

Table E.4 - Specific Resistivity of various Tantalum (Ta) films

"Ta" film	bcc-Ta	β - Ta	Ta_2N	Ta+ O	Ta + O + Ta_2O_5 [1]
ρ(micro-ohm-cm)	24 - 50	180-220	240-300	40-300	250 - 2000

1. Reactive sputtering with oxygen.

APPENDIX F

COMPUTER-AIDED SOLVING OF THE PROBLEM

F1. Programs and Subroutines-General

Formulation of the minimization problem, as it is described in chapter four, is a simple task that requires simple mathematical manipulations. However, the execution of the minimization algorithm is, by itself, a highly complex and tedious task.

Forty-eight computer programs are written to solve the minimization problem and fifty-seven programs to plot the amplitude and phase responses of the transfer functions of this filter.

Since both minimization algorithms, used as function subroutines ZXMIN and FMFP (called in the main programs), require external data to perform computations and iterations, these data are supplied by additional subroutines, such as FUNCT, FUNCTI and TRANF.

The "plot" programs also use function subroutine, such as USPLH to depict the proper graphs that represent the filter responses.

The computer programs were compiled in FORTRAN IV; they were run in BATCH and edited in +NTEX D text editor. PERMANENT-FILE "PARIS" was made which consisted of DATA and WORK-FILE, PERMANENT PROGRAMS, listed in proper DUMP FILES, stored on DISC BASA XXX of the NOS. 1.3 - 472 Computer System.

The input data and the repetition (loops) of the program "runs", which were designed so that different input parameters (i.e. Wo, Qo, penalty-multipliers Ki) were selected, were kept to a minimum. The algorithms require only initial values of variables, once, then they iterate different values by themselves, until minimum (or forced-logic termination) is reached.

F2 Description of minimization programs

Forty-eight minimization programs minimize the objective function F, per Table-4 (program no. 1 to 48). Program no. 1 to 12 use the Quasi-Newton's algorithm. Program no. 13 to 48 use the Fletcher-Powell's algorithm.

All the minimization programs, regardless of the algorithm used, follow similar procedure; gathering of data and computing the "minimum" by means of subroutines which employ the minimization algorithms.

F2.1 Description of main programs that use Quasi-Newton's algorithm

All twelve programs that minimize the total capacitance C_T are practically identical; the only difference is the type and the number of the constraint-functions gi. This distinction, in terms of the specific constraints, identifies the four basic cases of minimization per Table-4 (programs no. 1 to 12).

The functional structure of these programs is represented by the flow chart of figure F.1.
These programs share their variable "xi", the filter parameters (Wo and Qo) and penalty-function multipliers "K_i", as common elements, with their function sub-routines. To identify the problem as a whole and the different cases explored, proper description is printed. The minimization sub-routine ZXMIN will not recognize the requirements of the problem unless its predescribed arguments (such as size N of the variable $\bar{x}$ and gradient $\bar{g}$ vector, accuracy of computations, etc.) are determined.

Due to the large difference of magnitude between capacitance and resistance elements, truncation of the least significant decimal digits would occur during the computations so that the algorithm would not be able to derive the new variables for the next iteration (cycle of computations).

Therefore, initial scaling is required to bring these variables in the same order of magnitude.

Provided that the above requirements are met, the minimization algorithm (subroutine ZXMIN) can be called to perform the necessary steps and computations, iteration by iteration, until the objective is reached, while printing of the output variables in each iteration takes place. Upon completion of the required iterations for minimum, the main-program algorithm repeats the whole process with new filter parameters (unless zero frequency is encountered for which the program is terminated) and new multipliers K_i. Listing of two samples of the main programs, and subroutine FUNCT1 also demonstrates all the steps of the problem solution process.

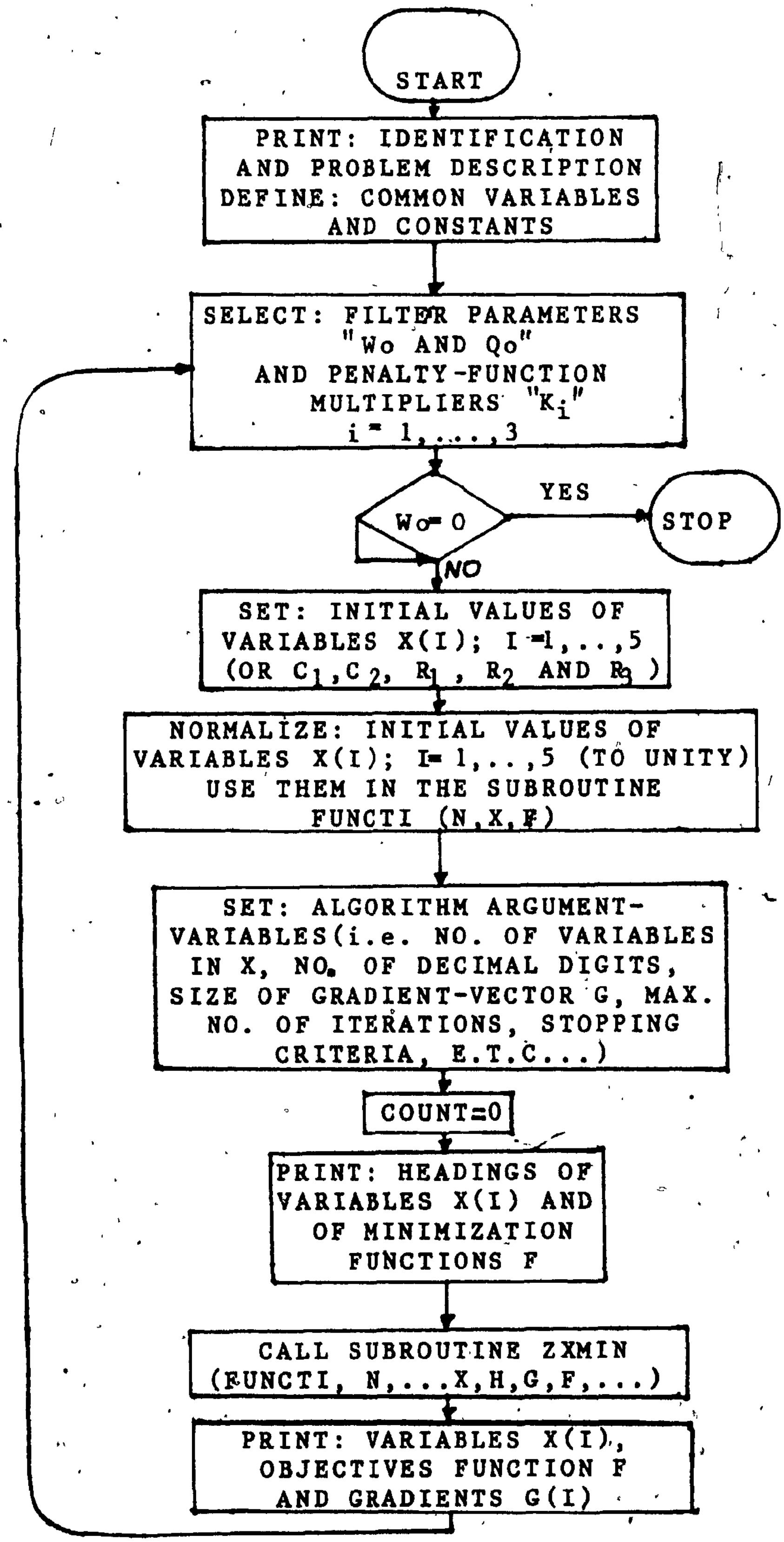


Fig. F.1 - Main Program of minimization by Quasi-Newton's algorithm.

```
PROGRAM MINCT    73/174  OPT=1                    FTN 4.8+498      80/06/08. 14.23.33        PAGE    1

      PROGRAM MINCT(INPUT,OUTPUT)
      EXTERNAL FUNCT1
      COMMON FO,FI,OP,K1,K2,FR,OPP,X1N,X2N,X3N,X4N,X5N,FIN,OPN
      REAL K1,K2
      DIMENSION W(20),X(5),H(15),G(5)
      PRINT 1
    1 FORMAT(////,5X,*CONCORDIA UNIVERSITY-SGWU CAMPUS.        MONTREAL
     * 1980.*)
      PRINT 3
    3 FORMAT(//,5X,*MAJOR TECHNICAL REPORT IN EL. ENGINEERING.*,/
     *5X,*UNITY_GAIN BAND PASS ACTIVE FILTER*,//
     *5X,*OPTIMIZATION OF FILTER ELEMENTS*,//
     *5X,*..........BY PARASKEVAS PROKOPIS,I.D. NO. 6901956.......*,//
     *5X,*..........ADVISOR DR. B. BHATTACHARYYA, EL. ENG...........*,///
     *5X,*THIS PROGRAM MINIMIZES THE TOTAL CAPACITANCE "CT" OF THE*,/
     *5X,*FILTER,GIVEN CONSTRAINTS "G1" AND "G2" FOR SPECIFIED*,/
     *5X,*RESONANCE FREQUENCY "FO" AND POLE_Q "OP" RESP. AND INITIAL*,/
     *5X,*COMPONENT VALUES R1,R2,R3,C1,AND C2(ALL INDEPENDENT FROM*,/
     *5X,*EACH OTHER.   THE BAND PASS INSERTION LOSS "HOP" IS*,/
     *5X,*DEPENDENT ON FILTER PASSIVE COMPONENTS AND IS GIVEN BY *,/
     *5X,*            HOP=R3/(R2+R3)*,//
     *5X,*....IN THIS ANALYSIS QUASI_NEWTON ALGORITHM IS USED....*,///)
  105 READ *,FO,OP,K1,K2
      IF(FO.EQ.0.) GO TO 100
      PRINT 5,FO,OP,K1,K2
    5 FORMAT(5X,10HFREQUENCY=,F6.1,5HHERTZ,7X,3HOP=,F5.1,7X,18
     *HPENALTY FACTOR K1=,F10.2,7X,18HPENALTY FACTOR K2=
     *,F10.2,//)
      PRINT 2
    2 FORMAT(5X,80H......MINIMIZE "CT" WHEN HOP IS FLOATING AND C1,C2,R1
     *,R2,R3 ARE DIFFERENT .......//)
   35 FI=2.*3.1415926*FO
      X(1)=1.E+5
      X(2)=1.E+3
      X(3)=1.E+3
      X(4)=(X(2)+X(3))/(X(1)*X(2))**OP/FI
      X(5)=(1./(X(2)+X(3)))*(1./(OP*FI))
      X1N=X(1)
      X2N=X(2)
      X3N=X(3)
      X4N=X(4)
      X5N=X(5)
      X(1)=X(1)/X1N
      X(2)=X(2)/X2N
      X(3)=X(3)/X3N
      X(4)=X(4)/X4N
      X(5)=X(5)/X5N
      FIN=FI/FI
      OPN=OP/OP
      N=5
      NSIG=24
      MAXFN=10000
      IOPT=0
      ICOUNT=0.
      PRINT 6
    6 FORMAT(5X,*HOP*,4X,*R1(OHMS)*,4X,*R2(OHMS)*,
     *4X,*R3(OHMS)*,4X,*C1(FARADS)*,4X,*C2(FARADS)*,3X,*P(X,K)*,7X,*CT(F
     *ARADS)*,1X,*COUNT*,3X,*FO*,6X,*OP*,5X,*G1*,3X,*G2*,//)
      CALL ZXMIN(FUNCT1,N,NSIG,MAXFN,IOPT,X,H,G,F,W,IER)
      PRINT 15
   15 FORMAT(//,13X,*X(1)*,7X,*X(2)*,10X,*X(3)*,12X,*X(4)*,13X,*X(5)*)
      PRINT 10,(X(I),I=1,5)
   10 FORMAT(/,5X,5G15.6)
      PRINT 20,F,G1,G2
   20 FORMAT(//,10X,1HF,10X,2HG1,10X,2HG2/1X,3G15.6)
      PRINT 25,FR,OPP,IER
   25 FORMAT(//,15X,2HFO,15X,2HOP,/,8X,2G15.6,//,5X,*IER=*,I3,//)
      GO TO 105
  100 STOP
      END
```

```
SUBROUTINE FUNCT1    73/174  OPT=1                FTN 4.8+498      80/06/08. 14.23.33        PAGE    1

      SUBROUTINE FUNCT1(N,X,F)
      DIMENSION X(N)
C     MINIMIZE TOTAL CAPACITANCE CT GIVEN CONSTRAINTS
C     IMPOSED BY CENTER FREQUENCY FO AND QP OF THE BAND PASS FILTER
C     CASE I-HOP FLOATING,R1,R2,R3,AND C1,C2 ARE DIFFERENT-
C
      COMMON FO,FI,OP,K1,K2,FR,OPP,X1N,X2N,X3N,X4N,X5N,FIN,OPN
      REAL K1,K2
C
C     CONSTRAINT ON CT IMPOSED BY THE EQUALITY-FO=F(R1,R2,C1,C2)-
      G1=(FI**2)*(X(1)*X(2)*X(4)*X(5)*X1N*X2N*X4N*X5N)-1.
C     CONSTRAINT ON CT IMPOSED BY THE EQUALITY-OP=F(R1,R2,R3,C1,C2)-
      G2=(OP**2)*(X(2)*X2N+X(3)*X3N)**2*(X(5)*X5N/(X(4)*X4N*X(1)*X1N*X
     *2)*X2N))-1.
C     UNCONSTRAINED TOTAL CAPACITANCE "CT"
      CT=((X(2)+X(3))/(X(1)*X(2)))*OPN*(1./(X(2)+X(3)))*(1./OPN)
C       CONSTRAINED TOTAL CAPACITANCE "CT" TO BE MINIMIZED GIVEN
C     ABOVE CONSTRAINTS
      P=K1*G1**2+K2*G2**2
      F=CT+P
      R1=X(1)*X1N
      R2=X(2)*X2N
      R3=X(3)*X3N
      C1=X(4)*X4N
      C2=X(5)*X5N
      R1=ABS(R1)
      R2=ABS(R2)
      R3=ABS(R3)
      C1=ABS(C1)
      C2=ABS(C2)
```

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      HOP=R3/(R2+R3)
      CT0=C1+C2
      FR=(1./6.2831853)*(1./SQRT(C1*C2*R1*R23))
      QPP=(1./(R2+R3))*SQRT(R1*C1*R2/C2)
   39 IP=(ICOUNT/20)*20
      IF(IP.EQ.ICOUNT) PRINT 17,HOP,R1,R2,R3,C1,C2,F,CTO,ICOUNT,FR,QPP,
     *G1,G2
      ICOUNT=ICOUNT+1
   17 FORMAT(1X,8G12.6,1X,I4,F10.2,F7.2,F7.4,F7.4)
   40 IF((C1.OR.C2).LT.1.E-10) STOP
      IF(R1.GT.5.E+6) STOP
      RETURN
      END
```

CONCORDIA UNIVERSITY-SGW CAMPUS. MONTREAL 1980.

MAJOR TECHNICAL REPORT IN EL. ENGINEERING.
UNITY_GAIN BAND PASS ACTIVE FILTER

OPTIMIZATION OF FILTER ELEMENTS

..........BY PARASKEVAS PROKOPIS,I.D. NO. 4901956......

.........ADVISOR DR. B. BHATTACHARYYA. EL. ENG..........

THIS PROGRAM MINIMIZES THE TOTAL CAPACITANCE "CT" OF THE FILTER,GIVEN CONSTRAINTS "G1" AND "G2" FOR SPECIFIED RESONANCE FREQUENCY "FO" AND POLE_Q "QP" RESP. AND INITIAL COMPONENT VALUES R1,R2,R3,C1,AND C2(ALL INDEPENDENT FROM EACH OTHER. THE BAND PASS INSERTION LOSS "HOP" IS DEPENDENT ON FILTER PASSIVE COMPONENTS AND IS GIVEN BY HOP=R3/(R2+R3)

....IN THIS ANALYSIS QUASI_NEWTON ALGORITHM IS USED....

FREQUENCY= 500.0HERTZ QP= 50.0 PENALTY FACTOR K1= 1000.00 PENALTY FACTOR K2= 500.00

......MINIMIZE "CT" WHEN HOP IS FLOATING AND C1,C2,R1,R2,R3 ARE DIFFERENT ......

HOP	R1(OHMS)	R2(OHMS)	R3(OHMS)	C1(FARADS)	C2(FARADS)	P(X,K)	CT(FARADS)	COUNT	FO	QP	G1	G2
.500000	100000.	1000.00	1000.00	.318310E-06	.318310E-08	2.50000	.321493E-06	0	500.00	50.00	-.0000	0.0000
.499545	100182.	1001.02	999.202	.317830E-06	.318118E-08	2.49657	.321020E-06	20	499.81	50.04	.0008	-.0017
.492015	101300.	1106.87	979.660	.279735E-06	.320381E-08	2.37007	.282942E-06	40	502.04	49.81	-.0001	.0070
.460734	104461.	1078.91	921.794	.282608E-06	.310767E-08	2.28130	.285876E-06	60	499.41	49.97	.0024	.0012
.427222	108748.	1088.77	812.086	.254770E-06	.334071E-08	2.16893	.258119E-06	80	501.35	49.99	-.0054	.0004
.392604	113923.	1223.82	791.041	.228335E-06	.318356E-08	2.01441	.231490E-06	100	501.51	49.79	-.0060	.0080
.389113	121149.	1265.64	806.167	.214410E-06	.306061E-08	1.85300	.217479E-06	120	501.08	49.96	-.0043	.0016
.353965	127483.	1310.63	718.101	.192729E-06	.314363E-08	1.71797	.195873E-06	140	500.22	49.09	-.0009	.0045
.292123	134825.	1444.50	596.187	.159830E-06	.311257E-08	1.74712	.162942E-06	160	503.54	49.76	-.0140	.0095
.262014	137700.	1414.92	509.433	.157029E-06	.331632E-08	1.51104	.160341E-06	180	499.52	50.06	.0019	-.0023
.229723	144325.	1494.03	435.551	.142113E-06	.330823E-08	1.42545	.145422E-06	200	499.87	49.88	.0005	.0049
.175978	149395.	1549.43	330.805	.129523E-06	.338302E-08	1.34779	.132906E-06	220	499.88	50.06	.0000	-.0024
.164464	160011.	1604.00	331.635	.118930E-06	.315061E-08	1.25334	.122089E-06	240	500.74	50.03	-.0030	-.0012
.168608	175606.	1812.62	367.601	.109326E-06	.291137E-08	1.17577	.112437E-06	260	499.56	50.19	.0017	-.0076
.157050	188781.	1899.52	364.557	.104230E-06	.290000E-08	1.12291	.107130E-06	280	500.74	49.93	-.0030	.0019
.161814	204650.	2022.93	390.532	.923207E-07	.264256E-08	1.03016	.949633E-07	300	500.79	49.83	-.0031	.0058
.166690	206390.	2042.40	408.576	.924710E-07	.259417E-08	.993401	.950652E-07	320	500.49	50.01	-.0020	-.0005
.165087	227047.	2211.62	437.384	.836140E-07	.240010E-08	.938269	.860149E-07	340	501.36	49.93	-.0054	.0020
.169537	220762.	2233.76	443.124	.835133E-07	.237579E-08	.901464	.858091E-07	360	499.84	50.07	.0007	-.0027
.160267	239279.	2331.79	449.626	.790650E-07	.229346E-08	.862103	.813597E-07	380	500.32	49.94	-.0013	.0023
.155701	251868.	2439.97	453.504	.747790E-07	.218495E-08	.814890	.769608E-07	400	500.29	49.98	-.0010	.0007
.150191	264024.	2508.69	457.904	.708895E-07	.208891E-08	.775093	.729784E-07	420	500.27	50.00	-.0011	.0001
.144236	275600.	2715.00	457.605	.675013E-07	.200732E-08	.739638	.695086E-07	440	499.83	50.00	.0007	.0000
.137530	290424.	2877.00	458.701	.635283E-07	.196670E-08	.700401	.654350E-07	460	500.27	50.02	-.0011	-.0007
.134901	296829.	2947.24	450.011	.619776E-07	.186922E-08	.683161	.630460E-07	480	499.93	50.01	.0003	-.0006
.127202	314287.	3136.62	457.131	.578087E-07	.176879E-08	.660376	.596374E-07	500	501.03	49.97	-.0041	.0011
.121909	329201.	3299.00	458.113	.549810E-07	.169853E-08	.614001	.566801E-07	520	500.02	49.99	-.0001	.0022
.118160	342273.	3431.19	459.754	.526461E-07	.163462E-08	.594906	.542807E-07	540	500.61	49.98	-.0025	.0007
.111434	369404.	3671.89	460.407	.489033E-07	.154093E-08	.556281	.504442E-07	560	500.47	49.94	-.0019	.0024
.107953	383426.	3852.96	466.276	.464674E-07	.147145E-08	.533305	.479388E-07	580	500.77	50.01	-.0031	-.0003
.103003	409973.	4000.60	460.577	.436029E-07	.139783E-08	.507267	.450003E-07	600	500.87	49.97	-.0035	.0012
.948562E-01	451972.	4558.16	477.601	.382653E-07	.125416E-08	.466126	.395194E-07	620	505.05	49.90	-.0199	.0042
.965182E-01	444723.	4464.23	476.320	.395951E-07	.128775E-08	.456323	.408829E-07	640	500.54	49.98	-.0022	.0009
.924909E-01	472175.	4732.98	482.373	.370912E-07	.121958E-08	.430320	.383108E-07	660	500.57	49.99	-.0023	.0005
.904633E-01	488296.	4889.77	486.341	.357937E-07	.118257E-08	.417542	.369762E-07	680	500.63	50.00	-.0025	-.0002
.870330E-01	509102.	5091.92	490.309	.342367E-07	.111945E-08	.398114	.353761E-07	700	500.48	50.00	-.0019	.0002
.859481E-01	525335.	5249.04	493.566	.331327E-07	.110823E-08	.382065	.342409E-07	720	500.17	50.00	-.0007	.0000
.832054E-01	551343.	5500.08	499.170	.315128E-07	.106098E-08	.365459	.325738E-07	740	499.84	50.03	.0007	-.0010
.808811E-01	574828.	5726.84	503.512	.301193E-07	.102699E-08	.351359	.311342E-07	760	500.30	50.02	-.0012	-.0006
.793959E-01	588240.	5856.68	505.099	.293977E-07	.100082E-08	.342032	.303985E-07	780	499.90	50.00	.0005	-.0002
.777372E-01	605798.	6026.11	507.938	.284557E-07	.973525E-09	.335619	.294292E-07	800	500.47	49.99	-.0019	.0003
.757070E-01	627832.	6230.80	511.013	.274259E-07	.943092E-09	.320488	.283690E-07	820	500.02	50.00	-.0001	-.0001
.723680E-01	665009.	6605.89	515.356	.257506E-07	.893844E-09	.303219	.266445E-07	840	500.21	49.99	-.0009	.0006
.687070E-01	713160.	7063.23	521.096	.239515E-07	.837791E-09	.289151	.247893E-07	860	500.60	50.04	-.0024	-.0014
.678181E-01	732764.	7254.81	521.871	.232683E-07	.818773E-09	.275271	.240871E-07	880	500.13	49.99	-.0005	.0005
.655932E-01	751910.	7439.56	522.240	.226414E-07	.799490E-09	.268304	.234409E-07	900	500.16	49.99	-.0006	.0004
.625772E-01	794900.	7852.00	524.215	.213932E-07	.759448E-09	.255621	.221127E-07	920	500.35	50.00	-.0014	.0001
.601012E-01	830305.	8201.17	524.410	.203852E-07	.729669E-09	.242989	.211149E-07	940	500.08	49.99	-.0003	.0005
.574539E-01	872724.	8613.67	525.055	.193176E-07	.695543E-09	.240745	.200131E-07	960	500.78	50.00	-.0031	.0000
.570104E-01	879341.	8678.35	524.668	.191972E-07	.691669E-09	.229308	.198888E-07	980	499.98	50.01	.0001	-.0003
.554264E-01	930185.	9173.74	522.905	.180515E-07	.656345E-09	.221056	.187148E-07	1000	500.47	49.97	-.0014	.0013
.528756E-01	940639.	9354.60	522.249	.177223E-07	.645001E-09	.213953	.183673E-07	1020	499.71	49.99	.0012	.0002
.507580E-01	987575.	[illegible]	[illegible]	[illegible]	.620410E-09	.208069	[illegible]	[illegible]	[illegible]	[illegible]	-.0019	[illegible]

```
PROGRAM MINCT1      73/174  OPT=1                FTN 4.8+498        80/06/08. 14.28.34      PAGE    1

            PROGRAM MINCT1(INPUT,OUTPUT)
            EXTERNAL FUNCT1
            COMMON F0,FI,QP,K1,K2,K3,FR,QPP,X1N,X2N,X3N,X4N,X5N,FIN,QPN
            REAL K1,K2,K3
            DIMENSION W(30),X(5),H(25),G(5)
            PRINT 1
      1     FORMAT(////,5X,*CONCORDIA UNIVERSITY-SGWU CAMPUS.          MONTREAL
     * 1980.*)
            PRINT 3
      3     FORMAT(//,5X,*MAJOR TECHNICAL REPORT IN EL. ENGINEERING.*,/
     *5X,*UNITY_GAIN BAND PASS ACTIVE FILTER*,//
     *5X,*OPTIMIZATION OF FILTER ELEMENTS*,//
     *5X,*...........BY PARASKEVAS PRODOPIS.I.D. NO. 4901956......*,//
     *5X,*..........ADVISOR DR. B. BHATTACHARYYA. EL. ENG...........*,///
     *5X,*THIS PROGRAM MINIMIZES THE TOTAL CAPACITANCE "CT" OF THE*,/
     *5X,*FILTER,GIVEN CONSTRAINTS "G1","G2",AND "G3" FOR SPECIFIED*,/
     *5X,*RESONANCE FREQUENCY "F0" AND POLE_Q "QP" RESP. AND INITIAL*,/
     *5X,*COMPONENT VALUES R1,R2,R3,C1,AND C2(ALL INDEPENDENT FROM*,/
     *5X,*EACH OTHER.  THE BAND PASS INSERTION LOSS "HOP" IS*,/
     *5X,*DEPENDENT ON FILTER PASSIVE COMPONENTS AND IS GIVEN BY *,/
     *5X,*                HOP=R3/(R2+R3)*,//
     *5X,*....IN THIS ANALYSIS QUASI_NEWTON ALGORITHM IS USED....*,////)
    105     READ *,F0,QP,K1,K2,K3
            IF(F0.EQ.0.) GO TO 100
            PRINT 5,F0,QP,K1,K2,K3
      5     FORMAT(5X,10HFREQUENCY=,F6.1,5HHERTZ,3X,3HQP=,F5.1,3X,*PENALTY COE
     *FFICIENTS *,2X,3HK1=,F10.2,2X,3HK2=,F10.2,2X,3HK3=,F10.2,//)
            PRINT 2
      2     FORMAT(5X,61H......MINIMIZE "CT" WHEN HOP IS FLOATING ,C1=C2,AND R
     *1,R2,R3 ARE DIFFERENT .......//)
     35     PI=2.*3.14159265359
            X(1)=1.E+5
            X(2)=1.E+2
            X(3)=1.E+2
            X(4)=(X(2)+X(3))/(X(1)*X(2))*QP/FI
            X(5)=(1./(X(2)+X(3)))*(1./(QP*FI))
            X1N=X(1)
            X2N=X(2)
            X3N=X(3)
            X4N=X(4)
            X5N=X(5)
            X(1)=X(1)/X1N
            X(2)=X(2)/X2N
            X(3)=X(3)/X3N
            X(4)=X(4)/X4N
            X(5)=X(5)/X5N
            FIN=FI/FI
            QPN=QP/QP
            N=5
            NSIG=24
            MAXFN=10000
            IOPT=0
            ICOUNT=0.
            PRINT 6
      6     FORMAT(5X,*R1(OHMS)*,4X,*R2(OHMS)*,
     *4X,*R3(OHMS)*,4X,*C1(FARADS)*,4X,*C2(FARADS)*,7X,*CT(FARADS)*,1X,*
     *COUNT*,3X,*F0*,6X,*QP*,5X,*G1*,3X,*G2*,3X,*G3*,//)
            CALL ZXMIN(FUNCT1,N,NSIG,MAXFN,IOPT,X,H,G,F,W,IER)
            PRINT 15
     15     FORMAT(//,15X,*X(1)*,7X,*X(2)*,10X,*X(3)*,12X,*X(4)*,15X,*X(5)*)
            PRINT 10,(X(I),I=1,5)
     10     FORMAT(/,5X,5G15.6)
            PRINT 20,F,G1,G2,G3
     20     FORMAT(//,10X,1HF,10X,2HG1,10X,2HG2,10X,2HG3/1X,4G15.6)
            PRINT 25,FR,QPP,IER
     25     FORMAT(//,15X,2HF0,15X,2HQP,/,8X,2G15.6,//,5X,4HIER=,I3,//)
            GO TO 105
    100     STOP
            END

SUBROUTINE FUNCT1       73/174  OPT=1            FTN 4.8+498        80/06/08. 14.28.34      PAGE    1

            SUBROUTINE FUNCT1(N,X,F)
            DIMENSION X(N)
C           MINIMIZE TOTAL CAPACITANCE CT GIVEN CONSTRAINTS
C           IMPOSED BY CENTER FREQUENCY F0 AND QP OF THE BAND PASS FILTER
C           CASE II---HOP FLOATING,R1,R2,R3 ARE DIFFERENT AND C1=C2----
C
            COMMON F0,FI,QP,K1,K2,K3,FR,QPP,X1N,X2N,X3N,X4N,X5N,FIN,QPN
            REAL K1,K2,K3
C
C           CONSTRAINT ON CT IMPOSED BY THE EQUALITY-F0=F(R1,R2,C1,C2)-
            G1=(FI**2)*(X(1)*X(2)*X(4)*X(5)*X1N*X2N*X4N*X5N)-1.
C           CONSTRAINT ON CT IMPOSED BY THE EQUALITY-QP=F(R1,R2,R3,C1,C2)-
            G2=(QP**2)*(X(2)*X2N+X(3)*X3N)**2*(X(5)*X5N/(X(4)*X4N*X(1)*X1N*X(2
     *)*X2N))-1.
C           CONSTRAINT ON CT IMPOSED BY THE EQUALITY-C1=C2-
            G3=(X(4)/X(5))*(X4N/X5N)-1.
C           UNCONSTRAINED TOTAL CAPACITANCE "CT"
            CT=((X(2)+X(3))/(X(1)*X(2)))*QPN+(1./(X(2)+X(3)))*(1./QPN)
C             CONSTRAINED TOTAL CAPACITANCE "CT" TO BE MINIMIZED GIVEN
C           ABOVE CONSTRAINTS
            F=K1*G1**2+K2*G2**2+K3*G3**2
```

```
      [illegible]
      R1=X(1)*X1N
      R2=X(2)*X2N
      R3=X(3)*X3N
      C1=X(4)*X4N
      C2=X(5)*X5N
      R1=ABS(R1)
      R2=ABS(R2)
      R3=ABS(R3)
      C1=ABS(C1)
      C2=ABS(C2)
      HBP=R3/(R2+R3)
      CTO=C1*C2
      FR=(1./6.283185)*(1./SQRT(C1*C2*R1*R2))
      QPP=(1./(R2+R3))*SQRT(R1*C1*R2/C2)
      IP=(ICOUNT/20)*20
      IF(IP.EQ.ICOUNT)  PRINT 17,HBP,R1,R2,R3,C1,C2,CTO,ICOUNT,FR,QPP,G1
     +,G2,G3
      ICOUNT=ICOUNT+1
   17 FORMAT(1X,7G12.4,1X,I4,F10.2,F7.2,F7.4,F7.4,F7.4)
      IF((C1.OR.C2).LT.1.E-10) STOP
      IF(R1.GT.5.E+6) STOP
      RETURN
      END

      SYMBOLIC REFERENCE MAP (R=1)

ENTRY POINTS
    3  FUNCT1
```

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F2.2 Description of Function Subroutine FUNCTI

This subroutine shares the "common" variables and constants with the main program and the second subroutine ZXMIN. These "common" elements feed the minimization algorithm ZXMIN.

The constraints and the final unconstrained objective function are calculated in this subroutine. The computed variables (filter components) and parameters are denormalized and printed every 20 iterations. Then, if the minimum point or the end-values of any of the five components is reached a "stop" command terminates the main program. Figure F.2 describes the function of FUNCTI in more detail

F2.3 Function subroutine ZXMIN

Again, the set of variables (COMMON) and constants, as well as the function subroutine FUNCTI, initialization of counter ($i=0, \bar{X} = \bar{x}^i$), and initialization of H(i.e. H = Ho = I) are called to prepare the algorithm for the process of minimization. Next, the loop is starting where all the minimization steps are included. In this loop, the gradients G^i (I) are computed, and are tested if they reached the minimum value "e", whereby minimum point is assumed and the algorithm terminates. Subsequently, the hessian matrix is computed; if it exists a step size "k" is properly estimated

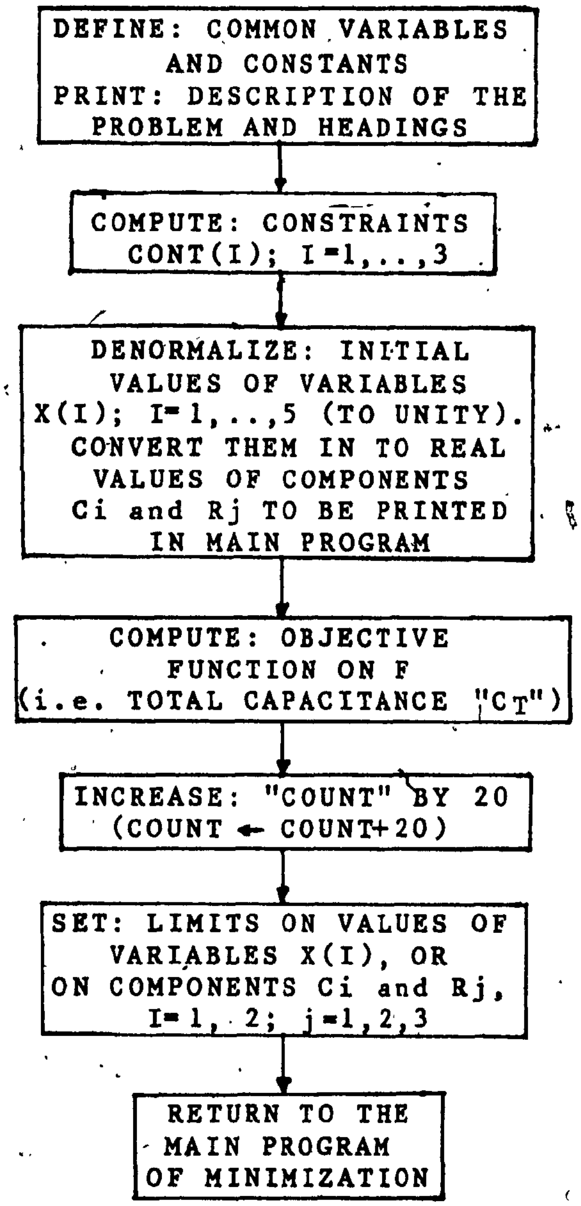
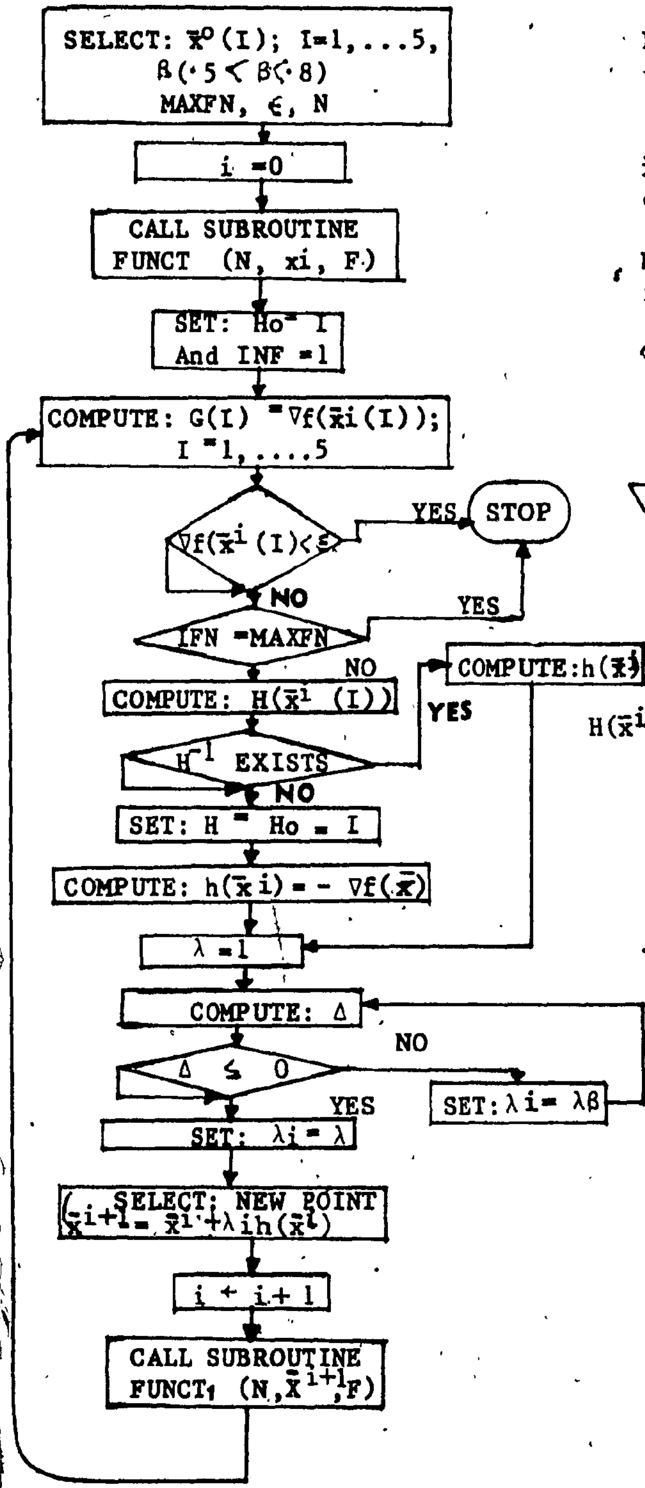


Fig E2 - Subroutine Function FUNCTI (N,X,F) and the new point $\bar{x}^{i+1}$ is calculated according to prescribed formula. Then, the counter is increased ($i \leftarrow i + 1$) and the process is repeated by assigning new value in F and gradients $G^{i+1}(I)$. Detailed description is found in the flow chart, Fig. F.3.

F2.4 Description of main programs and subroutines of the Fletcher-Powell's algorithm

This group of programs, which is the most important part of the minimization analysis in this report, minimizes the total capacitance, the total resistance area, and their combination, of the filter configuration under study. Each of the above three objective functions to be minimized consists of four cases, which describe the different constraints imposed, per Table - 4 (program No. 13 to 48). As in Quasi-Newton's algorithm, all programs are similar in formutation, the only difference being the constraints and consequently the objective functions.
The functional description of the main programs and subroutines are detailed in the flow charts, fig. F.4, F.5, F.6 and F.7 respectively and in their corresponding listings.



FUNCT1 = Function subroutine (calculates function F at point x̄i)

$\bar{x}^o(I)$ = initial guess of $\bar{x}$

MAXFN = max. no. of function evaluations

ϵ = tolerance no. (used in stopping criteria)

$$\nabla f(\bar{x}^i(I)) = \begin{bmatrix} \frac{\partial f(\bar{x})^i}{\partial x_1} \\ \\ \frac{\partial f(\bar{x})^i}{\partial x_n} \end{bmatrix}$$

$$H(\bar{x}^i) = \begin{bmatrix} \frac{\partial^2 f(\bar{x}^i)}{\partial x_1^2} & \cdots & \frac{\partial^2 f(\bar{x}^i)}{\partial x_1 \, \partial x_n} \\ \vdots & & \vdots \\ \frac{\partial^2 f(\bar{x}^i)}{\partial x_n \, \partial x_1} & \cdots & \frac{\partial^2 f(\bar{x}^i)}{\partial^2 x_n} \end{bmatrix} = \nabla\nabla f(\bar{x}^i)$$

$$h(\bar{x}^i) = - H(\bar{x}^i)^{-1} \nabla f(\bar{x}^i)$$

$$\Delta = f(\bar{x}^i + \lambda h(\bar{x}^i)) - f(\bar{x}^i) - \frac{\lambda}{2} \langle \nabla f(\bar{x}^i), h(\bar{x}^i) \rangle$$

where, $\langle \bar{x}, \bar{y} \rangle = \sum_{i=1}^{n} x_i y_i$

Figure F3 - Function subroutine ZXMIN (FUNCT1, N,...,X,H,G,F,..)

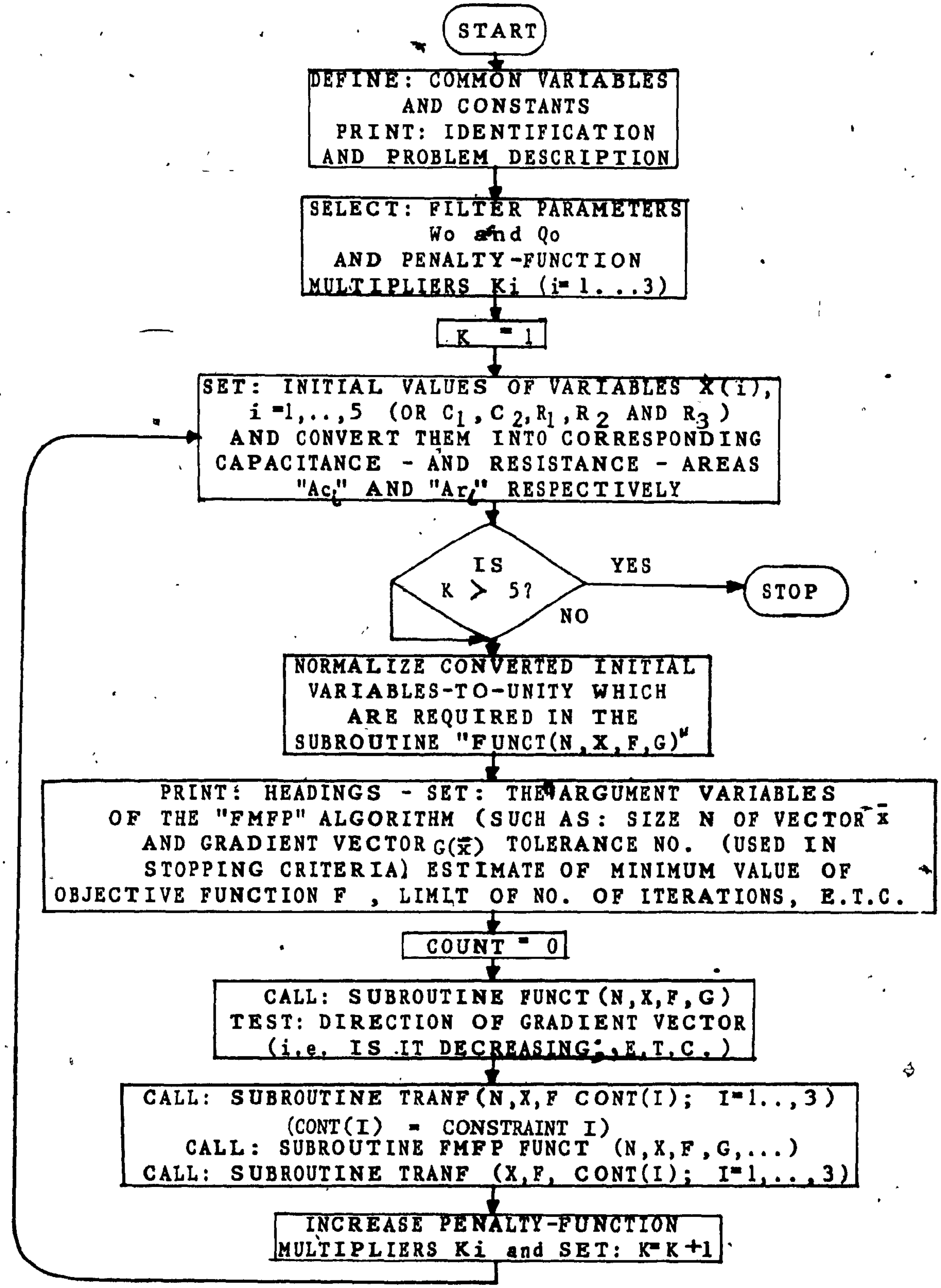


Fig F.4 - Main program of minimization by Fletcher-Powell's algorithm

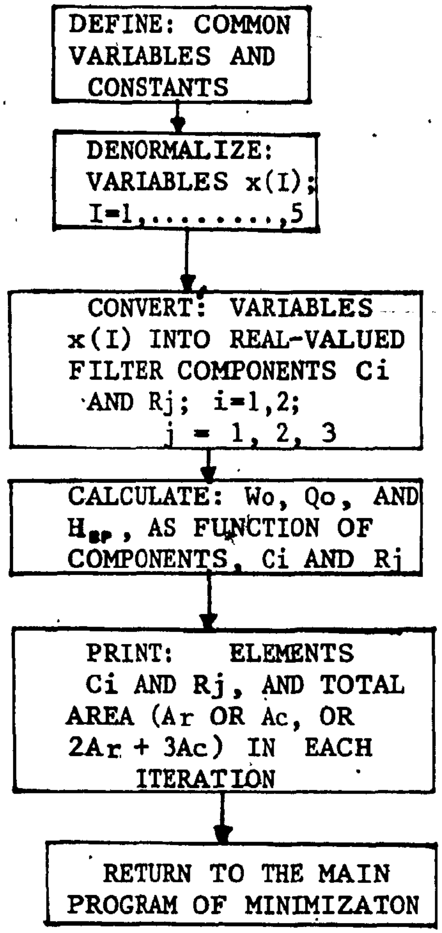


Fig. E5 - Subroutine TRANF (X, F, CONT (I); I = 1, ...3)

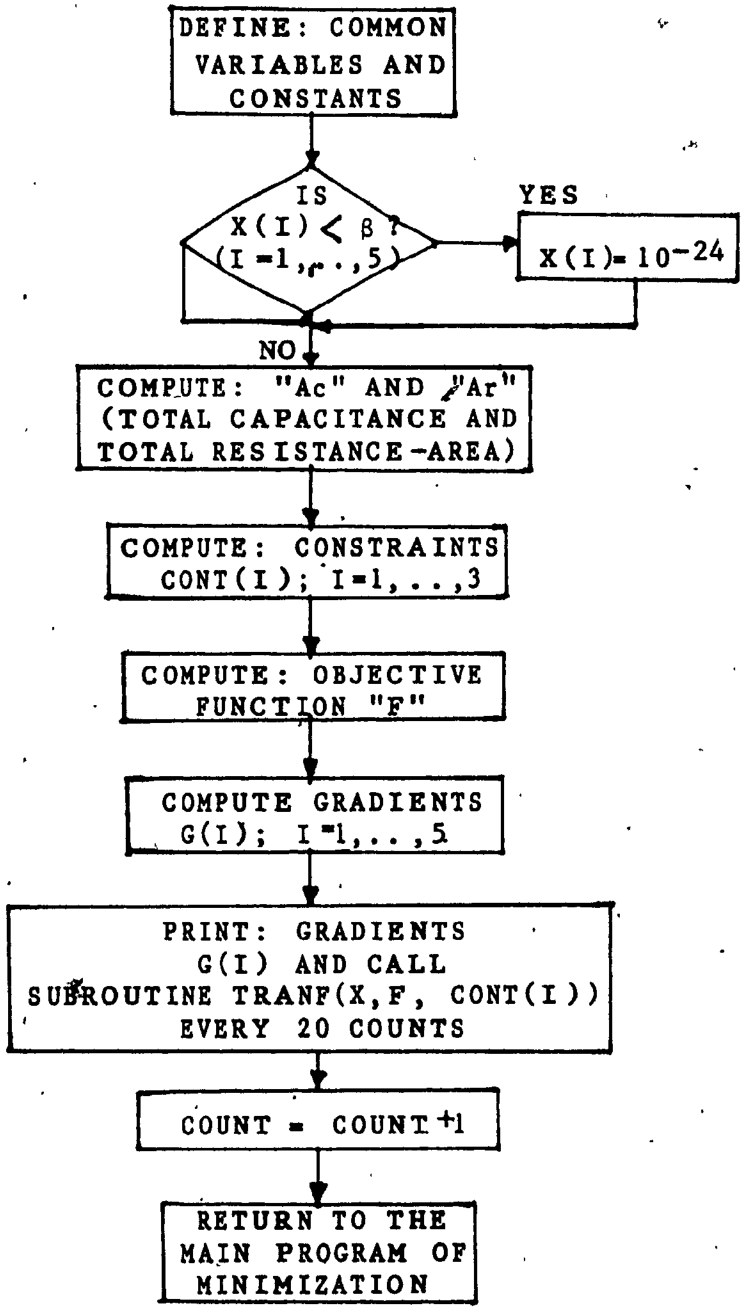
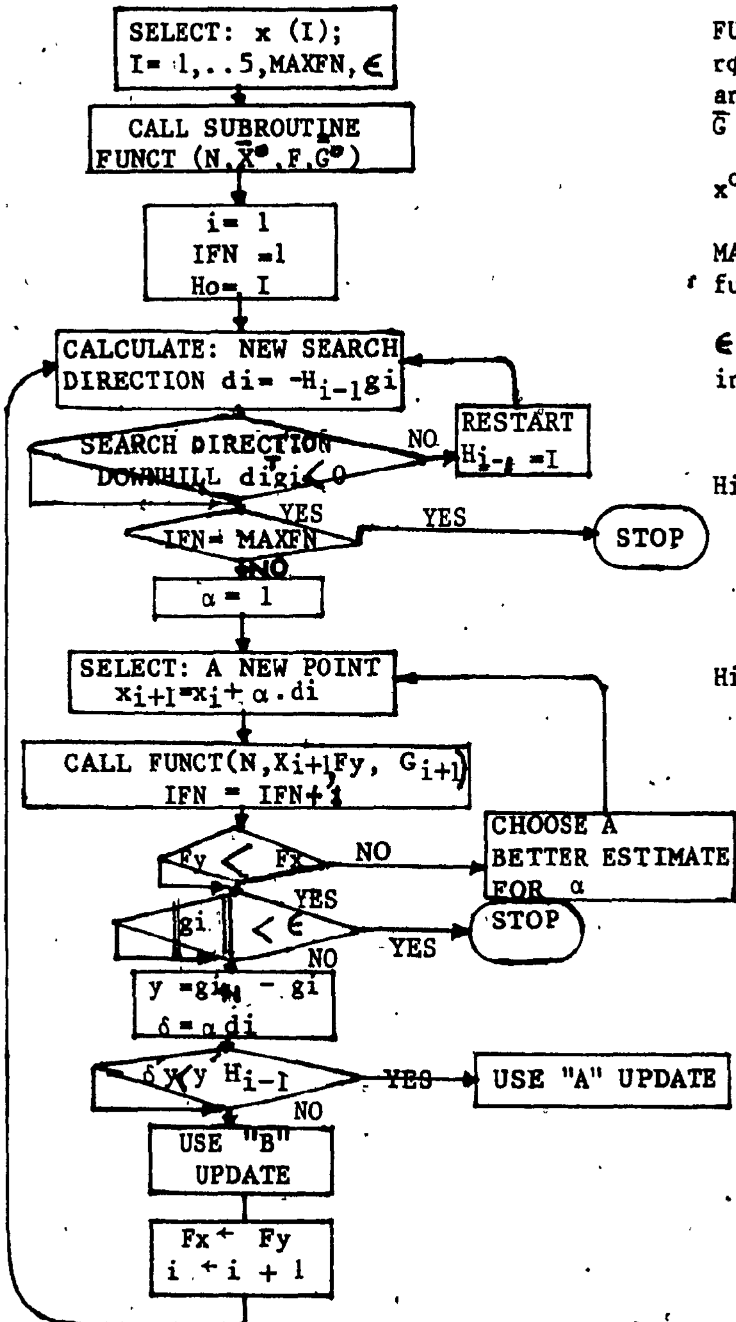


Fig F.6 - Subroutine FUNCT (N,X,F,G)



FUNCT Function subroutine (Calculates F and gradient vector $\bar{G}$ at point $\bar{x}i$)

$x^o(I)$ = initial guess

MAXFN= max. no. of function evaluations

∈ =tolerance no.(used in stopping criteria)

"A" UPDATE

$$H_i = H_{i-1} + \frac{\delta\delta'}{\delta' y} - \frac{H_{i-1} y y' H_{i-1}}{y' H_{i-1} y}$$

"B" UPDATE

$$H_i = \left(I - \frac{y\delta'}{y'\delta}\right) H_{i-1} \left(I - \frac{\delta y'}{y'\delta}\right) + \frac{y y'}{\delta' y}$$

Figure F.7 - Subroutine FMFP (FUNCT, N,X,F,G,...)

```
PROGRAM C1MIN     73/174  OPT=1                    FTN 4.8+498       80/05/05. 20.50.33     PAGE   1

            PROGRAM C1MIN(INPUT,OUTPUT)
            EXTERNAL FUNCT
            COMMON FI,OP,H1,H2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
            DIMENSION X(5),Y(5),G(5),H(40),GG(5)
            PRINT 25
         25 FORMAT(10X,42HMAJOR TECHNICAL REPORT IN EL. ENGINEERING.)
            PRINT 26
         26 FORMAT(5X,64HUNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
           *_TER ELEMENTS,/)
            PRINT 27
         27 FORMAT(5X,37HBY PARASKEVAS PROKOPIS  I.D.  6901956.,/)
            PRINT 28
         28 FORMAT(5X,31HADVISOR  DR. B.B. BHATTACHARYYA,//)
            PRINT 29
         29 FORMAT(5X,*THIS PROGRAM MINIMIZES THE AREA "AC" CORRESPONDING*,/
           *5X,* TO THE TOTAL CAPACITANCE "CT" OF THE IC_ACTIVE FILTER*,/
           *5X,*USING PROPER DEPOSITION THIN_FILM ON PROPER SUBSTRATE*,/
           *5X,*(I.E. THE SUBSTRATE CONFINES THE TOTAL AREA INCLUDING*,/
           *5X,*THAT OF THE ACTIVE COMPONENTS)  GIVEN CONSTRAINTS FOR*,/
           *5X,*SPECIFIED CENTER FREQUENCY "FO",POLE_Q*,/
           *5X,* "OP" AND FLOATING BAND PASS MAX. GAIN "HBP",AS WELL AS,*,/
           *5X,*ALL FIVE FILTER ELEMENTS  C1,C2,R1, R2, AND R3 *,/)
            PRINT 30
         30 FORMAT(5X,60HIN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD
           *IS USED,//)
            PRINT 45
         45 FORMAT(//,10X,*MINIMIZATION FUNCTION  F="AC"...........WHERE *,/
           *5X,*AC=(2/3).(VBR/(E0.ER.E)).CT=A1.CT  (CM_SQR)*,/
           *5X,*AR=((W_SQR)/RS).RT=A2.RT  (CM_SQR)*,/
           *5X,*VBR=BREAKING VOLTAGE  (VOLTS)*,/
           *5X,*E0=8.85X10**(-14) IS THE PERMITTIVITY OF THE FREE SPACE.*,/
           *5X,*(FARADS/CM)*,/
           *5X,*ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.*,/
           *5X,*E=DIELECTRIC STRENGTH OF THE THIN_FILM  (VOLTS/CM)*,/
           *5X,*W=WIDTH OF THE THIN_FILM RESISTIVE LINE  (CM)*,/
           *5X,*RS=SHEET RESISTANCE OF THE RESIST. LINE  (OHMS/SQR)*,/
           *5X,*CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER  (FARADS)*,/
           *5X,*RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER  (OHMS)*,//
           *5X,*NOTE  THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.*,///)
            PRINT 1
          1 FORMAT(5X,11HINPUT F0,OP)
            READ*,F0,OP,H1,H2
            FI=6.2831853*F0
            VBR=100.
            E0=8.85E-14
            ER=25.
            E=4.E+6
            W=5.E-3
            RS=50.
            A1=(2./3.)*VBR/(E0*ER*E)
            A2=W**2/RS
            PRINT 110
        110 FORMAT(/,8X,*VBR*,6X,*E0*,6X,*ER*,8X,*E*,9X,*W*,10X,*RS*,/)
            PRINT 115,VBR,E0,ER,E,W,RS
        115 FORMAT(6X,F6.1,1X,E10.3,1X,F5.1,1X,E10.3,1X,E10.3,3X,F5.1,//)
            PRINT 120
        120 FORMAT(5X,*A1=(2/3).(VBR/(E0.ER.E))*,5X,*A2=((W_SQR)/RS*,/)
            PRINT 125,A1,A2
        125 FORMAT(7X,E13.6,10X,E13.6,/)
            DO 100 K=1,5
            R1=1.E+6
            R2=1000.
            R3=1000.
            C1=((R2+R3)/(R1*R2))*OP/FI
            C2=(1./(R2+R3))*(1./(OP*FI))
            Y(1)=A1*C1
            Y(2)=A1*C2
            Y(3)=A2*R1
            Y(4)=A2*R2
            Y(5)=A2*R3
            A1N=Y(1)
            A2N=Y(2)
            A3N=Y(3)
            A4N=Y(4)
            A5N=Y(5)
            X(1)=Y(1)/A1N
            X(2)=Y(2)/A2N
            X(3)=Y(3)/A3N
            X(4)=Y(4)/A4N
            X(5)=Y(5)/A5N
            X1=A1/A1N
            X2=A1/A2N
            X3=A2/A3N
            X4=A2/A4N
            X5=A2/A5N
            PRINT 15,F0,OP
         15 FORMAT(5X,3HF0=,F8.1,6X,3HOP=,F5.1)
            PRINT 2
          2 FORMAT(//,5X,14HINPUT X VECTOR)
            PRINT 19,X(1),X(2),X(3),X(4),X(5)
         19 FORMAT(40X,4HX(I),/5E17.6,//)
            PRINT 3,H1,H2
          3 FORMAT(21X,2HH1,20X,2HH2,/,6X,2F22.12,/)
            N=5
            EST=0.
            EPS=1.E-8
            LIMIT=10000
            ICOUNT=0
         99 CALL FUNCT(N,X,F,G)
            DO 70 I=1,5
            X(I)=X(I)*1.0000001
            CALL FUNCT(N,X,FF,E)
            X(I)=X(I)/1.0000001
            GG(I)=(FF-F)/(X(I)*.0000001)
         70 CONTINUE
```

```
      PRINT 16,(G(I),I=1,5)
   16 FORMAT(//,42X,22HVERIFIED VALUE OF G(I),/,14X,5G18.6)
      PRINT 20
   20 FORMAT(////)
      CALL TRANF(X,F,CONT1,CONT2)
      PRINT 200
  200 FORMAT(/////,25X,44HMINIMIZATION ALGORITHM STARTS AT THIS POINT../
     */)
      PRINT 8
    8 FORMAT(30X,18HCIRCUIT PARAMETERS,/)
      CALL FMFP(FUNCT,N,X,F,G,EST,EPS,LIMIT,IER,H)
      CALL TRANF(X,F,CONT1,CONT2)
      H1=H1*2.
      H2=H2*2.
      PRINT 4,IER
    4 FORMAT(5X,4HIER=,I2,///)
  100 CONTINUE
      STOP
      END
```

SUBROUTINE TRANF   73/174 OPT=1   FTN 4.8+498   80/05/05. 20.50.33   PAGE 1

```
      SUBROUTINE TRANF(X,F,CONT1,CONT2)
      DIMENSION X(5),Y(5)
      COMMON F1,OP,H1,H2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
      C1=X(1)/X1
      C2=X(2)/X2
      R1=X(3)/X3
      R2=X(4)/X4
      R3=X(5)/X5
      IF(R1.GT.(5.E+6)) STOP
      IF(R2.GT.(5.E+6)) STOP
      IF(R3.GT.(5.E+6)) STOP
      C1=ABS(C1)
      C2=ABS(C2)
      R1=ABS(R1)
      R2=ABS(R2)
      R3=ABS(R3)
      HOP=R3/(R2+R3)
      BB=HOP
      CT=C1+C2
      RT=R1+R2+R3
      AC=A1*CT
      AR=A2*RT
      FR=(1./SQRT(C1*C2*R1*R2))*(1./6.283185)
      QPP=(1./(R2+R3))*SQRT(R1*R2*C1/C2)
      IA=ICOUNT-5
      IF(IA.GE.0) PRINT 50,IA
   50 FORMAT(/,56X,6HCOUNT=,I5,/)
      PRINT 12,C1,C2,R1,R2,R3,AR
   12 FORMAT(4X,3HC1=,G11.5,1HF,1X,3HC2=,G11.5,1HF,1X,3HR1=,G11.5,4HOHMS
     *,1X,3HR2=,G11.5,4HOHMS,1X,3HR3=,G11.5,4HOHMS,1X,3HAC=,G11.5,8H(CM
     *SQR),/)
      PRINT 2,AC,CONT1,CONT2,F
    2 FORMAT(5X,30HTOTAL CAPACITANCE SURFACE AREA "AC"=,G11.5,8H(CM SQR)
     *,2X,13HCONSTRAINTS  ,E12.6,1X,E12.6,3X,2HF=,G11.5,/)
      PRINT 10,FR,QPP,BB
   10 FORMAT(10X,3HFR=,F24.6,5HHERTZ,4X,3HQP=,F15.6,4X,5HGAIN=,F8.6,//)
      RETURN
      END .
```

SUBROUTINE FUNCT   73/174 OPT=1   FTN 4.8+498   80/05/05. 20.50.33   PAGE 1

```
      SUBROUTINE FUNCT(N,X,F,G)
      DIMENSION X(N),G(N)
      COMMON F1,OP,H1,H2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
      DO 10 I=1,5
      IF(ABS(X(I)).LT.1.E-24) X(I)=1.E-24
   10 CONTINUE
      AC=X(1)+X(2)
      AR=X(3)+X(4)+X(5)
      CONT1=F1**2*((X(1)*X(2)*X(3)*X(4))/(X1*X2*X3*X4))-1.
      CONT2=((OP**2)*((X(4)/X4+X(5)/X5)**2)*X(2)*X1*X3*X4/(X(1)*X(3)*X(4
     *)*X2))-1.
      F=AC+(H1*(CONT1**2))+(H2*(CONT2**2))
      G(1)=1.+(2./X(1))*(H1*CONT1*(CONT1+1.)-H2*CONT2*(CONT2+1.))
      G(2)=1.+(2./X(2))*(H1*CONT1*(CONT1+1.)+H2*CONT2*(CONT2+1.))
      G(3)=(2./X(3))*(H1*CONT1*(CONT1+1.)-H2*CONT2*(CONT2+1.))
      G(4)=(2./X(4))*(H1*CONT1*(CONT1+1.)+((X(4)/X4-X(5)/X5)/(X(4)/X4+X(
     *5)/X5))*H2*CONT2*(CONT2+1.))
      G(5)=(4./(X(4)*(X5/X4)+X(5)))*H2*CONT2*(CONT2+1.)
      IP=(ICOUNT/20)*20
      IF(IP.EQ.ICOUNT) PRINT 60,(G(I),I=1,5)
   60 FORMAT(45X,23HCOMPUTED GRADIENTS G(I),/10X,5G18.7,//)
      IF(IP.EQ.ICOUNT) CALL TRANF(X,F,CONT1,CONT2)
      ICOUNT=ICOUNT+1
      RETURN
      END
```

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```
     MAJOR TECHNICAL REPORT IN EL. ENGINEERING.
UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FILTER ELEMENTS

BY PARASKEVAS PHREMPIS  I.D.  6081956

ADVISOR  DR. R.B. BHATTACHARYYA

THIS PROGRAM MINIMIZES THE AREA "AC" CORRESPONDING
 TO THE TOTAL CAPACITANCE "CT" OF THE RC_ACTIVE FILTER
USING PROPER DEPOSITION THIN_FILM ON PROPER SUBSTRATE
(I.E. THE SUBSTRATE CONFINES THE TOTAL AREA INCLUDING
THAT OF THE ACTIVE COMPONENTS)  GIVEN CONSTRAINTS FOR
SPECIFIED CENTER FREQUENCY "FO",POLE_Q
 "QP" AND FLOATING BAND PASS MAX. GAIN "HOP",AS WELL AS,
ALL FIVE FILTER ELEMENTS  C1,C2,R1, R2, AND R3

IN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD IS USED

     MINIMIZATION FUNCTION  F="AC"..........WHERE
AC=(2/3).(VBR/(EO.ER.E)).CT=A1.CT  (CM_SQR)
AR=((W_SQR)/RS).RT=A2.RT  (CM_SQR)
VBR=BREAKING VOLTAGE  (VOLTS)
EO=0.55X10(-10) IS THE PERMITTIVITY OF THE FREE SPACE.
(FARADS/CM)
ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.
E=DIELECTRIC STRENGTH OF THE THIN_FILM  (VOLTS/CM)
W=WIDTH OF THE THIN_FILM RESISTIVE LINE  (CM)
RS=SHEET RESISTANCE OF THE RESIST. LINE  (OHMS/SQR)
CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER  (FARADS)
RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER  (OHMS)

NOTE  THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.

INPUT FO,QP
   VBR      EO       ER        E         W        RS
  100.0   .885E-13  25.0   .400E+07   .500E-02   50.0

A1=(2/3).(VBR/(EO.ER.E))     A2=((W_SQR)/RS
    .753296E+07             .500000E-06
FO=   500.0      QP= 50.0

INPUT X VECTOR
                                X(I)
 .100000E+01    .100000E+01    .100000E+01    .100000E+01    .100000E+01

            W1                  W2
     1000.00000000030    1000.00000000000
                          COMPUTED GRADIENTS G(I)
         1.000000       1.000000      .14210085E-10    -.14210085E-10    -.20421718E-10

C1= .310311E-07F C2= .310311E-08F R1= .10000E+07OHMS R2= 1000.0    OHMS R3= 1000.0    OHMS AC= .50100   (CM_SQR)
TOTAL CAPACITANCE_SURFACE AREA "AC"= .26376    (CM_SQR)  CONSTRAINTS  -.710543E-14 -.142109E-13   F= 2.0000
    FO=          500.000000HERTZ    QP=        50.000000   GAIN= .500000

                          VERIFIED VALUE OF G(I)
           1.00032        1.00002        .190952E-04       .994760E-05       .994760E-05

                              COUNT=     0
C1= .310311E-07F C2= .310311E-08F R1= .10000E+07OHMS R2= 1000.0    OHMS R3= 1000.0    OHMS AC= .50100   (CM_SQR)
TOTAL CAPACITANCE_SURFACE AREA "AC"= .26376    (CM_SQR)  CONSTRAINTS  0.          0.            F= 2.0000
    FO=          500.000000HERTZ    QP=        50.000000   GAIN= .500000

              MINIMIZATION ALGORITHM STARTS AT THIS POINT.

                 CIRCUIT PARAMETERS
                          COMPUTED GRADIENTS G(I)
        -9.046392      -10.04075      -9.116019      -9.507029      -.4657310

                              COUNT=    14
C1= .302736E-07F C2= .333[illegible]    1047.5    OHMS R3= 1049.7    OHMS [illegible]
```

```
TOTAL CAPACITANCE_SURFACE AREA "AC"= .25090    [CM_SQR]  CONSTRAINTS  -.5046595E-02 -.2437795E-03   F= 1.9295
     FO=            531.2664442HERTZ    QP=     50.006096    GAIN= .499500

                              COMPUTED GRADIENTS G(I)
        .6351473         1.491003        -.3304007         .5930282E-01       .3096578

                                   COUNT=    34
C1= .33250E-07F C2= .33330E-08F R1= .10495E+07OHMS R2= 1049.9    OHMS R3= 1045.2    OHMS AC= .52500    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .25003    [CM_SQR]  CONSTRAINTS  .3067295E-04  .1040592E-03   F= 1.9094
     FO=            499.9923320HERTZ    QP=     49.994099    GAIN= .490000

                              COMPUTED GRADIENTS G(I)
       -3.253900         3.712958        -4.244492        -1.115927          3.072079

                                   COUNT=    54
C1= .25979E-07F C2= .26504E-08F R1= .12016E+07OHMS R2= 1226.0    OHMS R3= 1177.9    OHMS AC= .60294    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .21571    [CM_SQR]  CONSTRAINTS  -.7109493E-03  .1030700E-02   F= 1.6046
     FO=            500.1777310HERTZ    QP=     49.954096    GAIN= .491213

                              COMPUTED GRADIENTS G(I)
       -11.44019        -6.457104        -7.796493        -5.704772          1.033172

                                   COUNT=    74
C1= .23070E-07F C2= .23694E-08F R1= .13420E+07OHMS R2= 1379.3    OHMS R3= 1300.7    OHMS AC= .67276    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .19170    [CM_SQR]  CONSTRAINTS  -.4021256E-02  .1220115E-02   F= 1.4071
     FO=            501.0063540HERTZ    QP=     49.969326    GAIN= .487700

                              COMPUTED GRADIENTS G(I)
       -10.61188        -12.51836        -5.169391        -5.654503         -.3207270

                                   COUNT=    94
C1= .21023E-07F C2= .21694E-08F R1= .14036E+07OHMS R2= 1493.9    OHMS R3= 1439.3    OHMS AC= .74325    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .17460    [CM_SQR]  CONSTRAINTS  -.4294836E-02 -.3019038E-03   F= 1.3588
     FO=            501.0619570HERTZ    QP=     50.009592    GAIN= .490601

                              COMPUTED GRADIENTS G(I)
        2.975814        -8.353956         .7700564        -1.526285         -2.277318

                                   COUNT=   114
C1= .19590E-07F C2= .23223E-08F R1= .15784E+07OHMS R2= 1618.4    OHMS R3= 1526.9    OHMS AC= .79076    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .16200    [CM_SQR]  CONSTRAINTS  -.1183238E-02 -.1702780E-02   F= 1.2994
     FO=            500.2960710HERTZ    QP=     50.044600    GAIN= .485122

                              COMPUTED GRADIENTS G(I)
       -6.000670        -8.449656        -2.279796        -2.676617         -.4624453

                                   COUNT=   134
C1= .17830E-07F C2= .18962E-08F R1= .17223E+07OHMS R2= 1773.3    OHMS R3= 1691.7    OHMS AC= .86206    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .14830    [CM_SQR]  CONSTRAINTS  -.2364018E-02 -.3961298E-03   F= 1.1490
     FO=            500.3722530HERTZ    QP=     50.009906    GAIN= .482291

                              COMPUTED GRADIENTS G(I)
       -7.811010        -11.09906        -2.430960        -2.902061         -.5540968

                                   COUNT=   154
C1= .16416E-07F C2= .17163E-08F R1= .18619E+07OHMS R2= 1918.3    OHMS R3= 1785.0    OHMS AC= .93642    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .13809    [CM_SQR]  CONSTRAINTS  -.2779158E-02 -.9940870E-03   F= 1.0620
     FO=            500.6940050HERTZ    QP=     50.012372    GAIN= .482007
```

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                              COMPUTED GRADIENTS G(I)
        -21.10169        -1.703942        -5.171299        -2.766976        2.202119

                                   COUNT= 174
C1= .150996E-07F C2= .139909E-08F R1= .202678+07OHMS R2= 2075.7   OHMS R3= 1924.6   OHMS AC= 1.0154   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .12560   (CM_SQR)  CONSTRAINTS  -.296600E-02  .227712E-02   F= .90797
     FO=             500.743359HERTZ    OP=      49.943169   GAIN= .481108

                              COMPUTED GRADIENTS G(I)
        -13.61670        -9.695770        -2.950947        -2.941097        .3426667

                                   COUNT= 194
C1= .146346E-07F C2= .167... 2234.1   OHMS R3= 2063.2   OHMS ...
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .11606   (CM_SQR)  CONSTRAINTS  -.286221E-02  .367994E-03   F= .91405
     FO=             500.717092HERTZ    OP=      49.990003   GAIN= .480116

                              COMPUTED GRADIENTS G(I)
        -11.15640        -11.16719        -2.169123        -2.177096        -.63327795E-01

                                   COUNT= 214
C1= .131608E-07F C2= .139132E-08F R1= .231046+07OHMS R2= 2379.1   OHMS R3= 2190.3   OHMS AC= 1.1615   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .10906   (CM_SQR)  CONSTRAINTS  -.299359E-02  -.723485E-04   F= .85752
     FO=             500.649650HERTZ    OP=      50.001009   GAIN= .479338

                              COMPUTED GRADIENTS G(I)
        -6.600193        -16.07009        -1.204052        -2.273611        -1.101036

                                   COUNT= 234
C1= .121718E-07F C2= .128026E-08F R1= .250511E+07OHMS R2= 2572.3   OHMS R3= 2399.3   OHMS AC= 1.2950   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .10139   (CM_SQR)  CONSTRAINTS  -.207305E-02  -.139933E-02   F= .79717
     FO=             500.720016HERTZ    OP=      50.034010   GAIN= .478405

                              COMPUTED GRADIENTS G(I)
        -12.92323        -13.32237        -1.001080        -1.922973        -.89203195E-01

                                   COUNT= 254
C1= .119428E-07F C2= .121618E-08F R1= .266078+07OHMS R2= 2729.5   OHMS R3= 2490.3   OHMS AC= 1.3330   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .953560-01(CM_SQR)  CONSTRAINTS  -.262610E-02  -.116703E-03   F= .74043
     FO=             500.657820HERTZ    OP=      50.002010   GAIN= .477893

                              COMPUTED GRADIENTS G(I)
        -17.40089        -6.003401        -2.213750        -1.402776        .6074561

                                   COUNT= 274
C1= .137660E-07F C2= .114895E-08F R1= .282478+07OHMS R2= 2096.7   OHMS R3= 2644.0   OHMS AC= 1.4151   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .897490-01(CM_SQR)  CONSTRAINTS  -.220711E-02  .923499E-03   F= .70475
     FO=             520.332093HERTZ    OP=      49.970980   GAIN= .477952

                              COMPUTED GRADIENTS G(I)
        3.631425         -7.702557        .2902111         -.3472629        -.5096760

                                   COUNT= 294
C1= .975300E-08F C2= .134290E-08F R1= .311200+07OHMS R2= 3196.5   OHMS R3= 2903.6   OHMS AC= 1.9996   (CM_SQR)
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .813760-01(CM_SQR)  CONSTRAINTS  -.511362E-03  -.815354E-03   F= .63939
     FO=             500.127800HERTZ    OP=      50.022900   GAIN= .475996

                              COMPUTED GRADIENTS G(I)
        5.420230         -33.06071        .3432907         -1.316045        -1.649207
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                                   COUNT=  314
C1= .00384E-00F C2= .92446E-09F R1= .35059E+07OHMS R2= 3613.1    OHMS R3= 3255.6    OHMS AC= 1.7567    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .71904E-01[CM_SQR]  CONSTRAINTS  -.222519E-02 -.204013E-02   F= .57465
      FO=             500.55973SHERTZ     QP=      50.871155    GAIN= .473909

                          COMPUTED GRADIENTS G(I)
      -23.76909       -9.272525       -1.722726       -1.109173       .4070002

                                   COUNT=  334
C1= .81732E-00F C2= .81004E-09F R1= .36010E+07OHMS R2= 3603.4    OHMS R3= 3418.9    OHMS AC= 1.8405    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= [illegible]-01[CM_SQR]  CONSTRAINTS  -.[illegible]-02  .[illegible]-03   F= .[illegible]
      FO=             500.977401HERTZ     QP=      49.970051    GAIN= .473301

                          COMPUTED GRADIENTS G(I)
      -25.31939       -3.[illegible]       -1.[illegible]       -.[illegible]       .[illegible]

                                   COUNT=  354
C1= .75107E-00F C2= .81212E-09F R1= .40659E+07OHMS R2= 4138.4    OHMS R3= 3690.2    OHMS AC= 2.0072    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .62695E-01[CM_SQR]  CONSTRAINTS  -.100533E-02  .120170E-02   F= .49611
      FO=             500.466905HERTZ     QP=      49.960906    GAIN= .471917

                          COMPUTED GRADIENTS G(I)
      -26.02165       -14.57572       -1.440671       -1.121505       .2706219

                                   COUNT=  374
C1= .71605E-00F C2= .77[illegible]                      4341.2    OHMS R3= 3866.6    OHMS[illegible]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .59777E-01[CM_SQR]  CONSTRAINTS  -.247370E-02  .571394E-03   F= .47984
      FO=             500.619574HERTZ     QP=      49.989721    GAIN= .471089

                          COMPUTED GRADIENTS G(I)
      -1.780025        3.172981       -.1369144       -.29103086E-02    .1292866

                                   COUNT=  394
C1= .68635E-00F C2= .74357E-09F R1= .43782E+07OHMS R2= 4534.4    OHMS R3= 4028.1    OHMS AC= 2.1934    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .57304E-01[CM_SQR]  CONSTRAINTS  -.229506E-04  .276669E-03   F= .44930
      FO=             500.005740HERTZ     QP=      49.993004    GAIN= .470444

                          COMPUTED GRADIENTS G(I)
      -33.89562        25.34156       -1.552961       -.1013586        1.506412

                                   COUNT=  414
C1= .65164E-00F C2= .7[illegible]E-09F R1= .4[illegible]E+07OHMS R2= 4763.3    OHMS R3= 4224.3    OHMS AC= 2.3049    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .54431E-01[CM_SQR]  CONSTRAINTS  -.430079E-03  .213210E-02   F= .43790
      FO=             500.107959HERTZ     QP=      49.921079    GAIN= .469907

                          COMPUTED GRADIENTS G(I)
      -20.87735       -24.24130       -.9053076       -.9922309       -.1172353

                                   COUNT=  434
C1= .62050E-00F C2= .61252E-09F R1= .47717E+07OHMS R2= 4937.4    OHMS R3= 4377.5    OHMS AC= 2.3906    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .52492E-01[CM_SQR]  CONSTRAINTS  -.243905E-02 -.273002E-03   F= .41702
      FO=             500.610601HERTZ     QP=      50.066620    GAIN= .469064

                          COMPUTED GRADIENTS G(I)
      -15.92794       -11.22350       -.6539906       -.5602039       .71979950E-01

                                   COUNT=  454
C1= .60727E-00F C2= .66043E-09F R1= .49385E+07OHMS R2= 5100.2    OHMS R3= 4523.2    OHMS AC= 2.4701    [CM_SQR]
 TOTAL CAPACITANCE_SURFACE AREA "AC"= .55720E-01[CM_SQR]  CONSTRAINTS  -.144340E-02  .173313E-03   F= .40037
      FO=             500.361269HERTZ     QP=      49.999060    GAIN= .469701
```

```
      PROGRAM RIMIN(INPUT,OUTPUT)
      EXTERNAL FUNCT
      COMMON FI,OP,H1,H2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5,
      DIMENSION X(5),Y(5),G(5),H(40),GG(5)
      PRINT 25
   25 FORMAT(10X,42HMAJOR TECHNICAL REPORT IN EL. ENGINEERING.)
      PRINT 26
   26 FORMAT(5X,*UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
     *LTER ELEMENTS*,/)
      PRINT 27
   27 FORMAT(5X,37HBY PARASKEVAS PRODROMIS I.D. 4901956,/)
      PRINT 28
   28 FORMAT(5X,31HADVISOR DR. R.B. BHATTACHARYYA,//)
      PRINT 29
   29 FORMAT(5X,*THIS PROGRAM MINIMIZES THE AREA "AR" CORRESPONDING*,/
     *5X,* TO THE TOTAL RESISTANCE "RT" OF THE RC_ACTIVE FILTER*,/
     *5X,*USING PROPER DEPOSITION THIN_FILM ON PROPER SUBSTRATE*,/
     *5X,*(I.E. THE SUBSTRATE CONFINES THE TOTAL AREA INCLUDING*,/
     *5X,*THAT OF THE ACTIVE COMPONENTS) GIVEN CONSTRAINTS FOR*,/
     *5X,*SPECIFIED CENTER FREQUENCY "FO",POLE_Q*,/
     *5X,* "QP" AND FIXED BAND PASS MAX. GAIN "HOP"="K",AS WELL AS,*,/
     *5X,*ALL FIVE FILTER ELEMENTS C1,C2,R1, R2, AND R3 *,/)
      PRINT 30
   30 FORMAT(5X,*IN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD
     *IS USED.///)
      PRINT 45
   45 FORMAT(//,10X,*MINIMIZATION FUNCTION F="AR"...........WHERE *,/
     *5X,*AC=(2/3).(VBR/(E0.ER.E)).CT=A1.CT (CM_SQR)*,/
     *5X,*AR=((W_SQR)/RS).RT=A2.RT (CM_SQR)*,/
     *5X,*VBR=BREAKING VOLTAGE (VOLTS)*,/
     *5X,*E0=8.85X10**(-14) IS THE PERMITTIVITY OF THE FREE SPACE.*,/
     *5X,*(FARADS/CM)*,/
     *5X,*ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.*,/
     *5X,*E=DIELECTRIC STRENGTH OF THE THIN_FILM (VOLTS/CM)*,/
     *5X,*W=WIDTH OF THE THIN_FILM RESISTIVE LINE (CM)*,/
     *5X,*RS=SHEET RESISTANCE OF THE RESIST. LINE (OHMS/SQR)*,/
     *5X,*CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER (FARADS)*,/
     *5X,*RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER (OHMS)*,//
     *5X,*NOTE THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.*,//)
      PRINT 1
    1 FORMAT(5X,11HINPUT FO,QP)
      READ*,FO,QP,H1,H2
      FI=6.2831854*FO
      VBR=100.
      E0=8.85E-14
      ER=25.
      E=4.E+6
      W=5.E-3
      RS=50.
      A1=(2./3.)*VBR/(E0*ER*E)
      A2=W**2/RS
      PRINT 110
  110 FORMAT(/,8X,*VBR*,6X,*E0*,6X,*ER*,8X,*E*,9X,*W*,10X,*RS*,/)
      PRINT 115,VBR,E0,ER,E,W,RS
  115 FORMAT(6X,F6.1,1X,E10.3,1X,F5.1,1X,E10.3,1X,E10.3,3X,F5.1,//)
      PRINT 120
  120 FORMAT(5X,*A1=(2/3).(VBR/(E0.ER.E))*,5X,*A2=((W_SQR)/RS*,/)
      PRINT 125,A1,A2
  125 FORMAT(7X,E13.6,10X,E13.6,/)
      DO 100 K=1,5
      R1=4.E+6
      R2=500.
      R3=1000.
      C1=((R2+R3)/(R1*R2))*QP/FI
      C2=(1./(R2+R3))*(1./(QP*FI))
      Y(1)=A1*C1
      Y(2)=A1*C2
      Y(3)=A2*R1
      Y(4)=A2*R2
      Y(5)=A2*R3
      A1N=Y(1)
      A2N=Y(2)
      A3N=Y(3)
      A4N=Y(4)
      A5N=Y(5)
      X(1)=Y(1)/A1N
      X(2)=Y(2)/A2N
      X(3)=Y(3)/A3N
      X(4)=Y(4)/A4N
      X(5)=Y(5)/A5N
      X1=A1/A1N
      X2=A1/A2N
      X3=A2/A3N
      X4=A2/A4N
      X5=A2/A5N
      PRINT 15,FO,QP
   15 FORMAT(5X,3HFO=,F6.1,6X,3HQP=,F5.1)
      PRINT 2
    2 FORMAT(//,5X,14HINPUT X VECTOR)
      PRINT 10,X(1),X(2),X(3),X(4),X(5)
   10 FORMAT(40X,4HX(I),/5E17.6,//)
      PRINT 3,H1,H2
    3 FORMAT(34X,2HH1,20X,2HH2,/,19X,2F22.2,/)
      N=5
      EST=0.
      EPS=1.E-8
      LIMIT=10000
      ICOUNT=0
   99 CALL FUNCT(N,X,F,G)
      DO 70 I=1,5
      X(I)=X(I)*1.00000001
      CALL FUNCT(N,X,FF,G)
```

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      X(I)=X(I)/1.00000001
      GG(I)=(FF-F)/(X(I)*.00000001)
   70 CONTINUE
      PRINT 16,(GG(I),I=1,5)
   16 FORMAT(//,42X,22HVERIFIED VALUE OF G(I),/,14X,5G10.6)
      PRINT 20
   20 FORMAT(////)
      CALL TRANF(X,F,CONT1,CONT2)
      PRINT 260
  260 FORMAT(/////,25X,44HMINIMIZATION ALGORITHM STARTS AT THIS POINT../
     */)
      PRINT 8
    8 FORMAT(30X,18HCIRCUIT PARAMETERS,/)
      CALL FMFP(FUNCT,N,X,F,G,EST,EPS,LIMIT,IER,H)
      CALL TRANF(X,F,CONT1,CONT2)
      M1=M1*2.
      M2=M2*2.
      PRINT 4,IER
    4 FORMAT(5X,4HIER=,I2,//////)
  100 CONTINUE
      STOP
      END
```

SUBROUTINE TRANF   73/174   OPT=1   FTN 4.8+498   80/06/06. 20.35.45   PAGE 1

```
      SUBROUTINE TRANF(X,F,CONT1,CONT2)
      DIMENSION X(5),Y(5)
      COMMON FI,QP,M1,M2,ICOUNT,A1M,A2M,A3M,A4M,A5M,A1,A2,X1,X2,X3,X4,X5
      C1=X(1)/X1
      C2=X(2)/X2
      IF(C1.GT.(1.E-01)) STOP
      IF(C2.GT.(1.E-01)) STOP
      R1=X(3)/X3
      R2=X(4)/X4
      R3=X(5)/X5
      C1=ABS(C1)
      C2=ABS(C2)
      R1=ABS(R1)
      R2=ABS(R2)
      R3=ABS(R3)
      HBP=R3/(R2+R3)
      BB=HBP
      CT=C1+C2
      RT=R1+R2+R3
      AC=A1*CT
      AR=A2*RT
      FR=(1./SQRT(C1*C2*R1*R2))*(1./6.283185)
      QPP=(1./(R2+R3))*SQRT(R1*C1*R2/C2)
      IA=ICOUNT-6
      IF(IA.GE.0) PRINT 50,IA
   50 FORMAT(/,50X,6HCOUNT=,I5,/)
      PRINT 12,C1,C2,R1,R2,R3,AC
   12 FORMAT(4X,3HC1=,G11.5,1HF,1X,3HC2=,G11.5,1HF,1X,3HR1=,G11.5,4HOHMS
     *,1X,3HR2=,G11.5,4HOHMS,1X,3HR3=,G11.5,4HOHMS,1X,3HAC=,G11.5,8H(CM_
     *SQ)),/)
      PRINT 2,AR,CONT1,CONT2,F
    2 FORMAT(5X,35HTOTAL RESISTANCE SURFACE AREA "AR"=,G11.5,8H(CM_SQ),
     *2X,13HCONSTRAINTS  ,E12.6,1X,E12.6,2X,2HF=,G11.5,/)
      PRINT 10,FR,QPP,BB
   10 FORMAT(10X,3HFO=,F14.6,5HHERTZ,4X,3HQP=,F15.6,4X,5HGAIN=,F8.6,//)
      RETURN
      END
```

SUBROUTINE FUNCT   73/174   OPT=1   FTN 4.8+498   80/06/03. 12.15.57   PAGE 1

```
      SUBROUTINE FUNCT(N,X,F,G)
      DIMENSION X(N),G(N)
      COMMON FI,QP,M1,M2,ICOUNT,A1M,A2M,A3M,A4M,A5M,A1,A2,X1,X2,X3,X4,X5
      DO 10 I=1,5
      IF(ABS(X(I)).LT.1.E-24) X(I)=1.E-24
   10 CONTINUE
      AC=X(1)+X(2)
      AR=X(3)+X(4)+X(5)
      CONT1=FI**2*((X(1)*X(2)*X(3)*X(4))/(X1*X2*X3*X4))-1.
      CONT2=((QP**2)*((X(4)/X4+X(5)/X5)**2)*X(2)*X1*X3*X4/(X(1)*X(3)*X(4
     *)*X2))-1.
      F=3.*AC+2.*AR+(M1*(CONT1**2))+(M2*(CONT2**2))
      G(1)=3.+(2./X(1))*(M1*CONT1*(CONT1+1.)-M2*CONT2*(CONT2+1.))
      G(2)=3.+(2./X(2))*(M1*CONT1*(CONT1+1.)+M2*CONT2*(CONT2+1.))
      G(3)=2.+(2./X(3))*(M1*CONT1*(CONT1+1.)-M2*CONT2*(CONT2+1.))
      G(4)=2.+(2./X(4))*(M1*CONT1*(CONT1+1.)+((X(4)/X4-X(5)/X5)/(X(4)/X4
     *+X(5)/X5))*M2*CONT2*(CONT2+1.))
      G(5)=2.+(4./(X(4)*(X5/X4)+X(5)))*M2*CONT2*(CONT2+1.)
      IP=(ICOUNT/20)*20
      IF(IP.EQ.ICOUNT) PRINT 60,(G(I),I=1,5)
   60 FORMAT(45X,23HCOMPUTED GRADIENTS G(I),/10X,5G18.7,//)
      IF(IP.EQ.ICOUNT) CALL TRANF(X,F,CONT1,CONT2)
      ICOUNT=ICOUNT+1
      RETURN
      END
```

```
    MAJOR TECHNICAL REPORT IN EL. ENGINEERING.
UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FILTER ELEMENTS

BY [illegible] T.S. [illegible]

ADVISOR  DR. R.B. BHATTACHARYYA

THIS PROGRAM MINIMIZES THE AREA "AR" CORRESPONDING
 TO THE TOTAL RESISTANCE "RT" OF THE RC_ACTIVE FILTER
USING PROPER DEPOSITION THIN_FILM ON PROPER SUBSTRATE
(I.E. THE SUBSTRATE CONFINES THE TOTAL AREA INCLUDING
THAT OF THE ACTIVE COMPONENTS). GIVEN CONSTRAINTS FOR
SPECIFIED CENTER FREQUENCY "FO",POLE_Q
 "QP" AND FINDS BAND PASS MAX. GAIN "[illegible]",AS WELL AS,
ALL FIVE FILTER ELEMENTS  C1,C2,R1, R2, AND R3

IN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD IS USED

    MINIMIZATION FUNCTION  F="AR"..........NONE
AC=(2/3).(VBR/(E0.ER.E)).CT=A1.CT  (CM_SQR)
AR=((W_SQR)/RS).RT=A2.RT  (CM_SQR)
VBR=BREAKING VOLTAGE  (VOLTS)
E0=8.85X10(-14) IS THE PERMITTIVITY OF THE FREE SPACE.
(FARADS/CM)
ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.
E=DIELECTRIC STRENGTH OF THE THIN_FILM  (VOLTS/CM)
W=WIDTH OF THE THIN_FILM RESISTIVE LINE  (CM)
RS=SHEET RESISTANCE OF THE RESIST. LINE  (OHMS/SQR)
CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER  (FARADS)
RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER  (OHMS)

NOTE  THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.

INPUT FO,QP

   VBR      E0       ER        E          W         RS
  100.0  .[illegible]E-13  25.0  .[illegible]E+07  .[illegible]E-02  50.0
```

```
PROGRAM RCMINI      73/174   OPT=1                    FTN 4.8+498        08/06/83. 12.13.57        PAGE     1

      PROGRAM RCMINI(INPUT,OUTPUT)
      EXTERNAL FUNCT
      COMMON FI,OP,H1,H2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
      DIMENSION X(5),Y(5),S(5),H(40),GG(5)
      PRINT 25
   25 FORMAT(10X,42HMAJOR TECHNICAL REPORT IN EL. ENGINEERING.)
      PRINT 26
   26 FORMAT(5X,66HUNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
     *LTER ELEMENTS,/)
      PRINT 27
   27 FORMAT(5X,37HBY PARASKEVAS PROKOPIS  I.D.  6001956,/)
      PRINT 28
   28 FORMAT(5X,31HADVISOR: DR. B.B. BHATTACHARYYA,//)
      PRINT 29
   29 FORMAT(5X,*THIS PROGRAM MINIMIZES SIMULTANEOUSLY THE AREA "AC"*,/
     *5X,*CORRESPONDING TO THE TOTAL CAPACITANCE "CT" AND THE*,/
     *5X,*AREA "AR" CORRESPONDING TO THE TOTAL RESISTANCE "RT" OF THE*,/
     *5X,*RC ACTIVE FILTER USING PROPER DEPOSITION THIN FILM ON*,/
     *5X,*PROPER SUBSTRATE(I.E. THE SUBSTRATE CONFINES THE TOTAL *,/
     *5X,*AREA INCLUDING THAT OF THE ACTIVE COMPONENTS) GIVEN*,/
     *5X,*CONSTRAINTS FOR SPECIFIED CENTER FREQUENCY "FO,",*,/
     *5X,*POLE_Q "QP" AND FLOATING BAND PASS MAX. GAIN "HOP"*,/
     *5X,*AS WELL AS FIVE FILTER ELEMENTS:C1,C2,R1,R2,AND R3.*,/)
      PRINT 30
   30 FORMAT(5X,60HIN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD
     *IS USED,//)
      PRINT 45
   45 FORMAT(//,10X,*MINIMIZATION FUNCTION: F=3"AC"+2"AR",WHERE:*,/
     *5X,*AC=(2/3).(VBR/(E0.ER.E)).CT=A1.CT  [CM_SQR]*,/
     *5X,*AR=((W_SQR)/RS).RT=A2.RT  [CM_SQR]*,/
     *5X,*VBR=BREAKING VOLTAGE  [VOLTS]*,/
     *5X,*E0=8.85X10**(-14) IS THE PERMITTIVITY OF THE FREE SPACE.*,/
     *5X,*[FARADS/CM]*,/
     *5X,*ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.*,/
     *5X,*E=DIELECTRIC STRENGTH OF THE THIN_FILM  [VOLTS/CM]*,/
     *5X,*W=WIDTH OF THE THIN FILM RESISTIVE LINE  [CM]*,/
     *5X,*RS=SHEET RESISTANCE OF THE RESIST. LINE  [OHMS/SQR]*,/
     *5X,*CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER  [FARADS]*,/
     *5X,*RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER  [OHMS]*,//
     *5X,*NOTE: THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.*,//)
      PRINT 1
    1 FORMAT(5X,11HINPUT F0,QP)
      READ*,F0,QP,H1,H2
      FI=6.283185*F0
      VBR=100.
      E0=8.85E-14
      ER=25.
      E=4.E+6
      W=5.E-3
      RS=50.
      A1=(2./3.)*VBR/(E0*ER*E)
      A2=W**2/RS
      PRINT 110
  110 FORMAT(/,8X,*VBR*,6X,*E0*,6X,*ER*,8X,*E*,9X,*W*,10X,*RS*,/)
      PRINT 115,VBR,E0,ER,E,W,RS
  115 FORMAT(6X,F5.1,1X,E10.3,1X,F5.1,1X,E10.3,1X,E10.3,1X,F5.1,//)
      PRINT 120
  120 FORMAT(5X,*A1=(2/3).(VBR/(E0.ER.E))*,5X,*A2=((W_SQR)/RS*,/)
      PRINT 125,A1,A2
  125 FORMAT(7X,E11.4,10X,E11.4,/)
      DO 100 K=1,5
      R1=4.E+6
      R2=1000.
      R3=10000.
      C1=((R2+R3)/(R1*R2))*QP/FI
      C2=(1./(R2+R3))*(1./(QP*FI))
      Y(1)=A1*C1
      Y(2)=A1*C2
      Y(3)=A2*R1
      Y(4)=A2*R2
      Y(5)=A2*R3
      A1N=Y(1)
      A2N=Y(2)
      A3N=Y(3)
      A4N=Y(4)
      A5N=Y(5)
      X(1)=Y(1)/A1N
      X(2)=Y(2)/A2N
      X(3)=Y(3)/A3N
      X(4)=Y(4)/A4N
      X(5)=Y(5)/A5N
      X1=A1/A1N
      X2=A1/A2N
      X3=A2/A3N
      X4=A2/A4N
      X5=A2/A5N
      PRINT 15,F0,QP
   15 FORMAT(5X,3HF0=,F8.1,6X,3HQP=,F5.1)
      PRINT 2
    2 FORMAT(//,5X,14HINPUT X VECTOR)
      PRINT 19,X(1),X(2),X(3),X(4),X(5)
   19 FORMAT(40X,4HX(I),/5E17.6,//)
      PRINT 3,H1,H2
    3 FORMAT(34X,2HH1,20X,2HH2,/,15X,2F22.2,/)
      N=5
      EST=0.
      EPS=1.E-6
      LIMIT=10000.
      ICOUNT=0
```

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```
   90 CALL FUNCT(N,X,F,G)
      DO 70 I=1,5
      X(I)=X(I)*1.0000001
      CALL FUNCT(N,X,FF,G)
      X(I)=X(I)/1.0000001
      GA(I)=(FF-F)/(X(I)*0.0000001)
   70 CONTINUE
      PRINT 16,(GA(I),I=1,5)
   16 FORMAT(///,42X,27HVERIFIED VALUE OF G(I),/,15X,5E18.6)
      PRINT 20
   20 FORMAT(////)
      CALL TRANF(X,F,CONT1,CONT2)
      PRINT 200
  200 FORMAT(/////,29X,44HMINIMIZATION ALGORITHM STARTS AT THIS POINT.,/
     */)
      PRINT 8
    8 FORMAT(30X,18HCIRCUIT PARAMETERS,/)
      CALL FMFP(FUNCT,N,X,F,G,EST,EPS,LIMIT,IER,H)
      CALL TRANF(X,F,CONT1,CONT2)
      M1=M1*2.
      M2=M2*2.
      PRINT 4,IER
    4 FORMAT(5X,4HIER=,I2,//////)
  100 CONTINUE
      STOP
      END
```

SUBROUTINE TRANF 73/174 OPT=1 FTN 4.8+498 88/06/03. 12.13.37 PAGE 1

```
      SUBROUTINE TRANF(X,F,CONT1,CONT2)
      DIMENSION X(5),Y(5)
      COMMON F1,GP,M1,M2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
      C1=X(1)/X1
      C2=X(2)/X2
      R1=X(3)/X3
      R2=X(4)/X4
      R3=X(5)/X5
      C1=ABS(C1)
      C2=ABS(C2)
      R1=ABS(R1)
      R2=ABS(R2)
      R3=ABS(R3)
      HOP=R3/(R2+R3)
      [illegible]
      CT=C1+C2
      RT=R1+R2+R3
      AC=A1*CT
      AR=A2*RT
      AT=3.*AC+2.*AR
      F0=(1./SQRT(C1*C2*R1*R2))*(1./6.283185)
      GPP=(1./(R2+R3))*SQRT(R1*C1*R2/C2)
      IA=ICOUNT-6
      IF(IA.GE.0) PRINT 50,IA
   50 FORMAT(/,50X,6HCOUNT=,I5,/)
      PRINT 12,C1,C2,R1,R2,R3,AC,AR
   12 FORMAT(9X,3HC1=,G11.5,1HF,1X,3HC2=,G11.5,1HF,1X,3HR1=,G11.5,4HOHMS
     *,1X,3HR2=,G11.5,4HOHMS,1X,3HR3=,G11.5,4HOHMS,1X,3HAC=,G11.5,8HCM
     *SQR),1X,3HAR=,F7.3,8H(CM SQR),/)
      PRINT 2,AT,CONT1,CONT2,F
    2 [illegible]
     *[illegible]
      PRINT 10,F0,GPP,GG
   10 [illegible]
     *=,F8.4,//)
      RETURN
      END
```

```
      SUBROUTINE FUNCT(N,X,F,G)
      DIMENSION X(N),G(N)
      COMMON F1,GP,M1,M2,ICOUNT,A1N,A2N,A3N,A4N,A5N,A1,A2,X1,X2,X3,X4,X5
      DO 10 I=1,5
      IF(ABS(X(I)).LT.1.E-06) X(I)=1.E-06
   10 CONTINUE
      AC=X(1)+X(2)
      AR=X(3)+X(4)+X(5)
      [illegible]
      [illegible]
     *[illegible]
      [illegible]
      G(1)=[illegible]
      G(2)=[illegible]
      G(3)=[illegible]
      G(4)=[illegible]
     *[illegible]
      G(5)=[illegible]
      IP=(ICOUNT/[illegible])
      IF(IP.EQ.ICOUNT) PRINT 60,(G(I),I=1,5)
   60 FORMAT([illegible]COMPUTED GRADIENTS G(I),/[illegible])
      IF(IP.EQ.ICOUNT) CALL TRANF(X,F,CONT1,CONT2)
      ICOUNT=ICOUNT+1
      RETURN
      END
```

```
     MAJOR TECHNICAL REPORT IN EL. ENGINEERING.
UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FILTER ELEMENTS

BY PARASKEVAS PRONDPIS  I.D.  [illegible]

ADVISOR: DR. [illegible] BHATTACHARYYA

THIS PROGRAM MINIMIZES SIMULTANEOUSLY THE AREA "AC"
CORRESPONDING TO THE TOTAL CAPACITANCE "CT" AND THE
AREA "AR" CORRESPONDING TO THE TOTAL RESISTANCE "RT" OF THE
RC ACTIVE FILTER USING PROPER DEPOSITION THIN FILM ON
PROPER SUBSTRATE(I.E. THE SUBSTRATE CONTAINS THE TOTAL
AREA INCLUDING THAT OF THE ACTIVE COMPONENTS) GIVEN
CONSTRAINTS FOR SPECIFIED CENTER FREQUENCY "FO",
POLE_Q "QP" AND FLOATING BAND PASS MAX. GAIN "HOP"
AS WELL AS FIVE FILTER ELEMENTS:C1,C2,R1,R2,AND R3.

IN THIS ANALYSIS FLETCHER_POWELL MINIMIZATION METHOD IS USED

     MINIMIZATION FUNCTION: F=[illegible]
AC=(2/3).(VBR/(E0.ER.S)).CT=A1.CT  (CM_SQR)
AR=((W_SQR)/RS).RT=A2.RT  (CM_SQR)
VBR=BREAKING VOLTAGE  (VOLTS)
E0=[illegible](-14) IS THE PERMITTIVITY OF THE FREE SPACE.
(FARADS/CM)
ER=DIELECTRIC CONSTANT RELATIVE TO THAT OF FREE SPACE.
S=DIELECTRIC STRENGTH OF THE THIN_FILM  (VOLTS/CM)
W=WIDTH OF THE THIN_FILM RESISTIVE LINE  (CM)
RS=SHEET RESISTANCE OF THE RESIST. LINE  (OHMS/SQR)
CT=TOTAL CAPACITANCE=C1+C2 OF THE FILTER  (FARADS)
RT=TOTAL RESISTANCE=R1+R2+R3 OF THE FILTER  (OHMS)

NOTE: THE ABOVE OBJECTIVE FUNCTION IS A CONSTRAINED ONE.

INPUT FO,QP

   VBR      E0       ER       S        W        RS
100.0   .[illegible]E-13  25.[illegible]  [illegible]  [illegible]  [illegible]
```

CONCORDIA UNIVERSITY COMPUTER CENTRE

F3 Description of "PLOT" programs

In all, fifty-seven programs plot the transfer function T(s) of the proposed filter. Brief descriptions of the function of these programs are outlined in chapter six and in Table - 4 (program no. 49 to 105). Forty-eight of these programs use data which are the "optimized" filter passive components, per Table - 9 and -10. The rest use arbitrary data, but the ideal and practical operation of the OAs, in either unity-or non-unity-gain mode, are verified in the present filter configuration.
The operation of this group of programs is demonstrated by the aid of the flow chart, as shown in fig. F.8, which serves the same purpose for all three subgroups of the "plot" computer programs, depending on the mode of operation of the connected OAs, in the same filter configuration.
This purpose is, as outlined previously, to gather required information from the filter designer, as input data, to process this data in order to provide the required variables for calculation of the amplitude and phase responses, and finally to feed these variables and responses into the subrountine USPLH, condition the plot points, and have these manipulated data be printed as tables, and as curves.

The listing of some of these programs further describes each step of the computer-aided presentation of the filter transfer function.

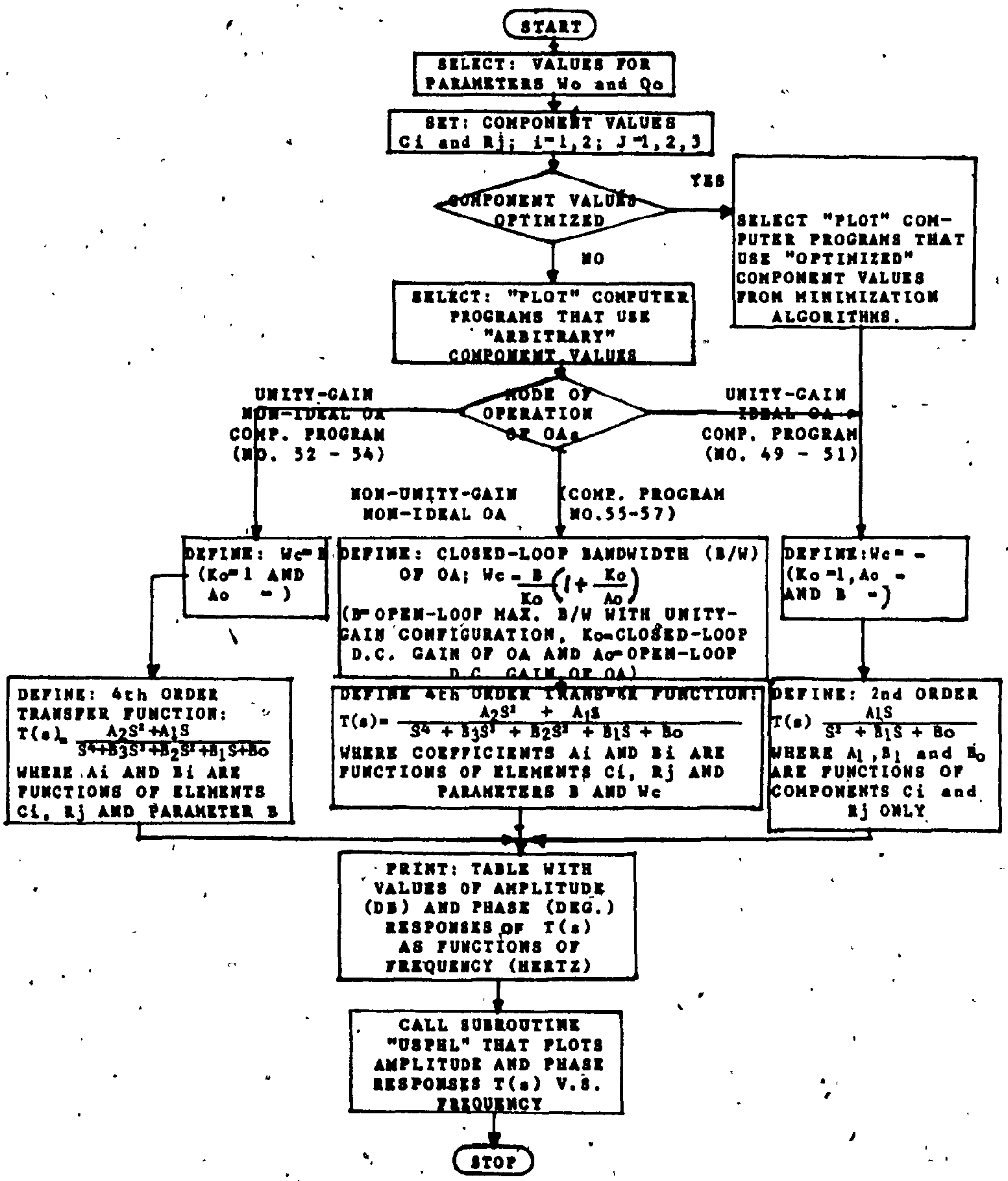

Fig F.8 - Organizational flow-chart of "PLOT" programs (computer program no. 49 - 105, per Table - 4)

```
PROGRAM PARIS2      73/174  OPT=1                              FTN 4.6+498         80/06/11. 17.27.22        PAGE    1

      PROGRAM PARIS2 (INPUT,OUTPUT)
      DIMENSION A(300),P(300),X(300),B(160),C(160),IMAG(5151)
      DIMENSION Y1(200,1),Y2(200,1)
      COMPLEX S,G
      PRINT 25
   25 FORMAT(10X,42HMAJOR TECHNICAL REPORT IN EL. ENGINEERING.)
      PRINT 26
   26 FORMAT(5X,66HUNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
     *LTER ELEMENTS./)
      PRINT 27
   27 FORMAT(5X,37HBY PARASKEVAS PROKOPIS  I.D.  6001956./)
      PRINT 28
   28 FORMAT(5X,28HPROFESSOR B.B. BHATTACHARYYA.//)
      READ 3,IFO,IOP
    3 FORMAT(I3,I2)
      PRINT 5,IFO,IOP
    5 FORMAT(//,5X,*THIS PROGRAM COMPUTES,DEPICTS(IN TABLES) AND PLOTS(I
     *N X_Y COORDINATES) THE AMPLITUDE AND*,/
     *5X,*PHASE RESPONSES OF THE PRACTICAL BAND_PASS ACTIVE FILTER(IDEAL
     * OP_AMP TRANSFER CHARACTERISTIC IS OF*,/
     *5X,*SECOND DEGREE BUT THAT OF THE NON_IDEAL OP_AMP IS OF THE FOURT
     *H DEGREE) USING APPROXIMATED COMPONENT_VALUES*,/
     *5X,*CLOSED TO THE OPTIMIZED ONES,AS WERE CALCULATED BY THE FLETCHE
     *R_POWELL MINIMIZATION ALGORITHM.*,//
     *5X,*CASE  FO=*,I5,*HERTZ,* AND OP=*,I3,///)
      R1=1000000.
      R2=10.
      R3=100.
      OP=IOP
      FO=IFO
      C1=((R2+R3)/(R1*R2))*(OP/(6.283185*FO))
      C2=(1./(R2+R3))*(1./(6.283185*FO*OP))
      IR1=R1
      IR2=R2
      IR3=R3
      PRINT 40,C1,C2,IR1,IR2,IR3
   40 FORMAT(5X,3HC1=,G13.6,1X,3HC2=,G13.6,1X,3HR1=,I10,1X,3HR2=,I5,1X,3
     *HR3=,I5,//)
      R1=IR1
      R2=IR2
      R3=IR3
      A1=R3/(R1*R2*C1)
      B1=(1./(R1*C1))*(1.+R3/R2)
      B0=1./(R1*R2*C1*C2)
      PRINT 8,A1,B1,B0
    8 FORMAT(5X,3HA1=,G13.6,2X,3HB1=,G13.6,2X,3HB0=,G13.6,///)
      DO 10 I=1,230
      IF(I.LE.40) F=I*10
      IF(I.GT.40) F=(I-40)*2+400
      IF(I.GT.140) F=(I-140)*10+600
      W=2.*3.14159265*F
      S=CMPLX(0.0,W)
      G=(A1*S)/(S**2+B1*S+B0)
      AMG=CABS(G)
      PHA=(180./3.14159265)*ATAN2(AIMAG(G),REAL(G))
      A(I)=20.*ALOG10(AMG)
      P(I)=PHA
      X(I)=F
      Y1(I,1)=A(I)
      Y2(I,1)=P(I)
      PRINT 11,F,AMG,A(I),PHA
   11 FORMAT (5X,*FREQ=*,2X,F10.3,5X,*MAG.IN RATIO=*,2X,E15.8,5X,*MAG.
     1IN DB=*,2X,E15.8,5X,*PHASE IN DEG=*,2X,E15.8)
   10 CONTINUE
      PRINT 15
   15 FORMAT(///)
      READ 12,(B(I),I=1,160)
      CALL USPLH (X,Y1,230,1,1,230,B,IMAG4,IER)
      READ 12,(C(I),I=1,160)
      PRINT 30
   30 FORMAT(///)
      CALL USPLH (X,Y2,230,1,1,230,C,IMAG4,IER)
   12 FORMAT (80A1)
      STOP
      END
```

```
     MAJOR TECHNICAL REPORT IN EL. ENGINEERING.
UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FILTER ELEMENTS

BY PARASKEVAS PROKOPIS  I.D.  6001956

PROFESSOR B.B. BHATTACHARYYA


THIS PROGRAM COMPUTES,DEPICTS(IN TABLES) AND PLOTS(IN X_Y COORDINATES) THE AMPLITUDE AND
PHASE RESPONSES OF THE PRACTICAL BAND_PASS ACTIVE FILTER(IDEAL OP_AMP TRANSFER CHARACTERISTIC IS OF
SECOND DEGREE BUT THAT OF THE NON_IDEAL OP_AMP IS OF THE FOURTH DEGREE) USING APPROXIMATED COMPONENT_VALUES
CLOSED TO THE OPTIMIZED ONES,AS WERE CALCULATED BY THE FLETCHER_POWELL MINIMIZATION ALGORITHM.

CASE  FO=  500HERTZ AND OP= 30


C1=  .175070E-06 C2=  .570745E-07 R1=    1000000 R2=    10 R3=  100


A1=  57.1199       B1=  62.8319       B0=  .986960E+07
```

FREQ=	10.000	MAG.IN RATIO=	.36378187E-03	MAG. IN DB=	-.68783179E+02	PHASE IN DEG=	.89977873E+02
FREQ=	20.000	MAG.IN RATIO=	.72043003E-03	MAG. IN DB=	-.62[illegible]21406E+02	PHASE IN DEG=	.89954090E+02
FREQ=	30.000	MAG.IN RATIO=	.10949490E-02	MAG. IN DB=	-.59[illegible]E+02	PHASE IN DEG=	.89930997E+02
FREQ=	40.000	MAG.IN RATIO=	.14439127E-02	MAG. IN DB=	-.56[illegible]E+02	PHASE IN DEG=	.89907738E+02
FREQ=	50.000	MAG.IN RATIO=	.18269430E-02	MAG. IN DB=	-.54719[illegible]E+02	PHASE IN DEG=	.89884251E+02
FREQ=	60.000	MAG.IN RATIO=	.22136809E-02	MAG. IN DB=	-.53092[illegible]E+02	PHASE IN DEG=	.89860401E+02
FREQ=	70.000	MAG.IN RATIO=	.25953327E-02	MAG. IN DB=	-.51712[illegible]E+02	PHASE IN DEG=	.89836369E+02
FREQ=	80.000	MAG.IN RATIO=	.29859043E-02	MAG. IN DB=	-.50499044E+02	PHASE IN DEG=	.89811037E+02
FREQ=	90.000	MAG.IN RATIO=	.33822910E-02	MAG. IN DB=	-.49415701E+02	PHASE IN DEG=	.89786029E+02
FREQ=	100.000	MAG.IN RATIO=	.37870461E-02	MAG. IN DB=	-.48432153E+02	PHASE IN DEG=	.89761208E+02
FREQ=	110.000	MAG.IN RATIO=	.42034021E-02	MAG. IN DB=	-.47527901E+02	PHASE IN DEG=	.89735070E+02
FREQ=	120.000	MAG.IN RATIO=	.46302844E-02	MAG. IN DB=	-.46687047E+02	PHASE IN DEG=	.89708173E+02
FREQ=	130.000	MAG.IN RATIO=	.50699265E-02	MAG. IN DB=	-.45899967E+02	PHASE IN DEG=	.89680466E+02
FREQ=	140.000	MAG.IN RATIO=	.55230002E-02	MAG. IN DB=	-.45155102E+02	PHASE IN DEG=	.89651053E+02
FREQ=	150.000	MAG.IN RATIO=	.59930761E-02	MAG. IN DB=	-.44445845E+02	PHASE IN DEG=	.89622231E+02
FREQ=	160.000	MAG.IN RATIO=	.64017672E-02	MAG. IN DB=	-.43766131E+02	PHASE IN DEG=	.89591481E+02
FREQ=	170.000	MAG.IN RATIO=	.69096308E-02	MAG. IN DB=	-.43110904E+02	PHASE IN DEG=	.89559471E+02
FREQ=	180.000	MAG.IN RATIO=	.75197967E-02	MAG. IN DB=	-.42475070E+02	PHASE IN DEG=	.89526057E+02
FREQ=	190.000	MAG.IN RATIO=	.80740233E-02	MAG. IN DB=	-.41857359E+02	PHASE IN DEG=	.89491875E+02
FREQ=	200.000	MAG.IN RATIO=	.86578164E-02	MAG. IN DB=	-.41252013E+02	PHASE IN DEG=	.89454342E+02
FREQ=	210.000	[illegible]	[illegible]	MAG. IN DB=	-.40657046E+02	[illegible]	[illegible]
FREQ=	220.000	MAG.IN RATIO=	.99280[illegible]E-02	MAG. IN DB=	-.40069727E+02	PHASE IN DEG=	.89374773E+02
FREQ=	230.000	MAG.IN RATIO=	.10607045E-01	MAG. IN DB=	-.39487620E+02	PHASE IN DEG=	.89331634E+02
FREQ=	240.000	MAG.IN RATIO=	.11379130E-01	MAG. IN DB=	-.38908409E+02	PHASE IN DEG=	.89283329E+02
FREQ=	250.000	MAG.IN RATIO=	.12128136E-01	MAG. IN DB=	-.38329050E+02	PHASE IN DEG=	.89236101E+02
FREQ=	260.000	MAG.IN RATIO=	.12957217E-01	MAG. IN DB=	-.37749765E+02	PHASE IN DEG=	.89183339E+02
FREQ=	270.000	MAG.IN RATIO=	.13850049E-01	MAG. IN DB=	-.37169950E+02	PHASE IN DEG=	.89126950E+02
FREQ=	280.000	MAG.IN RATIO=	.14811678E-01	MAG. IN DB=	-.36578179E+02	PHASE IN DEG=	.89065187E+02
FREQ=	290.000	MAG.IN RATIO=	.15888056E-01	MAG. IN DB=	-.35978147E+02	PHASE IN DEG=	.88999540E+02
FREQ=	300.000	MAG.IN RATIO=	.17042461E-01	MAG. IN DB=	-.35369354E+02	PHASE IN DEG=	.88925030E+02
FREQ=	310.000	MAG.IN RATIO=	.18300861E-01	MAG. IN DB=	-.34757173E+02	PHASE IN DEG=	.88846950E+02
FREQ=	320.000	MAG.IN RATIO=	.19704460E-01	MAG. IN DB=	-.34108621E+02	PHASE IN DEG=	.88756009E+02
FREQ=	330.000	MAG.IN RATIO=	.21235707E-01	MAG. IN DB=	-.33456409E+02	PHASE IN DEG=	.88660229E+02
FREQ=	340.000	MAG.IN RATIO=	.22900083E-01	MAG. IN DB=	-.32784030E+02	PHASE IN DEG=	.88550082E+02
FREQ=	350.000	MAG.IN RATIO=	.24946043E-01	MAG. IN DB=	-.32059967E+02	PHASE IN DEG=	.88427560E+02
FREQ=	360.000	MAG.IN RATIO=	.27169902E-01	MAG. IN DB=	-.31318213E+02	PHASE IN DEG=	.88287347E+02
FREQ=	370.000	MAG.IN RATIO=	.29724470E-01	MAG. IN DB=	-.30537715E+02	PHASE IN DEG=	.88126270E+02
FREQ=	380.000	MAG.IN RATIO=	.32692345E-01	MAG. IN DB=	-.29711079E+02	PHASE IN DEG=	.87939109E+02
FREQ=	390.000	MAG.IN RATIO=	.36106367E-01	MAG. IN DB=	-.28829100E+02	PHASE IN DEG=	.87710729E+02
FREQ=	400.000	MAG.IN RATIO=	.40[illegible]E-01	MAG. IN DB=	-.2788[illegible]E+02	PHASE IN DEG=	.87453159E+02
FREQ=	402.000	MAG.IN RATIO=	.41300206E-01	MAG. IN DB=	-.27680996E+02	PHASE IN DEG=	.87396144E+02
FREQ=	404.000	MAG.IN RATIO=	.42274595E-01	MAG. IN DB=	-.27470419E+02	PHASE IN DEG=	.87334670E+02
FREQ=	406.000	MAG.IN RATIO=	.432[illegible]E-01	MAG. IN DB=	-.27272311E+02	PHASE IN DEG=	.87270[illegible]E+02
FREQ=	408.000	MAG.IN RATIO=	.44340294E-01	MAG. IN DB=	-.27062469E+02	PHASE IN DEG=	.87203826E+02
FREQ=	410.000	MAG.IN RATIO=	.45453137E-01	MAG. IN DB=	-.26840723E+02	PHASE IN DEG=	.87134105E+02
FREQ=	412.000	MAG.IN RATIO=	.46607420E-01	MAG. IN DB=	[illegible]	PHASE IN DEG=	.87061299E+02
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FREQ=	1240.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1250.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1260.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1270.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1280.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1290.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1300.000	[illegible]	[illegible]	MAG. IN DB=	[illegible]	[illegible]	[illegible]

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FREQ=	1310.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1320.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1330.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1340.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1350.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1360.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1370.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1380.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1390.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1400.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1410.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1420.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1430.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1440.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1450.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1460.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1470.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1480.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1490.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]
FREQ=	1500.000	MAG.IN RATIO=	[illegible]	MAG. IN DB=	[illegible]	PHASE IN DEG=	[illegible]

```
      PROGRAM PARIS (INPUT,OUTPUT)
      DIMENSION A(300),P(300),X(300),B(160),C(160),IMAG4(5151)
      DIMENSION V1(200,1),V2(200,1)
      COMPLEX S,G
      PRINT 25
   25 FORMAT(10X,42HMAJOR TECHNICAL REPORT IN EL. ENGINEERING.)
      PRINT 26
   26 FORMAT(5X,66HUNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
     *LTER ELEMENTS./)
      PRINT 27
   27 FORMAT(5X,37HBY PARASKEVAS PROKOPIS  I.D.  6901956./),
      PRINT 28
   28 FORMAT(5X,20HPROFESSOR B.B. BHATTACHARYYA.//)
      READ 3,IF0,IOP
    3 FORMAT(I4,I2)
      PRINT 9,IF0,IOP
    9 FORMAT(//,5X,*THIS PROGRAM COMPUTES,DEPICTS(IN TABLES) AND PLOTS(I
     *N X_Y COORDINATES) THE AMPLITUDE AND*,/
     *5X,*PHASE RESPONSES OF THE PRACTICAL BAND_PASS ACTIVE FILTER(IDEAL
     * OP_AMP TRANSFER CHARACTERISTIC IS OF*,/
     *5X,*SECOND DEGREE BUT THAT OF THE NON_IDEAL OP_AMP IS OF THE FOURT
     *H DEGREE) USING [illegible] COMPONENT_VALUES*,/
     *5X,*CLOSED TO THE OPTIMIZED ONES,AS WERE CALCULATED BY THE FLETCHE
     *R_POWELL MINIMIZATION ALGORITHM.*,//
     *5X,*CASE  F0=*,I5,*HERTZ* AND OP=*,I3,////)
      R1=1000000.
      R2=10.
      R3=100.
      OP=IOP
      F0=IF0
      C1=((R2+R3)/(R1*R2))*(OP/(6.2831853*F0))
      C2=(1./(R2+R3))*(1./(6.283185*F0*OP))
      B=1000000000.
      IR1=R1
      IR2=R2
      IR3=R3
      PRINT 40,C1,C2,IR1,IR2,IR3
   40 FORMAT(5X,3HC1=,G13.6,1X,3HC2=,G13.6,1X,3HR1=,I10,1X,3HR2=,I5,1X,3
     *HR3=,I5,//)
      R1=IR1
      R2=IR2
      R3=IR3
      D=R1*R2*C1*C2+R1*R3*C1*C2
      A2=(R3*C2*B)/D
      A1=(R3*C2*B**2)/D
      B3=(2.*R1*R2*C1*C2*B+2.*R1*R3*C1*C2*B+R1*C1+R2*C2+R3*C2)/D
      B2=(R1*R2*C1*C2*B**2+2.*R1*C1*B+2.*R2*C2*B+2.*R3*C2*B+1.)/D
      B1=(R2*C2*B**2+R3*C2*B**2+2.*B)/D
      B0=B**2/D
      PRINT 8,A2,A1,B3,B2,B1,B0
    8 FORMAT(5X,3HA2=,G13.6,2X,3HA1=,G13.6,2X,3HB3=,G13.6,2X,3HB2=,G13.6
     *,2X,3HB1=,G13.6,2X,3HB0=,G13.6,///)
      DO 10 I=1,230
      IF(I.LE.40) F=I*10
      IF(I.GT.40) F=(I-40)*2+400
      IF(I.GT.140) F=(I-140)*10+600
      W=2.*3.14159265*F
      S=CMPLX(0.0,W)
      G=(A2*S**2+A1*S)/(S**4+B3*S**3+B2*S**2+B1*S+B0)
      AMG=CABS(G)
      PHA=(180./3.14159265)*ATAN2(AIMAG(G),REAL(G))
      A(I)=20.*ALOG10(AMG)
      P(I)=PHA
      X(I)=F
      V1(I,1)=A(I)
      V2(I,1)=P(I)
      PRINT 11,F,AMG,A(I),PHA
   11 FORMAT (5X,*FREQ=*,2X,F10.3,5X,*MAG.IN RATIO=*,2X,E15.8,5X,*MAG.
     1IN DB=*,2X,E15.8,5X,*PHASE IN DEG=*,2X,E15.8)
   10 CONTINUE
      PRINT 15
   15 FORMAT(////)
      READ 12,(B(I),I=1,160)
      CALL USPLH (X,V1,230,1,1,230,B,IMAG4,IER)
      READ 12,(C(I),I=1,160)
      PRINT 30
   30 FORMAT(////)
      CALL USPLH (X,V2,230,1,1,230,C,IMAG4,IER)
   12 FORMAT (80A1)
      STOP
      END
```

```
PROGRAM PARIS1     73/174  OPT=1                    FTN 4.8+498        80/08/11. 17.29.35        PAGE    1

      PROGRAM PARIS1 (INPUT,OUTPUT)
      DIMENSION A(300),P(300),X(300),B(160),C(160),IMAG4(5191)
      DIMENSION V1(200,1),V2(200,1)
      COMPLEX S,G
      PRINT 25
   25 FORMAT(10X,*MAJOR TECHNICAL REPORT IN EL. ENGINEERING.*)
      PRINT 26
   26 FORMAT(5X,*[illegible]UNITY_GAIN BAND PASS ACTIVE FILTER_OPTIMIZATION OF FI
     *LTER ELEMENTS*,/5X,*[illegible] DC CLOSED LOOP GAIN OF THE OA IS FINITE*)
      PRINT 27
   27 FORMAT(5X,*BY PARASKEVAS PRODROMOS  I.D.  4981990*,/)
      PRINT 28
   28 FORMAT(5X,*[illegible] D.E. [illegible]*,//)
      READ 3,IFO,IWP
    3 FORMAT(I3,I2)
      PRINT 5,IFO,IWP
    5 FORMAT(//,5X,*THIS PROGRAM COMPUTES,DEPICTS(IN TABLES) AND PLOTS(I
     *N X_Y COORDINATES) THE AMPLITUDE AND*,/
     *5X,*PHASE RESPONSES OF THE PRACTICAL BAND_PASS ACTIVE FILTER[illegible]
     * OP_AMP TRANSFER CHARACTERISTIC IS OF*,/
     *5X,*SECOND DEGREE BUT THAT OF THE NON_IDEAL OP_AMP IS OF THE FOURT
     *H [illegible] USING APPROXIMATED COMPONENT_VALUES*,/
     *5X,*CLOSED TO THE OPTIMIZED ONES,AS WERE CALCULATED BY THE FLETCHE
     *R_POWELL MINIMIZATION ALGORITHM.*,//
     *5X,*CASE  [illegible]*,I3,///)
      R1=1000000.
      R2=10.
      R3=[illegible]
      WP=IWP
      FO=IFO
      C1=[illegible]
      C2=(1./(R2*R3))*(1./(6.283185*FO*WP))
      B=100000000.
      [illegible]
      RAO=1.
      OMEGC=(B/[illegible])*(1.+[illegible]/A0)
      IR1=R1
      IR2=R2
      IR3=R3
      [illegible]
      IRO=RAO
      IB=B
      PRINT 20,IAO,IRO,IB
   20 FORMAT(5X,*[illegible]_OPEN LOOP GAIN=*,I7,3X,*[illegible]_UNITY CLOSED LOOP GAI
     *N=*,I5,3X,*[illegible]UNITY_GAIN BANDWTH=*,I10,/)
      PRINT 22,OMEGC
   22 FORMAT(5X,*[illegible]_DB BANDWTH=*,G15.7,//)
      PRINT 40,C1,C2,IR1,IR2,IR3
   40 FORMAT(5X,*C1=*,G13.6,1X,*C2=*,G13.6,1X,*R1=*,I10,1X,*R2=*,I5,1X,/
     **R3=*,I5,//)
      R1=IR1
      R2=IR2
      R3=IR3
      B=IB
      [illegible]
      A2=(R3*C2*B)/D
      A1=(R3*C2*OMEGC*B)/D
      B3=[illegible]/D
      B2=[illegible]
     *[illegible]/D
      B1=[illegible]
     *GC)/D
      B0=OMEGC*B2/D
      PRINT 8,A2,A1,B3,B2,B1,B0
    8 FORMAT(5X,*A2=*,G13.6,2X,*A1=*,G13.6,2X,*B3=*,G13.6,2X,*B2=*,G13.6
     *,2X,*B1=*,G13.6,2X,*B0=*,G13.6,///)
      DO 10 I=1,230
      IF(I.LE.40) F=I*10
      IF(I.GT.40) F=(I-40)*2+400
      IF(I.GT.140) F=(I-140)*10+[illegible]
      W=2.*3.14159265*F
      S=CMPLX(0.0,W)
      G=[illegible]
      AMG=CABS(G)
      PHA=(180./3.14159265)*ATAN2(AIMAG(G),REAL(G))
      A(I)=20.*ALOG10(AMG)
      P(I)=PHA
      X(I)=F
      V1(I,1)=A(I)
      V2(I,1)=P(I)
      PRINT 11,F,AMG,A(I),PHA
   11 FORMAT (5X,*FREQ=*,2X,F10.3,5X,*MAG.IN RATIO=*,2X,E15.8,5X,*MAG.
     *IN DB=*,2X,E15.8,5X,*PHASE IN DEG=*,2X,E15.8)
   10 CONTINUE
      PRINT 15
   15 FORMAT(////)
      READ 12,(B(I),I=1,160)
      CALL USPLT (X,V1,230,1,1,230,B,IMAG4,IER)
      READ 12,(C(I),I=1,160)
      PRINT 30
   30 FORMAT(////)
      CALL USPLT (X,V2,230,1,1,230,C,IMAG4,IER)
   12 FORMAT (80A1)
      STOP
      END
```