CANOP3 - AN INTERACTIVE CASCADED NETWORK OPTIMIZATION SYSTEM

J.W. Bandler and M.L. Renault

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Abstract

CANOP3 is an interactive software system for design optimization of cascaded, linear, time-invariant networks. Analysis is performed in the frequency domain and typical two-port network elements including resonant circuits, transmission-line elements, and microwave C- and D-sections are handled. The engineering specifications are taken directly as the optimization objectives and the network parameters as the optimization variables. The gain and phase responses may be optimized simultaneously and the variable network parameters may have their values constrained. The design solution is found in the minimax sense by the MMLC optimization package.

This document is a user's manual for the CANOP3 system. It contains a complete explanation of user data entries and of any required program statements. A typical sample session is included in addition to examples related to the design of group delay equalizers, two-section transmission-line transformers, lowpass lumped LC filters and high power output filters. The program and documentation have been adapted to the CDC 170/730 system with the NOS 2.2 operating system and the extended Fortran 5 compiler FTN5 level 587.

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The authors are with the Simulation Optimization Systems Research Laboratory and the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada L8S 4L7.

J.W. Bandler is also with Optimization Systems Associates, 163 Watson's Lane, Dundas, Ontario, Canada L9H 6L1.

I. INTRODUCTION

CANOP3 is an interactive software system for designing optimization of cascaded, linear, time-invariant networks in the frequency domain. It is a completely updated version of CANOP2 [1] and uses the MMLC [2,3] optimization method which finds the design solution in the minimax sense.

Analysis is performed in the frequency domain and typical two-port network elements including resonant circuits, transmission-line elements, and microwave C- and D-sections are handled. The engineering specifications are taken directly as the optimization objectives and the network parameters as the optimization variables. The gain and phase responses may be optimized simultaneously and the variable network parameters may have their values constrained.

This document contains a complete description of required data entries, a sample run and some typical examples.

II. GENERAL DESCRIPTION

The network to be optimized is assumed to be a cascade of two-port building blocks terminated in a unit normalized, frequency-independent resistance at the source and a user-specified frequency-independent resistance at the load. A variety of two-port lumped and distributed elements such as resistors, inductors, capacitors, lossless transmission lines, lossless short-circuited and open-circuited transmission-line stubs, series and parallel LC and RLC resonant circuits and microwave allpass C- and D-sections can be handled. The user enters the data interactively in free format and may interact at many points with the program to change parameters, frequency range, types and options and to request plots.

Depending on how data is supplied, only relevant questions appear. For example, when analysis only is required, there is no need for parameters concerning optimization. (Questions for initial data are listed in Appendix C.) It is advisable to print the input data before the computer processes it, make changes if desired, and correct all discovered misprints. After obtaining the results, the program may be rerun with some different input data or terminated.

Warning to the user: Make sure that all dimensions supplied through the main program are consistent with all the changes being made.

The optimization objectives are formulated directly from the gain and phase responses of the filter. The former is specified in terms of the reflection coefficient, or the insertion loss in units of decibels, and the latter in terms of the group delay in units of nanoseconds. The system incorporates the adjoint network method of sensitivity evaluation to produce accurate first derivatives needed by these efficient gradient minimization methods [2].

If equality (symmetry) of some parameters can be predicted, symmetry may be forced throughout the optimization. Upper and lower bounds on all relevant parameters can be specified by the user. Results may be automatically presented numerically and graphically and analysis of different responses and/or different frequency ranges may be performed at the user's discretion and a new optimization may be requested. A summary of available features and options is given in Table I.

The CANOP3 system will analyze and optimize only a cascade connection of the two-port elements listed in Tables II and III. Elements 1 to 19 may be connected in any order (sequentially from the source to the load) using as many as required or as many as the computer being used can accommodate.

The first six elements are one-parameter lumped elements. Their parameter values should be normalized by the user to his center frequency and source resistance, appropriately, as outlined in Appendix B.

The next four elements are three-parameter tuned circuits. They are characterized by resonant frequency, quality factor, and slope reactance or susceptance, as appropriate. The last four elements are two-parameter tuned circuits. They are characterized also by resonant frequency and slope reactance or susceptance. Normalization as before must again be carried out by the user.

Elements 11 to 15 are two-parameter lossless transmission-line components. All are characterized by normalized length and characteristic impedance (see Appendix B).

The allpass sections (Table III) are treated in the same way as, for example, Kudsia [4]. Group delay relative to delay level in nanoseconds is calculated.

The source and load are real constant resistances, the source being assumed to be unity.

TABLE I

SUMMARY OF FEATURES, OPTIONS AND PARAMETERS REQUIRED

Features	Type	Options		Parameters
Error Functions	Minimax			
Performance Specifications	Upper (+1)	Reflection coefficient	(1)	Normalization frequency Number of single frequency points / Number of frequency bands or intervals
	Lower (−1)	Insertion loss	(2)	For each: Specification Weighting factor Type (+1, −1,0) Option (1,2,3)
	Single (0)	Group delay	(3)	Frequency (sample point) / Lower and upper frequencies (band edges) Number of subintervals
Analysis		Analysis only	(0)	Option indicator (0, 1) Specified or default values for:
Optimization	Gradient	MMLC optimization method	(1)	Number of function evaluations Accuracy specification Intermediate printouts Initial optimization step-length
Circuit Elements	Cascaded Two-port	See Tables II and III		Number of elements Sequence of code numbers Parameter values Indicator for fixed, variable or equal (symmetrical) parameters Load resistance Parameters for C- and D-sections
Graph	Frequency response	Given response Other response Any frequency range Automatic scaling Specified scaling		As many plots as desired Option indicator

TABLE II

ELEMENTS AND CODE NUMBERS

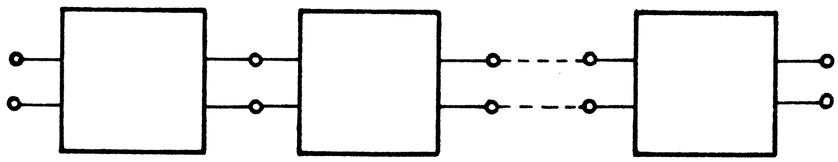
Element	Connection	Code	Parameters
inductor	series	1	inductance
	shunt	4	
capacitor	series	3	capacitance
	shunt	2	
resistor	series	5	resistance
	shunt	6	
resonant RLC circuit	series	7	resonant frequency quality factor
	shunt	10	slope reactance
antiresonant RLC circuit	series	9	antiresonant frequency quality factor
	shunt	8	slope susceptance
resonant LC circuit	series	16	resonant frequency
	shunt	19	slope reactance
antiresonant LC circuit	series	18	antiresonant frequency
	shunt	17	slope susceptance
lossless transmission line	series shorted	11	length characteristic impedance
	shunt shorted	14	
	series open	13	
	shunt open	12	
	cascade	15	

TABLE III

ALLPASS SECTIONS

Parameters	
All fixed or all variable (determined by one indicator)	Fixed
location of real zeros of C-sections	number of C-sections
location of real parts of zeros of D-sections location of imaginary parts of zeros of D-sections	number of D-sections
delay level	cutoff frequency

III. CIRCUIT CONFIGURATION AND BUILDING BLOCKS



CIRCUIT
CONFIGURATION

Possibilities

1. A cascade connection of two-port circuit blocks consisting of any of the elements depicted on the following pages in any order, and as many as required.
2. As many C- and D-sections as required.
3. Modification of program to accommodate new blocks is readily effected.

Implementation*

1. All blocks are numbered sequentially from left to right.
2. Each block has a code number associated with it defining the element it contains.

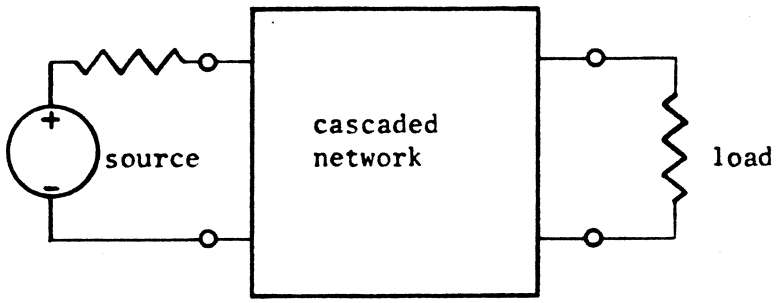
*Except allpass networks.

Parameters Required

Other than the parameters listed and defined together with the individual blocks, the following values must be supplied.

1. The total number of blocks (not including C- and D-sections).
2. The total number of parameters in these blocks.
3. The number of C-sections.
4. The number of D-sections.
5. The center frequency (e.g., in MHz, for normalization).
6. The cutoff frequency for C- and D-sections (e.g., in MHz).

7. The d-level for allpass networks [4]. This parameter is treated like any other circuit parameter. It is the very last variable to be entered.



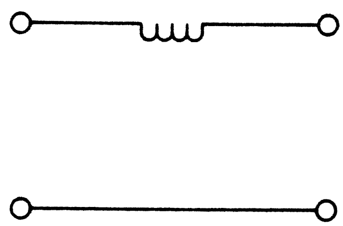
SOURCE
AND
LOAD
CONFIGURATION

Possibilities

1. Complex (but constant) load impedance; will, therefore, usually be a resistance.
2. Modification of program needed to have frequency dependent source and load impedances (source is assumed to be unity).

Parameters required

1. Load impedance.



SERIES
INDUCTOR

Code

1

Parameters

1 2 3

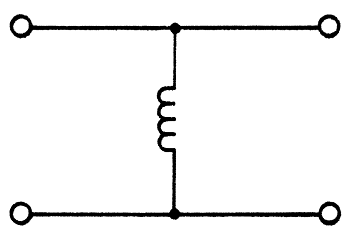
L

Parameter Definition

L = inductance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.



SHUNT
INDUCTOR

Code

4

Parameters

1 2 3

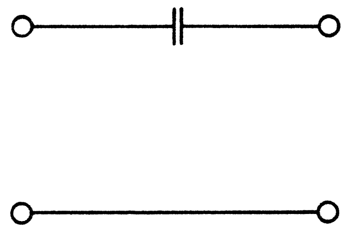
L

Parameter Definition

L = inductance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.



SERIES
CAPACITOR

Code

3

Parameters

1 2 3

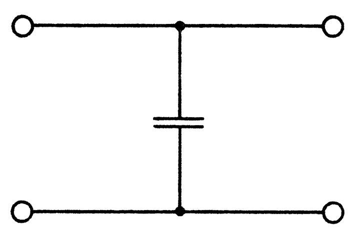
C

Parameter Definition

C = capacitance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.



SHUNT
CAPACITOR

Code

2

Parameters

1 2 3

C

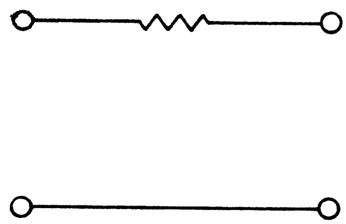
Parameter Definition

C = capacitance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES
RESISTOR



Code

5

Parameters

1 2 3

R

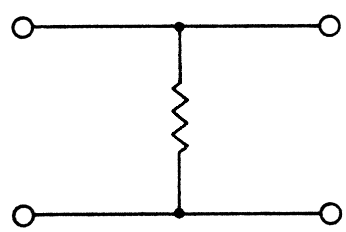
Parameter Definition

R = resistance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT
RESISTOR



Code

6

Parameters

1 2 3

R

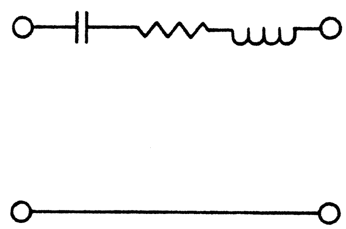
Parameter Definition

R = resistance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES
RESONANT
RLC CIRCUIT



Code

7

Parameters

1	2	3
ω_R	Q	X′

Parameter Definition

ω_R = resonant frequency (normalized)

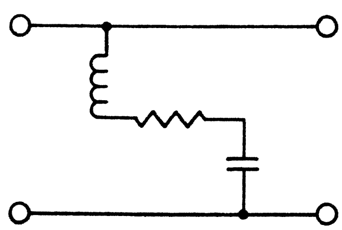
Q = quality factor

X′ = slope of reactance at resonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT
RESONANT
RLC CIRCUIT



Code

10

Parameters

1	2	3
ω_R	Q	X′

Parameter Definition

ω_R = resonant frequency (normalized)

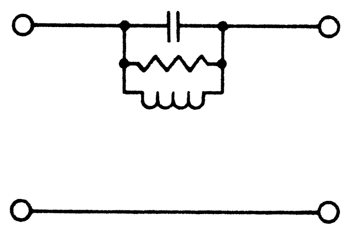
Q = quality factor

X′ = slope of reactance at resonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES
ANTIRESONANT
RLC CIRCUIT



Code

9

Parameters

1	2	3
ω_R	Q	B′

Parameter Definition

ω_R = antiresonant frequency (normalized)

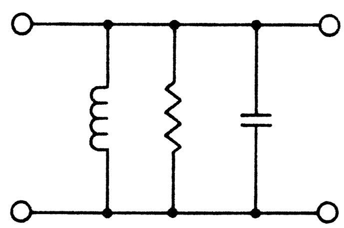
Q = quality factor

B′ = slope of susceptance at antiresonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT
ANTIRESONANT
RLC CIRCUIT



Code

8

Parameters

1	2	3
ω_R	Q	B′

Parameter Definition

ω_R = antiresonant frequency (normalized)

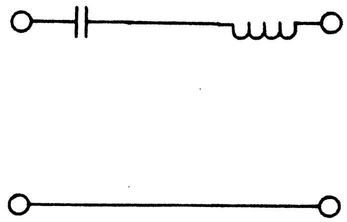
Q = quality factor

B′ = slope of reactance at antiresonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES
RESONANT
LC CIRCUIT



Code

16

Parameters

1 2 3

ω_R X′

Parameter Definition

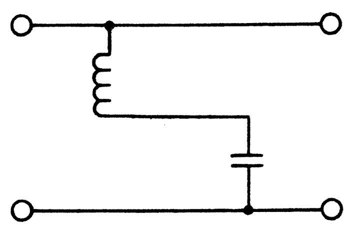
ω_R = resonant frequency (normalized)

X′ = slope of reactance at resonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT
RESONANT
LC CIRCUIT



Code

19

Parameters

1 2 3

ω_R X′

Parameter Definition

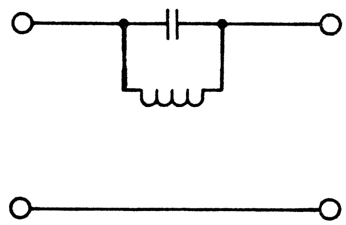
ω_R = resonant frequency (normalized)

X′ = slope of reactance at resonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES
ANTIRESONANT
LC CIRCUIT



Code

18

Parameters

1	2	3
ω_R	B′	

Parameter Definition

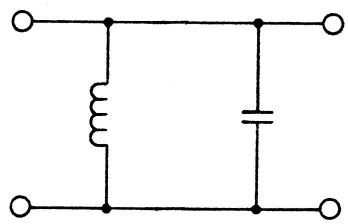
ω_R = antiresonant frequency (normalized)

B′ = slope of susceptance at antiresonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT
ANTIRESONANT
LC CIRCUIT



Code

17

Parameters

1	2	3
ω_R	B′	

Parameter Definition

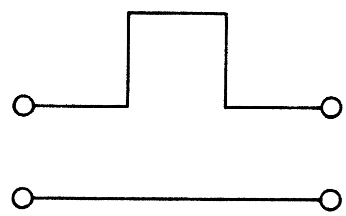
ω_R = antiresonant frequency (normalized)

B′ = slope of susceptance at antiresonance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES SHORTED
LOSSLESS
TRANSMISSION LINE



Code

11

Parameters

1 2 3

ℓ Z_0

Parameter Definition

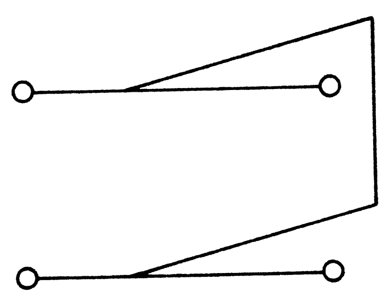
ℓ = length (normalized)

Z_0 = characteristic impedance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT SHORTED
LOSSLESS
TRANSMISSION LINE



Code

14

Parameters

1 2 3

ℓ Z_0

Parameter Definition

ℓ = length (normalized)

Z_0 = characteristic impedance (normalized)

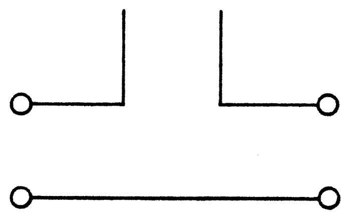
Comments

Upper and lower bounds or fixed values can be accommodated.

SERIES OPEN
LOSSLESS
TRANSMISSION LINE

Code

13



Parameters

1 2 3

ℓ Z_0

Parameter Definition

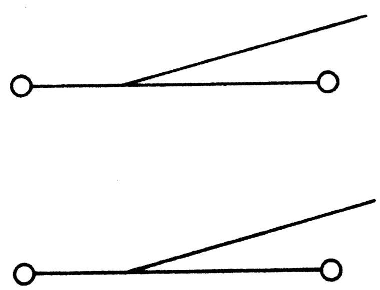
ℓ = length (normalized)

Z_0 = characteristic impedance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

SHUNT OPEN
LOSSLESS
TRANSMISSION LINE



Code

12

Parameters

1 2 3

ℓ Z_0

Parameter Definition

ℓ = length (normalized)

Z_0 = characteristic impedance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.

CASCADE
LOSSLESS
TRANSMISSION LINE

Code

15

Parameters

1	2	3
ℓ	Z_0	

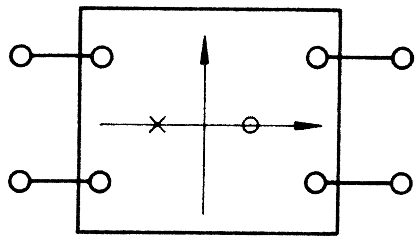
Parameter Definition

ℓ = length (normalized)

Z_0 = characteristic impedance (normalized)

Comments

Upper and lower bounds or fixed values can be accommodated.



ALLPASS
C-SECTIONS
(Total number n_C)

Code

C – section

Parameters

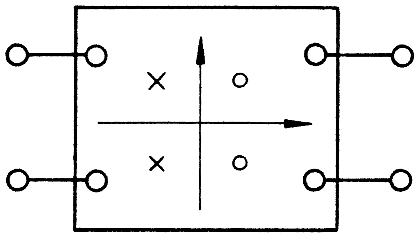
1	2	3	...	n_C
σ_1	σ_2	σ_3	...	σ_{n_C}

Parameter Definition

σ_i = location of ith real zero

Comments

1. The user specifies the number of C-sections required.
2. One cutoff frequency and one d-level must be specified whenever any C- or D-section is used.
3. The user should consult theoretical concepts reviewed by Kudsia [4].
4. C- and D-section parameters and the d-level are either all fixed or all variable.



ALLPASS
D-SECTIONS
(Total number n_D)

Code	Parameters
D – section	<u>1</u> <u>2</u> <u>3</u> ... $\underline{n}_D + 1$ $\underline{n}_D + 2$ $\underline{n}_D + 3$ ...
	σ_1 σ_2 σ_3 ... ω_1 ω_2 ω_3 ...

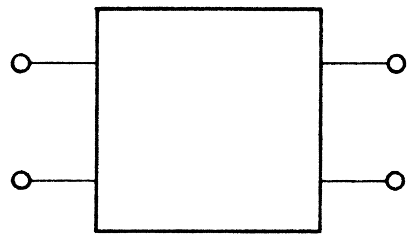
Parameter Definition

σ_i = location of real part of ith zero

ω_i = location of imaginary part of ith zero

Comments

1. The user specifies the number of D-sections required.
2. One cutoff frequency and one d-level must be specified whenever any C- or D-section is used.
3. The user should consult theoretical concepts reviewed by Kudsia [4].
4. C- and D-section parameters and the d-level are either all fixed or all variable.



TWO-PORT
SECTION

Possibilities

Addition of various new blocks is possible because of the modular approach which has been used in the development of the system. The following basic procedure has to be carried out.

Implementation

An analysis subroutine must be written to calculate input voltage and current given the output voltage and current (ABCD matrix analysis). The subroutine is called exactly as any other analysis subroutine in the package is called and sensitivity formulas obtained by the adjoint network method if the parameters of the two-port are to be varied. The user is asked to refer to the CANOP2 report [1] for more complete instructions on the insertion of additional elements.

Comments

A wide variety of other two-ports can be added, e.g., distributed RC lines, transistor amplifier stages, operational amplifier stages, etc.

IV. SPECIFICATIONS AND CONSTRAINTS

Possibilities

1. As many upper and lower specifications on reflection coefficient, insertion loss and relative group delay as the user desires can be accommodated.
2. Upper and lower bounds on all variables can be specified.

Parameters Required

1. Total number of frequency intervals and individual frequency points.
2. When asked for: +1 to denote an upper specification

   -1 to denote a lower specification

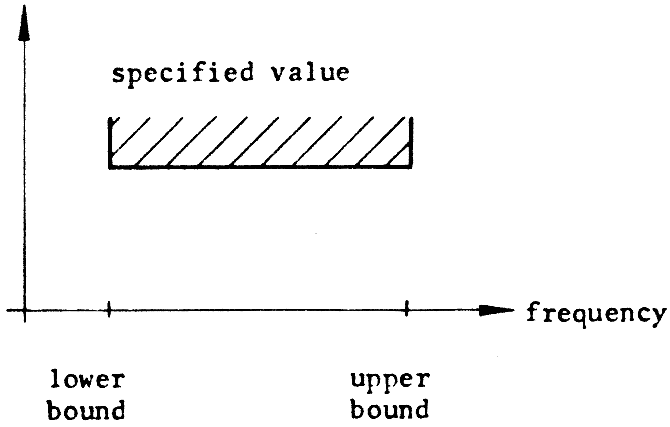
   0 to denote a single specification.
3. When asked for: 1 denotes reflection coefficient

   2 denotes insertion loss

   3 denotes relative group delay.

Comment

Single specifications imply equal upper and lower bounds.



UPPER RESPONSE
SPECIFICATION

Defining Parameters

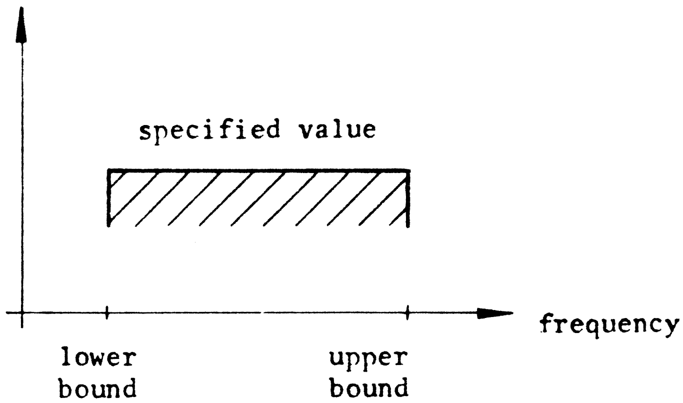
1. Lower bound (frequency point).
2. Upper bound (frequency point).
3. Number of subintervals (equals sample points minus one).
4. Specified value.

Associated Quantities

1. Weighting factor (positive). If in doubt use 1.
2. Upper specification may be
   (i) reflection coefficient
   (ii) insertion loss (dB)
   (iii) relative group delay (nsec).

Comments

For frequency points rather than frequency intervals, defining parameters 1-3 are replaced by the individual frequency values.



LOWER RESPONSE
SPECIFICATION

Defining Parameters

1. Lower bound (frequency point).

2. Upper bound (frequency point).

3. Number of subintervals (equals sample points minus one).

4. Specified value.

Associated Quantities

1. Weighting factor (positive). If in doubt use 1.

2. Lower specification may be

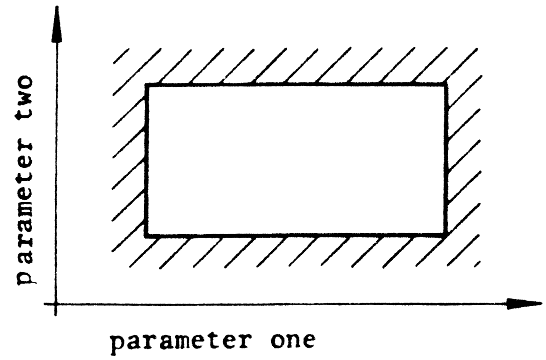
    (i) reflection coefficient

    (ii) insertion loss (dB)

    (iii) relative group delay (nsec).

Comments

For frequency points rather than frequency intervals, defining parameters 1-3 are replaced by the individual frequency values.



PARAMETER
CONSTRAINTS

Possibilities

1. Any circuit parameter may be fixed or varied as specified by the user.

2. If variable parameters are to be constrained, then each must have an associated lower and/or upper desired bound supplied by the user.

Defining Parameters

1. When asked for:
   0 denotes no constraints
   1 denotes an upper bound
   –1 denotes a lower bound
   2 denotes an upper and lower bound.

2. When asked for, supply the values of the bounds.

Comment

The constraints are handled directly by the optimization package and no constraint violation will occur during the optimization process.

V. OPTIMIZATION

Possibilities

CANOP3 employs a fast and robust gradient-based minimax algorithm. MMLC [2,3] is a package of subroutines for solving linearly constrained minimax optimization problems and is used in the form of a library by the system.

The program terminates when the stopping criterion for the optimization method is satisfied, or when the relative change in the variables in two successive optimizations is less than a small prescribed quantity.

Parameters Required

1. A small test quantity used in the optimization to test for convergence (default = 1.0 E-6).
2. Maximum number of function evaluations (default = 100).
3. Integer denoting how many function evaluations should be executed before printout of intermediate results (default = 20).
4. An initial step-length for the algorithm (usually 1% - 10% of the average value of the optimization variable).

VI. STRUCTURE OF THE SYSTEM

The CANOP3 system comprises the following modules:

-	CANOP3M	array dimensioning
-	CANOP3	interactive features and general coordination of information
-	FDF	array dimensioning
-	FDFSRC	calculations of error functions and gradients
-	APPROX	cascaded network circuit analysis
-	CODE1,...,CODED	two port component circuit analysis
-	PLOT	low resolution plotting routine
-	SUBANS	subroutine used to read Y/N (yes/no) answers
-	MMLC	minimax optimization library.

A block diagram of the structure is shown in Fig. 1.

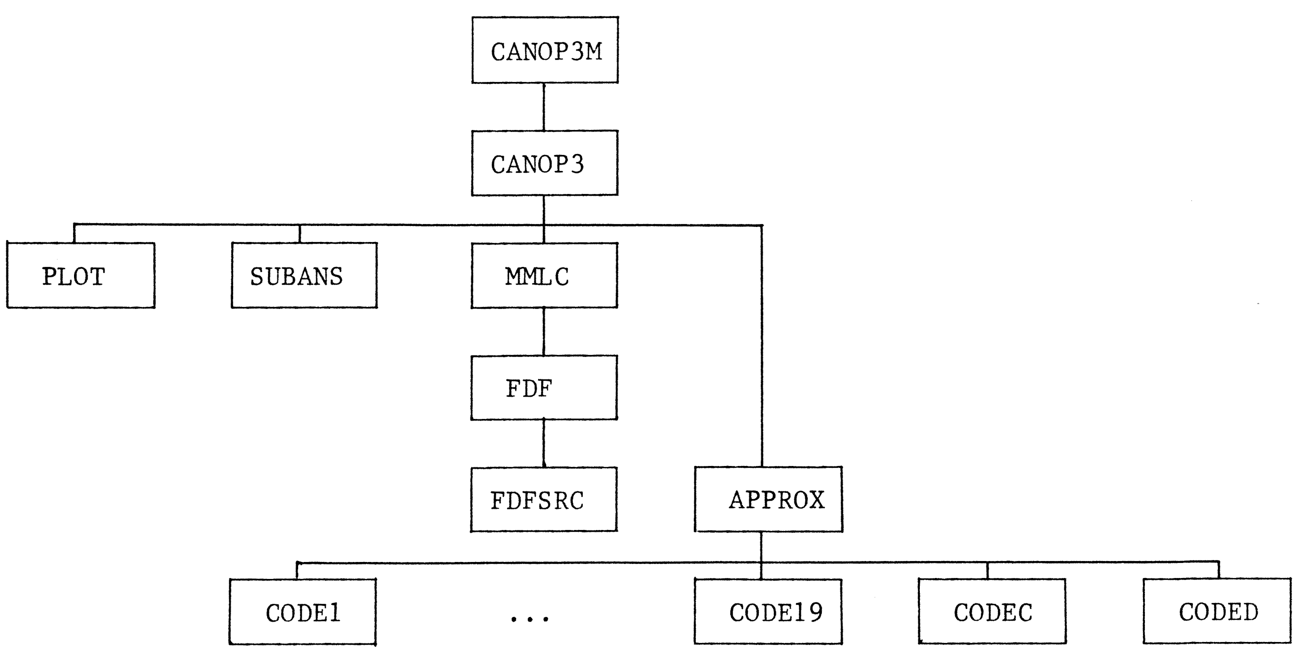


Fig. 1. Structure of the CANOP3 System.

VII. HOW TO USE CANOP3

The system is available at McMaster University on the CDC 170/730 or CDC 170/815 computer as files under the charge RJWBAND. Table IV lists the necessary files, their routines, and the format in which they are being stored.

TABLE IV

CANOP3 SYSTEM FILES

File Name	Routine(s)	Format
LIBRMML	MMLC subroutines	library of binary relocatable routines
LIBCOP3	CANOP3, SUBANS, FDFSRC, APPROX, PLOT CODE1, ..., CODED	library of binary relocatable routines
CANOP3M	CANOP3M, FDF	Fortran 77 source code

The general sequence of NOS commands to use the CANOP3 system may be as follows:

/ FETCH, LIBCOP3/GR.	fetch the group library
/ FETCH, LIBRMML/GR.	fetch the group library
/ LIBRARY, LIBCOP3, LIBRMML.	indicate library to loader
/ FETCH, CANOP3M/GR.	fetch the permanent file
/ FTN5, I=CANOP3M, L=0, B=B, REW.	compile the source code
/ LOAD, B.	link the files
? NOGO, EXE.	create an executable file
/ EXE.	run the CANOP3 system

VIII. LIMITS OF THE SYSTEM

The size of a problem that can be accommodated by the CANOP3 software system is determined by the dimension of various arrays in the CANOP3M file. The present limits, adequate for all examples presented herein, are:

10 = total number of elements

20 = total number of parameters in all elements

20 = total number of variable parameters in all elements

1 = total number of C-sections

1 = total number of variable C-sections

1 = total number of D-sections

1 = total number of variable D-sections

40 = total number of frequency bands (count as 2 those which have a single specification, i.e., upper spec. = lower spec.) plus the number of other frequency points (also counting as 2 those with single specifications)

50 = total number of sample frequency points for optimization purposes

150 = total number of frequency points for simulation/plot purposes

15 = total number of bounds on the optimization variables.

If a larger problem is to be solved, the CANOP3M file will need to be edited by the user before compiling it. A self-explanatory listing of CANOP3M appears in Appendix D.

IX. EXAMPLES

Example 1: Design of Optimum Group Delay Equalizer

It is desired to use one microwave C-section to optimize a set of group delay specifications over a given band. Table V shows the given set of frequencies and corresponding group delay. Starting and optimized values for the parameters and total relative group delays are also shown.

The number of intervals was taken as 32, i.e., 16 corresponding to upper specifications and 16 to lower specifications. The upper and lower specifications at every frequency point were the same. They were equal to the negative of the given group delay. Cut-off frequency was 5269.1 MHz and the center frequency was 7983.5 MHz. Source and load resistance are each taken as unity. The weighting was 1 throughout. The test quantity and initial step-length was taken as 1.E-6 and 5.0, respectively. The number of parameters (unconstrained) is two, namely, σ and d.

Starting and optimized values for the parameters and the corresponding total relative group delay are also shown in Table V.

Example 2: Optimization of Two-Section Transmission-Line Transformer

To demonstrate how close to known optimal solutions the package will allow a user to come, a two-section, four-variable lossless transmission-line transformer was optimized from a poor starting point. A relative bandwidth of 100% is assumed and a load to source impedance ratio of 10:1 is taken. The modulus of the reflection coefficient is considered. The problem itself has frequently been used as a test problem for optimization strategies. ℓ_1 and ℓ_2 are the normalized lengths of sections 1 and 2; Z_{01} and Z_{02} are the corresponding normalized characteristic impedances.

One upper specification of 0 reflection coefficient with 20 subintervals (21 uniformly distributed sample points) was taken. The test quantity and initial step-length was taken as 1.E-6 and 0.005, respectively. Table VI shows the results obtained.

Example 3: Lowpass Lumped LC Filter Design

It is desired to approximate a certain lowpass filter insertion loss specification using a ladder network consisting of lumped lossless inductors and capacitors. The first element is a shunt capacitor, followed by a series inductor and so on, with a total of three capacitors and three inductors. The source and load resistances are each taken as unity. The convergence test quantity was 1.E-6 and the initial step-length was taken as 0.01. The response specification and the results are summarized in Table VII.

Example 4: High Power Output Filter for CTS

A six element filter consisting of an alternating sequence of blocks 8 and 7 and with unity terminations was to meet the following insertion loss specifications: an 0.85 dB upper specification for the frequency interval 11843 to 11928 MHz, 66 dB, 31 dB and 41 dB lower specifications for the frequency points 11700 MHz, 12038 MHz and 12080 MHz, respectively.

The problem that was tried took the center frequency equal to the resonant frequency f_R = 11,885.5 MHz. The resonant and antiresonant frequencies were thereby normalized to 1.0. The quality factors were to be 6,000. The normalized slope parameters were to be varied between 210 and 570.

Convergence test quantity and the initial step-length were taken as 1.E-6 and 2.0, respectively. The results are shown in Table VIII.

TABLE V

DESIGN OF OPTIMUM GROUP DELAY EQUALIZER

Optimization parameter values:		Start	Solution
		$\sigma = 340$	368.77
		$d = 86$	87.75

Frequency (MHz)	Given Group Delay (nsec)	Total Relative Group Delay (nsec)	
7,976	69.03	4.11	2.49
7,977	62.61	0.30	–1.04
7,978	58.03	–1.48	–2.43
7,979	54.79	–1.83	–2.29
7,980	52.52	–1.29	–1.19
7,981	50.79	–0.36	0.29
7,982	49.98	0.56	1.69
7,983	49.49	1.09	2.49
7,984	49.49	1.08	2.49
7,985	49.97	0.54	1.67
7,986	50.95	–0.38	0.29
7,987	52.50	–1.32	–1.23
7,988	54.75	–1.89	–2.35
7,989	57.99	–1.54	–2.49
7,990	62.55	0.22	–1.12
7,991	68.94	4.01	2.39
Maximum		4.11	2.49
Execution Time (sec)		0	0.3

TABLE VI

OPTIMIZATION OF TWO-SECTION TRANSMISSION-LINE TRANSFORMER

Variable Parameters	Start	Solution
ℓ_1	0.8	1.0000
Z_{01}	3.0	2.2361
ℓ_2	0.8	1.0000
Z_{02}	3.5	4.4722

Normalized Frequency	Reflection Coefficient	
.50	.467	.4286
.55	.347	.3099
.60	.205	.1783
.65	.051	.0436
.70	.119	.0830
.75	.266	.1928
.80	.392	.2813
.85	.495	.3478
.90	.574	.3934
.95	.634	.4199
1.00	.678	.4286
1.05	.711	.4199
1.10	.734	.3934
1.15	.749	.3478
1.20	.758	.2813
1.25	.760	.1928
1.30	.758	.0830
1.35	.749	.0436
1.40	.734	.1783
1.45	.711	.3099
1.50	.678	.4285
Maximum	.760	.4286
Execution Time (sec)	0	1.2

TABLE VII

LOWPASS LUMPED LC FILTER DESIGN

Frequency (Hz)	Specification (dB)	Type
0 - 0.9	0	Upper
1.75	40	Lower
1.75	41	Upper
2.50	60	Lower

Variable Parameters	Start	Solution
C_1	1.0	1.011
L_1	1.0	1.654
C_2	1.0	1.915
L_2	1.0	1.915
C_3	1.0	1.654
L_3	1.0	1.011

Frequency (Hz)	Weighting Factor	Insertion Loss (dB)	
0	5.0	0	0
0.09	5.0	0.001	0.001
0.18	5.0	0.009	0.007
0.27	5.0	0.042	0.024
0.36	5.0	0.112	0.042
0.45	5.0	0.216	0.038
0.54	5.0	0.327	0.012
0.63	5.0	0.402	0.002
0.72	5.0	0.398	0.041
0.81	5.0	0.294	0.042
0.90	5.0	0.122	0.042
1.75	1.0	0.166	39.8
2.50	1.0	34.5	60.3
Execution Time (sec)		0	1.7

TABLE VIII

HIGH POWER OUTPUT FILTER FOR CTS

Variable Parameters	Start	Solution
B_1'	240	195.77
X_1'	420	283.51
B_2'	570	321.44
X_2'	460	321.44
B_3'	450	283.51
X_3'	210	195.77

Frequency (MHz)	Insertion Loss (dB)	
11,843	2.81	0.704
11,847	1.52	0.689
11,852	1.21	0.699
11,856	1.09	0.704
11,860	1.02	0.691
11,864	0.97	0.662
11,869	0.94	0.629
11,873	0.90	0.603
11,877	0.88	0.587
11,881	0.86	0.581
11,886	0.85	0.580
11,890	0.86	0.581
11,894	0.88	0.587
11,898	0.91	0.603
11,903	0.94	0.629
11,907	0.97	0.661
11,911	1.01	0.690
11,915	1.08	0.704
11,920	1.21	0.699
11,924	1.50	0.689
11,928	2.73	0.703
11,700	85.1	66.15
12,038	73.9	54.35
12,080	86.8	67.88
Execution Time (sec)	0	14.4

X. CONCLUSION

The CANOP3 system is a completely updated version of CANOP2 [1] that incorporates the MMLC [2,3] optimization method whereas the latter utilized the Fletcher method. This revision provides twofold benefits. Firstly, and although not reported formally, identical optimal solutions are reached faster. Approximate time reduction factors are 23, 15, 4 and 4 for examples 1 to 4 respectively. Secondly, since the MMLC package directly accommodates linearly constrained optimization variables, no constraint violations are permitted in the optimization proces. This differs from the CANOP2 method of introducing artificial sample frequency points and treating constraints by the objective function in essentially the same way as the performance specifications. The disadvantage in CANOP2 is that violations in constraints are as likely to occur as violations in the response. In short, the CANOP3 version is found to be a much more efficient and straightforward system since it features the latest methods of computer-aided design currently available.

APPENDIX A

SAMPLE RUN

Consider a seven-section equal-ripple band-pass microwave filter of 3 to 1 bandwidth (ratio of upper band edge to lower band edge) consisting of two unit elements and five stubs as represented in Fig. 2. The terminations of the filter are unity. The filter is to have a 0.1 dB insertion loss ripple in the passband, from 1.0875 to 3.2625 GHz, and an attenuation above 50 dB at frequency points 0.6 and 3.75 GHz in the stop-band. All section lengths were kept fixed at normalized values of 1, and the normalized characteristic impedances are used as variables. The starting value of the variable vector (see Fig. 2) was $Z_0 = [.63\ .33\ 1.27\ .26\ 1.27\ .33\ .63]^T$. 21 uniformly spaced sample points were used in the passband. The weighting is set to be 1 everywhere and the default values are used for the optimization. Symmetry of the variable characteristic impedances is taken into account.

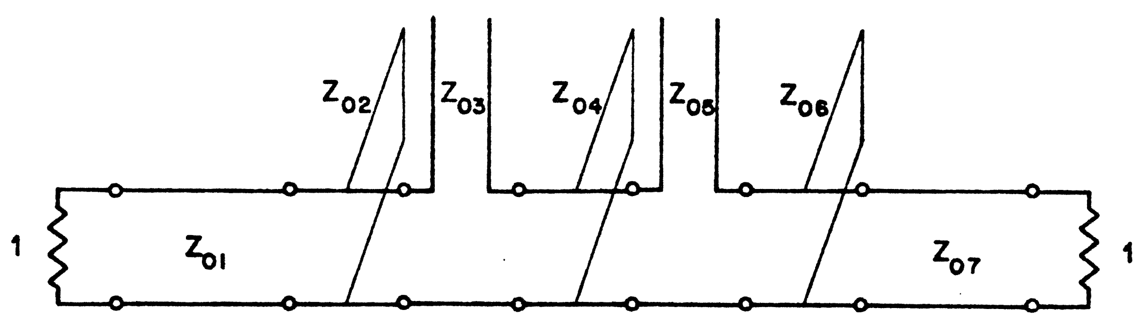


Fig. 2. Seven-section band-pass filter example.

```
YOU ARE WELCOME TO USE THE CASCADED NETWORK OPTIMIZATION PROGRAM.
ENTER YOUR DATA IN ANY FORMAT, HOWEVER, BE REASONABLE.
PLEASE SEPARATE EACH VALUE BY A COMMA, A BLANK OR TYPING THE RETURN
 KEY.
GOOD LUCK.


DO YOU WANT TO SEE THE TABLE OF ELEMENTS AND CODE NUMBERS.
*INPUT*  N
DO YOU WANT QUESTIONS FULLY WORDED TO BE PRINTED OUT.
*INPUT*  Y
SPECIFY THE NUMBER OF ELEMENTS IN THE CIRCUIT NOT INCLUDING C- AND D-SECTIONS.
SET TO 0 IF YOU DO NOT WANT ANY.
 1)
*INPUT*  7
SUPPLY A SEQUENCE OF   7 CODE NUMBERS OF ELEMENTS TO BE CONNECTED SEQUENTIALLY
FROM SOURCE TO LOAD.
(SEE TABLE FOR ELEMENTS AND CODE NUMBERS.)
 2)
*INPUT*  15 14 13 14 13 14 15
DATA CORRECT ?  Y/N
*INPUT*  Y
SPECIFY VALUES OF  14 PARAMETERS IN THE CIRCUIT INCLUDING STARTING VALUES
FOR VARIABLES. (FOLLOW THE SUPPLIED SEQUENCE OF THE CODE NUMBERS OF ELEMENTS.)
(SEE TABLE FOR THE SEQUENCE OF PARAMETERS.)
 3)
*INPUT*  1 .63 1 .33 1 1.27 1 .26 1 1.27 1 .33 1 .63
DATA CORRECT ?  Y/N
*INPUT*  Y
INDICATE WHICH OF THE  14 PARAMETERS ARE FIXED OR VARIABLE.
SET TO 0 IF FIXED AND A POSITIVE INTEGER IF VARIABLE SUCH
THAT THE INTEGER INDICATES WHETHER THE VARIABLE IS NEW OR REPEATED.
 4)
*INPUT*  0 1 0 2 0 3 0 4 0 3 0 2 0 1
DATA CORRECT ?  Y/N
*INPUT*  Y
SPECIFY THE NUMBER OF C-SECTIONS.
SET TO 0 IF YOU DO NOT WANT ANY.
 5)
*INPUT*  0
SPECIFY THE NUMBER OF D-SECTIONS.
SET TO 0 IF YOU DO NOT WANT ANY.
 6)
*INPUT*  0
FOR THE  4 DISTINCT VARIABLES, PLEASE INDICATE THE
CONSTRAINTS:  0  FOR NONE
              1 FOR AN UPPER LIMIT
             -1 FOR A LOWER LIMIT
              2 FOR BOTH.
 9)
*INPUT*  0 0 0 0
DATA CORRECT ?  Y/N
*INPUT*  Y
```

```
SPECIFY THE LOAD RESISTANCE.
10)
*INPUT*  1
SPECIFY THE NUMBER OF FREQUENCY BANDS OR INTERVALS.
11)
*INPUT*  1
SPECIFY THE NUMBER OF OTHER FREQUENCY POINTS.
12)
*INPUT*  2
FOR EACH INTERVAL, SUPPLY THE FOLLOWING INFORMATION:
1.  LOWER FREQUENCY BOUND (BAND EDGE),
2.  UPPER FREQUENCY BOUND (BAND EDGE),
3.  NUMBER OF SUBINTERVALS (EQUALS SAMPLE POINTS MINUS ONE),
4.  PERFORMANCE SPECIFICATION,
5.  WEIGHTING FACTOR (POSITIVE). SET TO 1 IF UNSURE,
6.  TYPE OF SPECIFICATION:
         SET TO  1 FOR UPPER,
         SET TO -1 FOR LOWER,
         SET  TO  0 FOR SINGLE,
7.  APPROXIMATING FUNCTION:
         SET TO 1 FOR REFLECTION COEFFICIENT,
         SET TO 2 FOR INSERTION LOSS (DB),
         SET TO 3 FOR GROUP DELAY (NSEC).
12) INTERVAL( 1)
*INPUT*  1087.5,3262.5,20,.1,1,1,2
DATA CORRECT ?  Y/N
*INPUT*  Y
FOR EACH FREQUENCY POINT SUPPLY THE FOLLOWING INFORMATION:
1.  FREQUENCY,
2.  PERFORMANCE SPECIFICATION,
3.  WEIGHTING FACTOR (POSITIVE). SET TO 1 IF UNSURE,
4.  TYPE OF SPECIFICATION :
         SET TO 1 FOR UPPER,
         SET TO -1 FOR LOWER,
         SET TO  0 FOR SINGLE,
5.  APPROXIMATING FUNCTION:
         SET TO 1 FOR REFLECTION COEFFICIENT,
         SET TO 2 FOR INSERTION LOSS (DB),
         SET TO 3 FOR GROUP DELAY (NSEC)
13) FREQUENCY POINT( 1)
*INPUT*  600,50,1,-1,2
DATA CORRECT ?  Y/N
*INPUT*  Y
13) FREQUENCY POINT( 2)
*INPUT*  3750,50,1,-1,2
DATA CORRECT ?  Y/N
*INPUT*  Y
SPECIFY THE CENTER FREQUENCY (FOR NORMALIZATION).
15)
*INPUT*  2175
SET TO 1 IF YOU WANT OPTIMIZATION.
SET TO 0 IF OPTIMIZATION IS NOT TO BE USED.
17)
*INPUT*  11
SET TO 1 IF YOU WANT OPTIMIZATION.
```

```
SET TO 0 IF OPTIMIZATION IS NOT TO BE USED.
17)
*INPUT*  1
DO YOU WANT TO USE DEFAULT VALUES FOR THE OPTIMIZATION:
    ( EPS=1.E-6, MAX=100, IPRINT=20 )
*INPUT*  Y
SPECIFY THE OPTIMIZATION STEP LENGTH.
(USUALLY 1 % OF THE AVERAGE VARIABLE PARAMETER VALUE)
21)
*INPUT*  .005



ANY MODIFICATION
"
*INPUT*  N
DO YOU WANT TO PRINT OUT YOUR INPUT DATA.
"
*INPUT*  Y
INPUT DATA
----------

NUMBER OF ELEMENTS                                              7
THE CALCULATED NUMBER OF PARAMETERS                            14
  CODE         PARAMETER          PARAMETER         PARAMETER
 NUMBER         NUMBER              VALUE           CONDITION
   15              1             .100000E+01         FIXED
   15              2             .630000E+00         VARIABLE
   14              3             .100000E+01         FIXED
   14              4             .330000E+00         VARIABLE
   13              5             .100000E+01         FIXED
   13              6             .127000E+01         VARIABLE
   14              7             .100000E+01         FIXED
   14              8             .260000E+00         VARIABLE
   13              9             .100000E+01         FIXED
   13             10             .127000E+01         VARIABLE
   14             11             .100000E+01         FIXED
   14             12             .330000E+00         VARIABLE
   15             13             .100000E+01         FIXED
   15             14             .630000E+00         VARIABLE
NUMBER OF C-SECTIONS                                            0
NUMBER OF D-SECTIONS                                            0
 CONSTRAINTS ON THE VARIABLES:
VARIABLE  X 1  NO CONSTRAINTS
VARIABLE  X 2  NO CONSTRAINTS
VARIABLE  X 3  NO CONSTRAINTS
VARIABLE  X 4  NO CONSTRAINTS
LOAD RESISTANCE                                       .100000E+01
NUMBER OF FREQUENCY INTERVALS                                   1
NUMBER OF FREQUENCY POINTS                                      2

     LOWER         UPPER     NO. OF     SPECIFICATION           TYPE   WEIGHTING
   FREQUENCY     FREQUENCY   SUBINT.                                     FACTOR
  .108750E+04   .326250E+04    20    .1000E+00 INSERTION LOSS   UPPER    .10E+01
```

FREQUENCY	SPECIFICATION		TYPE	WEIGHTING FACTOR
.600000E+03	.500000E+02	INSERTION LOSS	LOWER	.100000E+01
.375000E+04	.500000E+02	INSERTION LOSS	LOWER	.100000E+01

THE CALCULATED TOTAL NUMBER OF INTERVALS 3
CENTER FREQUENCY .217500E+04

DEFAULT VALUES ARE USED FOR THE OPTIMIZATION:
MINIMAX METHOD WILL BE USED
CONVERGENCE TEST QUANTITY .100000E-05
MAXIMUM NUMBER OF ALLOWABLE FUNCTION EVALUATIONS 100
FUNCTION EVALUATIONS BETWEEN INTERMEDIATE PRINTOUTS 20
OPTIMIZATION STEP-LENGTH .500000E-02

ANY MODIFICATION
"
INPUT N

YOUR DATA IS NOW BEING PROCESSED. IT MAY TAKE SOME TIME BEFORE RESULTS ARE AVAILABLE. PLEASE BE PATIENT.

RESPONSE AT THE STARTING POINT

FREQUENCY	INSERTION LOSS
.108750E+04	.135250E+02
.119625E+04	.377724E+01
.130500E+04	.245398E+00
.141375E+04	.511379E-03
.152250E+04	.781660E-01
.163125E+04	.254450E+00
.174000E+04	.443708E+00
.184875E+04	.496993E+00
.195750E+04	.352689E+00
.206625E+04	.116872E+00
.217500E+04	.000000E+00
.228375E+04	.116872E+00
.239250E+04	.352689E+00
.250125E+04	.496993E+00
.261000E+04	.443708E+00
.271875E+04	.254450E+00
.282750E+04	.781660E-01
.293625E+04	.511379E-03
.304500E+04	.245398E+00
.315375E+04	.377724E+01
.326250E+04	.135250E+02
.600000E+03	.588821E+02
.375000E+04	.588821E+02

DO YOU WANT A PLOT.
INPUT Y
DO YOU WANT TO PLOT THE ABOVE RESPONSE.

```
*INPUT*  Y
DO YOU WANT TO SCALE AUTOMATICALLY.
*INPUT*  Y



          -1.00E+01        1.00E+01        3.00E+01        5.00E+01     7.00E+01

   FREQUENCY - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
.6000000E+03 .               .               .               .      *        .
.1087500E+04 .               .  *            .               .               .
.1196250E+04 .          *    .               .               .               .
.1305000E+04 .       *       .               .               .               .
.1413750E+04 .       *       .               .               .               .
.1522500E+04 .       *       .               .               .               .
.1631250E+04 .       *       .               .               .               .
.1740000E+04 .       *       .               .               .               .
.1848750E+04 .       *       .               .               .               .
.1957500E+04 .       *       .               .               .               .
.2066250E+04 .       *       .               .               .               .
.2175000E+04 .       *       .               .               .               .
.2283750E+04 .       *       .               .               .               .
.2392500E+04 .       *       .               .               .               .
.2501250E+04 .       *       .               .               .               .
.2610000E+04 .       *       .               .               .               .
.2718750E+04 .       *       .               .               .               .
.2827500E+04 .       *       .               .               .               .
.2936250E+04 .       *       .               .               .               .
.3045000E+04 .       *       .               .               .               .
.3153750E+04 .          *    .               .               .               .
.3262500E+04 .               .  *            .               .               .
.3750000E+04 .               .               .               .      *        .
             - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

-         -1.00E+01        1.00E+01        3.00E+01        5.00E+01     7.00E+01


DO YOU WANT MORE PLOTS.
*INPUT*  Y
DO YOU WANT SOME MORE DETAILS FROM THE ABOVE PLOT.
*INPUT*  Y
ENTER MINIMUM AND MAXIMUM RESPONSE RANGE TO BE PLOTTED.
*INPUT*  -.05,3.
```

```
          -5.00E-02        7.13E-01        1.48E+00        2.24E+00     3.00E+00

   FREQUENCY - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
.6000000E+03 .               .               .               .               *
.1087500E+04 .               .               .               .               *
.1196250E+04 .               .               .               .               *
.1305000E+04 .     *         .               .               .               .
.1413750E+04 .*              .               .               .               .
.1522500E+04 .  *            .               .               .               .
.1631250E+04 .     *         .               .               .               .
.1740000E+04 .         *     .               .               .               .
.1848750E+04 .          *    .               .               .               .
.1957500E+04 .       *       .               .               .               .
.2066250E+04 .   *           .               .               .               .
.2175000E+04 .*              .               .               .               .
.2283750E+04 .   *           .               .               .               .
.2392500E+04 .       *       .               .               .               .
.2501250E+04 .          *    .               .               .               .
.2610000E+04 .         *     .               .               .               .
.2718750E+04 .     *         .               .               .               .
.2827500E+04 .  *            .               .               .               .
.2936250E+04 .*              .               .               .               .
.3045000E+04 .     *         .               .               .               .
.3153750E+04 .               .               .               .               *
.3262500E+04 .               .               .               .               *
.3750000E+04 .               .               .               .               *
             - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

          -5.00E-02        7.13E-01        1.48E+00        2.24E+00     3.00E+00


DO YOU WANT MORE PLOTS.
*INPUT*  N
```

DATE : 84/11/13. TIME : 14.11.13. PAGE : 1
LINEARLY CONSTRAINED MINIMAX OPTIMIZATION (MMLC PACKAGE) (V:82.04)

INPUT DATA

NUMBER OF VARIABLES (N) 4

NUMBER OF FUNCTIONS (M) 23

TOTAL NUMBER OF LINEAR CONSTRAINTS (L) 0

NUMBER OF EQUALITY CONSTRAINTS (LEQ) 0

STEP LENGTH (DX) 5.000E-03

ACCURACY (EPS) 1.000E-06

MAX NUMBER OF FUNCTION EVALUATIONS (MAXF) 100

NUMBER OF SUCCESSIVE ITERATIONS (KEQS) 3

WORKING SPACE (IW) 5679

PRINTOUT CONTROL (IPR) 20000

STARTING POINT :

	VARIABLES		FUNCTION VALUES
1	6.300000000000E-01	1	1.342495534227E+01
2	3.300000000000E-01	2	3.677237293999E+00
3	1.270000000000E+00	3	1.453980876625E-01
4	2.600000000000E-01	4	-9.948862106819E-02
		5	-2.183400750211E-02
		6	1.544496570947E-01
		7	3.437080213072E-01
		8	3.969934000201E-01
		9	2.526892696083E-01
		10	1.687159175846E-02
		11	-1.000000000000E-01
		12	1.687159175843E-02
		13	2.526892696082E-01
		14	3.969934000201E-01
		15	3.437080213073E-01
		16	1.544496570947E-01
		17	-2.183400750208E-02
		18	-9.948862106819E-02
		19	1.453980876625E-01
		20	3.677237293999E+00
		21	1.342495534228E+01
		22	-8.882107857726E+00
		23	-8.882107857726E+00

SOLUTION

	VARIABLES		FUNCTION VALUES
1	6.064600309813E-01	1	-3.469908464646E-02
2	3.030627702063E-01	2	-3.469908464656E-02

3	7.220849317546E-01	3	-9.626394026024E-02
4	2.356115777481E-01	4	-3.469908464653E-02
		5	-5.517157369700E-02
		6	-9.876354039385E-02
		7	-7.784214551442E-02
		8	-3.469908464646E-02
		9	-3.548327895008E-02
		10	-7.583221549472E-02
		11	-1.000000000000E-01
		12	-7.583221549472E-02
		13	-3.548327895017E-02
		14	-3.469908464646E-02
		15	-7.784214551458E-02
		16	-9.876354039395E-02
		17	-5.517157369700E-02
		18	-3.469908464649E-02
		19	-9.626394026024E-02
		20	-3.469908464656E-02
		21	-3.469908464649E-02
		22	-3.469908464672E-02
		23	-3.469908464649E-02

TYPE OF SOLUTION (IFALL) 0

NUMBER OF FUNCTION EVALUATIONS 13

NUMBER OF SHIFTS TO STAGE-2 1

EXECUTION TIME (IN SECONDS) 2.811

RETURN FROM MMLC: REGULAR SOLUTION; REQUIRED ACCURACY OBTAINED

FINAL RESPONSE OF THE CIRCUIT

FREQUENCY	INSERTION LOSS
.108750E+04	.653009E-01
.119625E+04	.653009E-01
.130500E+04	.373606E-02
.141375E+04	.653009E-01
.152250E+04	.448284E-01
.163125E+04	.123646E-02
.174000E+04	.221579E-01
.184875E+04	.653009E-01
.195750E+04	.645167E-01
.206625E+04	.241678E-01
.217500E+04	.000000E+00
.228375E+04	.241678E-01
.239250E+04	.645167E-01
.250125E+04	.653009E-01
.261000E+04	.221579E-01
.271875E+04	.123646E-02

```
        .282750E+04                    .448284E-01
        .293625E+04                    .653009E-01
        .304500E+04                    .373606E-02
        .315375E+04                    .653009E-01
        .326250E+04                    .653009E-01
        .600000E+03                    .500347E+02
        .375000E+04                    .500347E+02
DO YOU WANT A PLOT.
*INPUT*  Y
DO YOU WANT TO PLOT THE ABOVE RESPONSE.
*INPUT*  Y
DO YOU WANT TO SCALE AUTOMATICALLY.
*INPUT*  N
SUPPLY MINIMUM AND MAXIMUM RESPONSE VALUES TO BE PLOTTED.
*INPUT*  -.05,3.


          -5.00E-02          7.13E-01          1.48E+00          2.24E+00      3.00E+00

   FREQUENCY - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
.6000000E+03 .               .                 .                 .                 *
.1087500E+04 . *             .                 .                 .                 .
.1196250E+04 . *             .                 .                 .                 .
.1305000E+04 .*              .                 .                 .                 .
.1413750E+04 . *             .                 .                 .                 .
.1522500E+04 . *             .                 .                 .                 .
.1631250E+04 .*              .                 .                 .                 .
.1740000E+04 . *             .                 .                 .                 .
.1848750E+04 . *             .                 .                 .                 .
.1957500E+04 . *             .                 .                 .                 .
.2066250E+04 . *             .                 .                 .                 .
.2175000E+04 .*              .                 .                 .                 .
.2283750E+04 . *             .                 .                 .                 .
.2392500E+04 . *             .                 .                 .                 .
.2501250E+04 . *             .                 .                 .                 .
.2610000E+04 . *             .                 .                 .                 .
.2718750E+04 .*              .                 .                 .                 .
.2827500E+04 . *             .                 .                 .                 .
.2936250E+04 . *             .                 .                 .                 .
.3045000E+04 .*              .                 .                 .                 .
.3153750E+04 . *             .                 .                 .                 .
.3262500E+04 . *             .                 .                 .                 .
.3750000E+04 .               .                 .                 .                 *
             - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

          -5.00E-02          7.13E-01          1.48E+00          2.24E+00      3.00E+00
```

```
DO YOU WANT MORE PLOTS.
*INPUT*  Y
DO YOU WANT SOME MORE DETAILS FROM THE ABOVE PLOT.
*INPUT*  Y
ENTER MINIMUM AND MAXIMUM RESPONSE RANGE TO BE PLOTTED.
*INPUT*  -.05,.1


          -5.00E-02       -1.25E-02        2.50E-02         6.25E-02     1.00E-01

   FREQUENCY - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
.6000000E+03 .               .               .               .               *
.1087500E+04 .               .               .               .*              .
.1196250E+04 .               .               .               .*              .
.1305000E+04 .               .      *        .               .               .
.1413750E+04 .               .               .               .*              .
.1522500E+04 .               .               .       *       .               .
.1631250E+04 .               .     *         .               .               .
.1740000E+04 .               .              *.               .               .
.1848750E+04 .               .               .               .*              .
.1957500E+04 .               .               .               .*              .
.2066250E+04 .               .               *               .               .
.2175000E+04 .               .    *          .               .               .
.2283750E+04 .               .               *               .               .
.2392500E+04 .               .               .               .*              .
.2501250E+04 .               .               .               .*              .
.2610000E+04 .               .              *.               .               .
.2718750E+04 .               .     *         .               .               .
.2827500E+04 .               .               .       *       .               .
.2936250E+04 .               .               .               .*              .
.3045000E+04 .               .      *        .               .               .
.3153750E+04 .               .               .               .*              .
.3262500E+04 .               .               .               .*              .
.3750000E+04 .               .               .               .               *
             - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

          -5.00E-02       -1.25E-02        2.50E-02         6.25E-02     1.00E-01


DO YOU WANT MORE PLOTS.
*INPUT*  N

DO YOU WANT TO TERMINATE THE PROGRAM
"
*INPUT*  Y
```

APPENDIX B

NORMALIZATION OF PARAMETER VALUES

To illustrate the normalization process we may consider the following examples. For element 1, a series inductance, we consider a parameter L_n such that $\omega_n L_n$, where ω_n is the normalized frequency, yields the desired reactance in ohms. Thus, if the normalization frequency is 3 GHz, the inductance 2nH, then at the normalized frequency

$$L_n = 2\pi f.L = 12\pi.$$

For elements 11-15, for example, we consider a length ℓ_n such that tan $(\pi/2)\ \omega_n \ell_n$ yields the desired value of the frequency variable for lossless transmission lines.

APPENDIX C

INPUT DATA RECORDS

1) Specify the number of elements in the circuit not including C- and D- sections. Set to 0 if you do not want any.

2) Supply a sequence of ## code numbers of elements to be connected sequentially from source to load. (See table for elements and code numbers.)

3) Specify values of ## parameters in the circuit including starting values for variables. (Follow the supplied sequence of the code numbers of elements.) (See table for the sequence of parameters.)

4) Indicate which of the ## parameters are fixed or variable. Set to 0 if fixed and a positive integer if variable such that the integer indicates whether the variable is new or repeated.

5) Specify the number of C-sections. Set to 0 if you do not want any.

6) Specify the number of D-sections. Set to 0 if you do not want any.

7) Indicate whether C- and D-section parameters are all fixed or variable. Set to 0 if fixed and 1 if variable.

8) Specify ## values of the parameters of the C- and ## values of the D- sections and a d-level.

9) For the ## distinct variables, please indicate the constraints: 0 for none, 1 for an upper limit, –1 for a lower limit, 2 for both.

10) Specify the load resistance.

11) Specify the number of frequency bands or intervals.

12) Specify the number of other frequency points.

13) For each interval, supply the following information:

   1. lower frequency bound (band edge)
   2. upper frequency bound (band edge)
   3. number of subintervals (equals sample points minus one)
   4. performance specification
   5. weighting factor (positive)
   6. type of specification: (1 for upper, –1 for lower, 0 for single)
   7. approximating function: (1 for reflection coefficient, 2 for insertion loss, 3 for group delay (nsec)).

14) For each frequency point, supply the following:

   1. frequency
   2. performance specification
   3. weighting factor (positive)
   4. type of specification: (1 for upper, –1 for lower, 0 for single)
   5. approximating function: (1 for reflection coefficient, 2 for insertion loss, 3 for group delay (nsec)).

15) Specify the center frequency (for normalization).

16) Specify the cut-off frequency for C- and D-sections.

17) Set to 1 if you want optimization.

Set to 0 if optimization is not to be used.

18) Specify EPS: small quantity for testing convergence in the minimax method. (e.g., 1.E-6).

19) Specify the maximum number of function evaluations (e.g., 100).

20) Specify the number of function evaluations after which you want an intermediate output to be printed out. Set to 0 if no intermediate output is desired.

21) Specify the optimization step-length. (Usually 1%-10% of the average variable parameter value.)

APPENDIX D

LISTING OF CANOP3M

```
      PROGRAM CANOP3M
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*  THIS FILE IS USED FOR DEFINING THE MAXIMUM SIZE OF A PROBLEM TO
*  BE HANDLED BY CANOP3:
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
*
*    SECTIONS WHICH REQUIRE USER INTERVENTION (IN EDIT MODE) ARE
*    FRAMED BY HERRINGBONE SYMBOLS, AS IS THIS MESSAGE.
*
*<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
* GIVEN THE FOLLOWING REQUIREMENTS :
* (NOTE THAT THE TERMS 'ELEMENTS' AND 'SECTIONS' ARE
* MUTUALLY EXCLUSIVE)
* NE =TOTAL NUMBER OF ELEMENTS
* NPE=TOTAL NUMBER OF PARAMETERS IN ALL ELEMENTS
* NPVE=NUMBER OF VARIABLE PARAMETERS IN ALL ELEMENTS
* NC=NUMBER OF C SECTIONS
* ND=NUMBER OF D SECTIONS
* NVC =NUMBER OF VARIABLE C SECTIONS
* NVD =NUMBER OF VARIABLE D SECTIONS
* NINT=NUMBER OF FREQUENCY BANDS (COUNT AS 2 THOSE WHICH HAVE BOTH
*                                 UPPER AND LOWER SPECS)
*     +NUMBER OF FREQUENCY POINTS(COUNT AS 2 THOSE WHICH HAVE BOTH
*                                 UPPER AND LOWER SPECS)
* NFRE =TOTAL NUMBER OF SAMPLE FREQUENCY POINTS
* JJ=MAX(NINT,NPE)
* NCONSTR=NUMBER BOUNDS ON OPTIMIZATION VARIABLES
* NFRSIM=NUMBER OF FREQUENCY POINTS FOR SIMULATION/PLOT
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
*
* THE USER MUST ASSIGN APPROPRIATE VALUES HERE :
*
      PARAMETER ( NE=10, NPE=20, NPVE=20, NC=1, ND=1, NVC=1, NVD=1 )
      PARAMETER ( NINT=40, NFRE=50, JJ=40, NCONSTR=15, NFRSIM=150   )
*
*<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
* THE FOLLOWING PARAMETERS ARE AUTOMATICALLY DEFINED:
      PARAMETER ( IPAR1=NPE, IPAR2=2*ND+NC+1, IPAR3=NINT )
      PARAMETER ( IPAR4=NFRE, IPAR5=NPVE+2*NVD+NVC+1 )
      PARAMETER ( IPAR6=JJ, IPAR7=IPAR5-NPVE+NPE )
      PARAMETER ( IPAR8=IPAR5*(IPAR5+7)/2, IPAR9=IPAR1+NE )
      PARAMETER ( IPAR10=NCONSTR, IPAR11=NFRSIM )
      PARAMETER ( IPAR12=2*IPAR4*IPAR5+5*IPAR5**2 )
      PARAMETER ( IPARW=IPAR12+4*IPAR4+8*IPAR5+7 )
```

```
* THE FOLLOWING ARRAYS ARE AUTOMATICALLY DIMENSIONED:
      DIMENSION A1(IPAR1),A2(IPAR1),A3(IPAR2),A4(IPAR3)
      DIMENSION A5(IPAR3),A6(3,IPAR3),A7(IPAR3),A8(IPAR3)
      DIMENSION A9(IPAR3),A0(IPAR4),B1(IPAR4),B2(IPAR4)
      DIMENSION B3(IPAR5),B4(IPAR5),B5(IPAR5),B6(IPAR5)
      DIMENSION B7(IPAR5),B8(2,IPAR5),B9(IPAR5),B0(IPAR5)
      DIMENSION C1(IPAR5),C2(IPAR6),C3(IPAR7),C4(IPAR8)
      DIMENSION C5(IPAR9),C6(IPAR10),C7(IPAR11),C8(IPAR11)
      DIMENSION C9(IPAR10,IPAR5),C0(IPARW)
*
      COMMON /DIM/ I1,I2,I3,I4,I5,I6,I7,I8,I9,I10,I11,IW
      COMMON /MR1/ C3,A2,A3,A8,A9,A6,A0,B1,B2
      COMMON /MR2/ C4,C5,A4,C2,B9,B0,C1
*
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
      I1=IPAR1
      I2=IPAR2
      I3=IPAR3
      I4=IPAR4
      I5=IPAR5
      I6=IPAR6
      I7=IPAR7
      I8=IPAR8
      I9=IPAR9
      I10=IPAR10
      I11=IPAR11
      IW=IPARW
*
*
      CALL CANOP3(A1,A2,A3,A4,A5,A6,A7,A8,A9,A0,B1,B2,B3,
     +B4,B5,B6,B7,B8,B9,B0,C1,C2,C3,C4,C5,C6,C7,C8,C9,C0)
*
      STOP
      END
*
*
```

```
      SUBROUTINE FDF(N,M,A,DF,F)
*
      DIMENSION A(N),DF(M,N),F(M)
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
*
* THE USER MUST ASSIGN APPROPRIATE VALUES HERE :
*
      PARAMETER ( NE=10, NPE=20, NPVE=20, NC=1, ND=1, NVC=1, NVD=1 )
      PARAMETER ( NINT=40, NFRE=50, JJ=40, NCONSTR=15, NFRSIM=150  )
*
*<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
* THE FOLLOWING PARAMETERS ARE AUTOMATICALLY DEFINED:
      PARAMETER ( IPAR1=NPE, IPAR2=2*ND+NC+1, IPAR3=NINT )
      PARAMETER ( IPAR4=NFRE, IPAR5=NPVE+2*NVD+NVC+1 )
      PARAMETER ( IPAR6=JJ, IPAR7=IPAR5-NPVE+NPE )
      PARAMETER ( IPAR8=IPAR5*(IPAR5+7)/2, IPAR9=IPAR1+NE )
      PARAMETER ( IPAR10=NCONSTR, IPAR11=NFRSIM )
      PARAMETER ( IPAR12=2*IPAR4*IPAR5+5*IPAR5**2 )
      PARAMETER ( IPARW=IPAR12+4*IPAR4+8*IPAR5+7 )
* THE FOLLOWING ARRAYS ARE THEREBY AUTOMATICALLY DIMENSIONED:
      DIMENSION A2(IPAR1),A3(IPAR2),A4(IPAR3),A6(3,IPAR3)
      DIMENSION A8(IPAR3),A9(IPAR3),A0(IPAR4)
      DIMENSION B1(IPAR4),B2(IPAR4),B9(IPAR5),B0(IPAR5)
      DIMENSION C1(IPAR5),C2(IPAR6),C3(IPAR7),C4(IPAR8)
      DIMENSION C5(IPAR9),AP(IPAR4)
*
      COMMON /MR1/ C3,A2,A3,A8,A9,A6,A0,B1,B2
      COMMON /MR2/ C4,C5,A4,C2,B9,B0,C1
*
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
      CALL FDFSRC(N,M,A,DF,F,A2,A3,A4,A6,A8,
     +A9,A0,B1,B2,B9,B0,C1,C2,C3,C4,C5,AP)
*
      RETURN
      END
```

REFERENCES

[1] J.W. Bandler and J.R. Popovic, "CANOP2 - interactive cascaded network optimization package", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOC-69, 1974.

[2] J.W. Bandler and W.M. Zuberek, "MMLC - a Fortran package for linearly constrained minimax optimization", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-82-5-U2, 1983.

[3] J. Hald and K. Madsen, "Combined LP and quasi-Newton methods for minimax optimization", Mathematical Programming, vol. 20, 1981, pp. 49-62.

[4] C.M. Kudsia, "Synthesis of optimum reflection type microwave equalizers", RCA Review, vol. 31, Sept. 1970, pp. 571-595.