

HEWLETT-PACKARD

HP-67/HP-97

E.E. Pac I



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ATTENTION: APPLICATIONS

INTRODUCTION

The 18 programs of EE Pac 1 have been drawn from the fields of network analysis, network synthesis, transistor theory, and microwave engineering.

Each program in this pac is represented by one or more magnetic cards and a section in this manual. The manual provides a description of the program with relevant equations, a set of instructions for using the program, and one or more example problems, each of which includes a list of the actual key-strokes required for its solution. Program listings for all the programs in the pac appear at the back of this manual. Explanatory comments have been incorporated in the listings to facilitate your understanding of the actual working of each program. Thorough study of a commented listing can help you to expand your programming repertoire since interesting techniques can often be found in this way.

On the face of each magnetic card are various mnemonic symbols which provide shorthand instructions to the use of the program. You should first familiarize yourself with a program by running it once or twice while following the complete User Instructions in the manual. Thereafter, the mnemonics on the cards themselves should provide the necessary instructions, including what variables are to be input, which user-definable keys are to be pressed, and what values will be output. A full explanation of the mnemonic symbols for magnetic cards may be found in appendix A.

If you have already worked through a few programs in Standard Pac, you will understand how to load a program and how to interpret the User Instructions form. If these procedures are not clear to you, take a few minutes to review the sections, Loading a Program and Format of User Instructions, in your Standard Pac.

We hope that EE Pac 1 will assist you in the solution of numerous problems in your discipline. We would very much appreciate knowing your reactions to the programs in this pac, and to this end we have provided a questionnaire inside the front cover of this manual. Would you please take a few minutes to give us your comments on these programs? It is in the comments we receive from you that we learn how best to increase the usefulness of programs like these.

TABLE OF CONTENTS

Program	Page
Introduction	i
A Word about Program Usage	iv
1. Network Transfer Functions	01-01
This program computes various transfer functions of a ladder network composed of any number of standard elements.	
2. Reactive L-Network Impedance Matching	02-01
This program computes networks which will match any two complex impedances.	
3. Class A Transistor Amplifier Bias Optimization	03-01
This program simplifies the design of a class A transistor amplifier.	
4. Transistor Amplifier Performance	04-01
This program computes the small-signal properties of a transistor amplifier given the h-parameter matrix and the source and load impedances.	
5. Transistor Configuration Conversion	05-01
This program permits conversion among h-parameter matrices for CB, CE, or CC transistor configurations.	
6. Parameter Conversion: $S \rightleftharpoons Y, Z, G, H$	06-01
This program allows conversion among various commonly used parameter sets.	
7. Fourier Series	07-01
This program computes Fourier coefficients from samples of a periodic function.	
8. Active Filter Design	08-01
This program computes element values for a standard filter circuit.	
9. Butterworth or Chebyshev Filter Design	09-01
This program computes component values for Butterworth or Chebyshev filters between equal terminations. The user may select various filter characteristics.	
10. Bode Plot of Butterworth and Chebyshev Filters	10-01
This program provides gain, phase, and group delay information for Bode plots of n-pole Butterworth or Chebyshev filters.	
11. Resistive Attenuator Design	11-01
This program computes values for the resistors which yield an attenuator having any desired loss.	
12. Smith Chart Conversions	12-01
This program converts among various radially scaled parameters (σ , ρ , SWR, R.L.) and also interconverts impedance and reflection coefficient.	
13. Transmission Line Impedance	13-01
This program computes high frequency characteristic impedance for five types of transmission lines.	
14. Microstrip Transmission Line Calculations	14-01
This program computes relative phase velocity and characteristic impedance for lossless microstrip. It also computes copper loss and resistance per unit length.	
15. Transmission Line Calculations	15-01
This program computes the input impedance of lossy transmission line terminated in Z_L .	

16.	Unilateral Design: Figure of Merit, Maximum Unilateral Gain, Gain Circles	16-01
	This program computes u , G_u , $G_{\min}$, $G_{\max}$, G_0 , $G_{1\max}$, and $G_{2\max}$ from a transistor's s-parameters. It also computes r_{oi} and ρ_{oi} from $G_i \leq G_{i\max}$ ($i = 1, 2$).	
17.	Bilateral Design: Stability Factor, Maximum Gain, Optimum Matching	17-01
	This program computes the maximum gain available and the load and source reflection coefficients which yield the maximum gain.	
18.	Bilateral Design: Gain and Stability Circles, Load and Source Mapping	18-01
	This program computes the location and radius of stability circles. It also computes the source or load reflection coefficient corresponding to a given load or source termination.	
	Program Listing Contents	L00-01
	Appendix A	A-1

A WORD ABOUT PROGRAM USAGE

This application pac has been designed for both the HP-97 Programmable Printing Calculator and the HP-67 Programmable Pocket Calculator. The most significant difference between the HP-67 and the HP-97 calculators is the printing capability of the HP-97. The two calculators also differ in a few minor ways. The purpose of this section is to discuss the ways that the programs in this pac are affected by the differences in the two machines, and to suggest how you can make optimal use of your machine, be it an HP-67 or an HP-97.

Most of the computed results in this pac are output by PRINT statements: most often by the statement PRINTx, and occasionally by the command PRINT STACK. On the HP-97, these results will be output on the printer. On the HP-67, each PRINT command will be interpreted as a PAUSE: the program will halt, display the result for about five seconds, then continue execution. The term "PRINT/PAUSE" is used to describe this output condition.

If you own an HP-67, you may want more time to copy down the number displayed by a PRINT/PAUSE. All you need to do is press down any key on the keyboard. If the command being executed is PRINTx (eight rapid blinks of the decimal point), pressing down a key will cause the program to halt. If the command being executed is PRINT STACK (two slow blinks of the decimal point for each value), the number in the display will remain there until the depressed key is released; then the next register in the stack will be displayed, and so on. After display of all four registers, the program will halt execution if a key was pressed at any time during the display of the stack contents. In both cases, execution of the halted program may be re-initiated by pressing **R/S**.

For output purposes, a "display" subroutine has been incorporated into most of the programs in this pac. This routine makes important use of internal flag 0 as follows:

Flag 0 "Set" — PRINT/PAUSE is enabled for output of result.

Flag 0 "Clear" — PRINT/PAUSE is skipped and program execution halts with result in display.

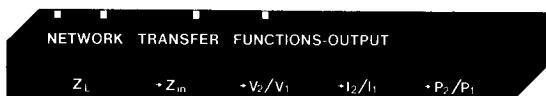
Every program with this feature has flag 0 "set", initially. Thus, the user who is content to have his data output by PRINT/PAUSE simply loads the program and begins execution. The user who desires that the machine stop to display each result must press **CLF** **0** (CLEAR FLAG 0) after loading the program.

The HP-97 users may also want to keep a permanent record of the values input to a certain program. A convenient way to do this is to set the Print Mode switch to NORMAL before running the program. In this mode, all input values and their corresponding user-definable keys will be listed on the printer, thus providing a record of the entire operation of the program.

Another area that could reflect differences between the HP-67 and the HP-97 is in the keystroke solutions to example problems. It is sometimes necessary in these solutions to include operations that involve prefix keys, namely, **f** on the HP-97 and **f**, **g**, and **h** on the HP-67. For example, the operation 10^x is performed on the HP-97 as **f** 10^x and on the HP-67 as **g** 10^x . In such cases, the keystroke solution omits the prefix key and indicates only the operation (as here, 10^x). As you work through the example problems, take care to press the appropriate prefix keys (if any) for your calculator.

Also in keystroke solutions, those values which are output by the command PRINTx will be followed by three asterisks (***)

NETWORK TRANSFER FUNCTIONS



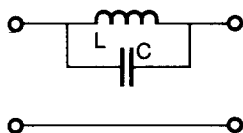
This program computes various transfer functions of a ladder network composed of any number of standard elements. The ladder is built up one element at a time by selecting shunt or series elements from the following menu.

MENU OF CIRCUIT ELEMENTS

Name	Circuit	Chain-Parameter Matrix*
Series resistor		$\Psi = \begin{bmatrix} 1 \angle 0 & R \angle 0 \\ 0 & 1 \angle 0 \end{bmatrix}$
Shunt resistor		$\Psi = \begin{bmatrix} 1 \angle 0 & 0 \\ \frac{1}{R} \angle 0 & 1 \angle 0 \end{bmatrix}$
Series inductor		$\Psi = \begin{bmatrix} 1 \angle 0 & \omega L \angle 90 \\ 0 & 1 \angle 0 \end{bmatrix}$
Shunt inductor		$\Psi = \begin{bmatrix} 1 \angle 0 & 0 \\ \frac{1}{\omega L} \angle -90 & 1 \angle 0 \end{bmatrix}$
Series capacitor		$\Psi = \begin{bmatrix} 1 \angle 0 & \frac{1}{\omega C} \angle -90 \\ 0 & 1 \angle 0 \end{bmatrix}$
Shunt capacitor		$\Psi = \begin{bmatrix} 1 \angle 0 & 0 \\ \omega C \angle 90 & 1 \angle 0 \end{bmatrix}$

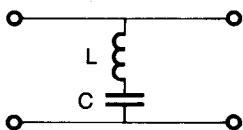
* Ψ is the Cyrillic letter "cha".

Series tank



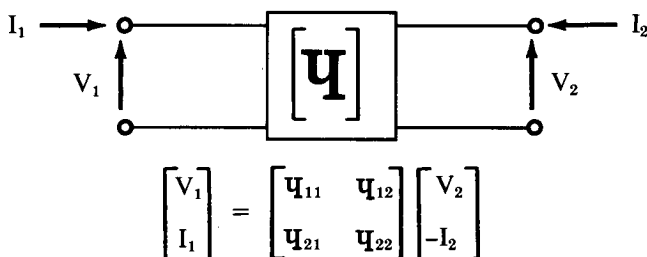
$$\mathbf{q} = \begin{bmatrix} 1 \angle 0 & \frac{\omega L}{1 - \omega^2 LC} \angle 90 \\ 0 & 1 \angle 0 \end{bmatrix}$$

Shunt L-C



$$\mathbf{q} = \begin{bmatrix} 1 \angle 0 & 0 \\ \frac{\omega C}{1 - \omega^2 LC} \angle 90 & 1 \angle 0 \end{bmatrix}$$

The chain-parameter matrix is defined by the following sketch and matrix equation.



The operation of the program is based on the fact that the chain-parameter matrix of two cascaded circuits is equal to the product of their individual chain-parameter matrices.

As the circuit is built up from right to left, the overall chain-parameter matrix is updated with the addition of each element. When the circuit description is complete, the second card is read in and any of the following transfer functions may be computed from the overall chain-parameter matrix.

Input impedance

$$Z_{in} = \frac{q_{11} Z_L + q_{12}}{q_{21} Z_L + q_{22}}$$

Power Gain

$$\frac{P_{out}}{P_{in}} = \left| \frac{I_2}{I_1} \right|^2 \frac{\text{Re} \{Z_L\}}{\text{Re} \{Z_{in}\}}$$

Voltage transfer ratio

$$\frac{V_2}{V_1} = \frac{Z_L}{q_{11} Z_L + q_{12}}$$

Forward transfer admittance

$$\frac{I_2}{V_1} = \frac{-1}{q_{11} Z_L + q_{12}}$$

Current transfer ratio

$$\frac{I_2}{I_1} = \frac{-1}{q_{21} Z_L + q_{22}}$$

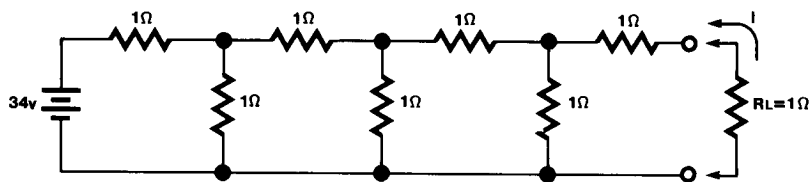
Forward transfer impedance

$$\frac{V_2}{I_1} = \frac{Z_L}{q_{21} Z_L + q_{22}}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program 1.			
2	Input frequency and initialize.	f, Hz	A	0
3	Build circuit by selecting any sequence of the following elements.			
	Series resistor	R	B	
	Series inductor	L	C	
	Series capacitor	C	D	
	Series tank	L	ENTER+	
		C	E	
	Shunt resistor	R	f B	
	Shunt inductor	L	f C	
	Shunt capacitor	C	f D	
	Shunt L-C	L	ENTER+	
		C	f E	
4	Load program 2.			
5	Input load impedance.	$\angle Z_L$	ENTER+	
		$ Z_L $	A	
6	Select desired network function:			
	Input impedance		B	$\angle Z_{in}$
				$ Z_{in} $
	voltage gain		C	$\angle V_2/V_1$
				$ V_2/V_1 $
	current gain		D	$\angle I_2/I_1$
				$ I_2/I_1 $
	Transfer admittance		f C	$\angle I_2/V_1$
				$ I_2/V_1 $
	Transfer impedance		f D	$\angle V_2/I_1$
				$ V_2/I_1 $
	Power gain		E	P_2/P_1

Example 1:

What current will flow in a 1Ω resistor placed on the output of this network?
What is the input impedance?

**Keystrokes:****Outputs:**

Load card EE1-01A1

A $\longrightarrow$ 0.000 00

Note:

No frequency need be input for a purely resistive network, but initialization is still necessary.

1 **B** 1 **f** **B** 1 **B** 1 **f** **B** 1

B 1 **f** **B** 1 **B** $\longrightarrow$ 0.000 00

Load card EE1-01A2

0 **ENTER** 1 **A** **f** **C** $\longrightarrow$ 0.000+00 *** Angle of transfer admittance

-29.41 -03 *** Magnitude of transfer admittance

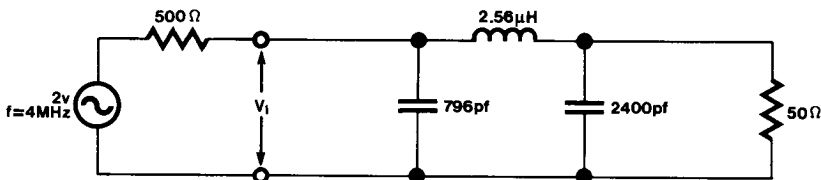
34 **x** $\longrightarrow$ -1.000+00 Current in load resistor

B $\longrightarrow$ 0.000+00 *** Angle of input impedance

1.619+00 *** Magnitude of input impedance

Example 2:

This program can be used to compute voltages within a network by dividing the problem into two parts. Find the voltage V_1 in the circuit shown.



Solution:

First compute the input impedance of the circuit to the right of V_1 .

Keystrokes:

Load EE1-01A1

4 **EEX** 6 **A** 2400 **EEX** **CHS**

12 **f** **D** 2.56 **EEX** **CHS** 6 **C**

796 **EEX** **CHS** 12 **f** **D** $\longrightarrow$

Load EE1-01A2

0 **ENTER** 50 **A** **B** $\longrightarrow$

Outputs:

0.000 00

984.0-03 *** Angle of input
impedance

497.7 00 *** Magnitude of input
impedance

Then compute the voltage transfer ratio for the network to the left of V_1 terminated in $497.7 \angle 0.984$.

Keystrokes:

Load EE1-01A1

4 **EEX** 6 **A** 500 **B** $\longrightarrow$

Load EE1-01A2

.984 **ENTER** 497.7 **A** **C** $\longrightarrow$

2 **x** $\longrightarrow$

Outputs:

0.000 00

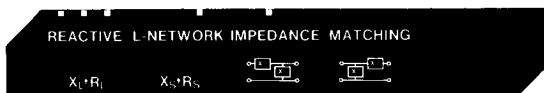
493.1-03 *** Angle of voltage
ratio

498.9-03 ***

997.7-03 Magnitude of V_1

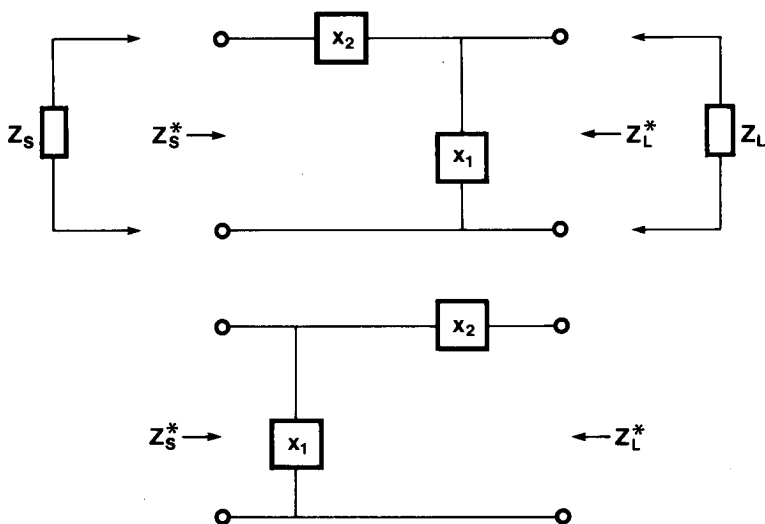
Notes

2. REACTIVE L-NETWORK IMPEDANCE MATCHING



An L-network consisting of purely reactive elements may be used to transform any complex impedance into any other complex impedance. In general, there are four possible networks, but in some situations there are only two. This program accepts complex load and source impedances in rectangular form and outputs all possible solutions, displaying an error message if a given topology is not suitable.

Either of these two networks is possible:



For each network there are two sets of reactances (X_1, X_2) that will transform Z_L into Z_S^* . These are given by:

$$X_1 = \frac{R_S X_L}{R_S - R_L} \pm \sqrt{\left(\frac{R_S X_L}{R_S - R_L} \right)^2 - \frac{R_S (X_L^2 + R_L^2)}{R_S - R_L}}$$

$$X_2 = \frac{R_S (X_1 + X_L) - R_L (X_1 + X_S)}{R_L}$$

By reversing the subscripts S and L in these two equations, we get the two sets of reactances for the second network.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input			
	Load impedance			
	Reactive part	X_L, Ω	ENTER	X_L, Ω
	Resistive part	R_L, Ω	A	X_L, Ω
	Source impedance			
	Reactive part	X_S, Ω	ENTER	X_S, Ω
	Resistive part	R_S, Ω	B	X_S, Ω
3	Compute values for first network.			
	Shunt reactance		C	X_1, Ω
	Series reactance			X_2, Ω
	Shunt reactance		F C	X_1, Ω
	Series reactance			X_2, Ω
4	Compute values for second network.			
	Shunt reactance		D	X_1, Ω
	Series reactance			X_2, Ω
	Shunt reactance		F D	X_1, Ω
	Series reactance			X_2, Ω
	Note: If one of the above networks is inappropriate, an error message will occur.			
	Simply press any key and continue with the next type of network.			

Example:

What reactive L-networks could be used to match $Z_L = 50 + j50$ to $Z_S = 25 + j50$?

Keystrokes:

50 **ENTER** 50 **A** 50 **ENTER**
 25 **B** **f** **C** →

C →

f **D** →

D →

Outputs:

-36.60 *** X_1
 -6.70 *** X_2

136.60 *** X_1
 -93.30 *** X_2

-161.24 *** X_1
 -111.24 *** X_2

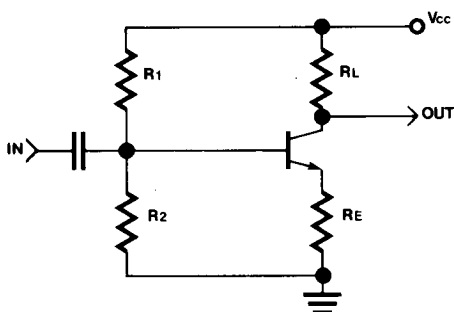
-38.76 *** X_1
 11.24 *** X_2

Notes

3. CLASS A TRANSISTOR AMPLIFIER BIAS OPTIMIZATION



This program is an automation of the method of bias optimization described in "Designing class A amplifiers to meet specified tolerances" by Ward J. Helms (Electronics/August 8, 1974). The program requires the user to specify a number of items from which it determines by an iterative technique the optimum values for R_1 , R_2 , R_E , and R_L . The minimum power gain is also computed.



Equations:

First, values are specified for the following parameters:

ΔI_{CQ} = maximum desired percentage variation of quiescent current

T_{Amax} = maximum ambient temperature (use the maximum case temperature for a transistor mounted on a heat sink)

T_{Amin} = minimum ambient temperature

T_{Jmax} = maximum junction temperature rating

P_D = maximum rated power dissipation at 25°C

I_1 = collector current, usually selected for convenience so that I_1 and $10 I_1$ bracket the expected operating point

ΔV_{BE} = typical base-emitter voltage change over the range of I_1 to $10 I_1$ at 25°C

V_{BE1min} = minimum base-emitter voltage at I_1 , 25°C

V_{BE1max} = maximum base-emitter voltage at I_1 , 25°C

Then the transistor's thermal resistance is calculated:

$$\theta_{JA} = (T_{max} - 25^\circ\text{C})/P_D$$

And the minimum load resistance and emitter resistance are estimated :

$$R_{L1} = \frac{\theta_{JA} V_{CC}^2}{4.4 (T_{Jmax} - T_{Amax})} = R_{Ln}$$

$$R_{E1} = 0.1 R_{L1} = R_{En}$$

Next, the quiescent, maximum, and minimum collector currents are calculated:

$$I_{CQ} = \frac{V_{CC}}{2 (R_{Ln} + R_{En})}$$

$$I_{Cmax} = I_{CQ} (1 + \Delta I_{CQ})$$

$$I_{Cmin} = I_{CQ} (1 - \Delta I_{CQ})$$

From these, we can calculate the base-emitter voltage under hot, high-current conditions (V_{BEX}) and under cold, low-current conditions (V_{BEN}).

$$T_{max} = \theta_{JA} I_{CQ} \frac{V_{CC}}{2} + T_{Amax}$$

$$V_{BEX} = V_{BE1min} + \Delta V_{BE} \log \frac{I_{Cmax}}{I_1} - 0.0022 (T_{max} - 25^\circ C)$$

$$T_{min} = \theta_{JA} I_{CQ} \frac{V_{CC}}{2} (1 - (\Delta I_{CQ})^2) + T_{Amin}$$

$$V_{BEN} = V_{BE1max} + \Delta V_{BE} \log \frac{I_{Cmin}}{I_1} - 0.0022 (T_{min} - 25^\circ C)$$

Now, a better estimate for the emitter resistance can be made:

$$R_{E(n+1)} = \frac{-2 (V_{BEX} - V_{BEN})}{I_{Cmax} - I_{Cmin}}$$

From this point, if $V_{BEX} > V_{BEN}$, then R_E is set to zero, R_L is increased by 10%, and the design procedure is repeated. Iterations continue until $\frac{R_{E(n+1)} - R_{En}}{R_{En}} < .5\%$. If at any time the condition $T_{max} > T_{Jmax}$ occurs, R_L is increased by 10%.

When the iterative procedure is complete, $T_{\max}$, $I_{C\max}$, $T_{\min}$, and $I_{C\min}$ are displayed.

Then values for

$h_{FE\max}$ = maximum worst-case current gain at $T_{\max}$ or $T_{\min}$ and $I_{C\max}$ or $I_{C\min}$

and

$h_{FE\min}$ = minimum worst-case current gain at $T_{\max}$ or $T_{\min}$ and $I_{C\max}$ or $I_{C\min}$

are determined from the transistor's data sheet and the Thevenin-equivalent resistance (R_B) and voltage (V_{BB}) of the amplifier's bias network are calculated:

$$R_B = \frac{h_{FE\max} h_{FE\min} [R_{E(n+1)} (I_{C\max} - I_{C\min}) + V_{BEX} - V_{BEN}]}{h_{FE\max} I_{C\min} - h_{FE\min} I_{C\max}}$$

$$V_{BB} = V_{BEN} + I_{C\min} \left(\frac{R_B}{h_{FE\min}} + R_{E(n+1)} \right)$$

Now the bias resistors R_1 and R_2 are calculated:

$$R_1 = \frac{R_B V_{CC}}{V_{BB}}$$

$$R_2 = \frac{R_B V_{CC}}{(V_{CC} - V_{BB})}$$

Finally, the minimum power gain and minimum signal power are calculated:

$$A_P = \frac{R_B R_L h_{FE\min}}{R_E (R_B + h_{FE\min} R_E)}$$

$$P_S = (1 - \Delta I_{CQ})^2 \left(\frac{V_{CC}^2 R_L}{8 (R_L + R_E)^2} \right)$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Store design objectives.			
	Power supply voltage	V_{CC}	STO 0	
	Maximum desired percent variation of quiescent current	ΔI_{CQ}	STO 1	
	Maximum ambient temperature	$T_{Amax}, ^\circ C$	STO 2	
	Minimum ambient temperature	$T_{Amin}, ^\circ C$	STO 3	
3	Store values from transistor's data sheet			
		T_{Jmax}	STO 4	
		P_D	STO 5	
		I_1	STO 6	
		ΔV_{BE}	STO 7	
		V_{BE1min}	STO 8	
		V_{BE1max}	STO 9	
4	Compute maximum and minimum temperatures and currents ; then stop with 500.0 -03 in display.		A	T_{max}
				I_{Cmax}
				T_{min}
				I_{Cmin}
5	Input maximum h_{FE} and minimum h_{FE} and compute	h_{FEmax}	ENTER ↑	
	resistor R_1	h_{FEmin}	R/S	R_1
	resistor R_2			R_2
	load resistance			R_L
	emitter resistance			R_E
	minimum power gain			A_p

Example:

A single-stage class A amplifier is needed to operate from a 30-V power supply. The maximum power output and maximum power gain must be obtained from a Texas Instruments type TIS98 transistor over an ambient temperature range of 0°C to 70°C, with a maximum quiescent-current variation of $\pm 20\%$.

From the transistor's data sheet, determine:

$$\begin{aligned} T_{J\max} &= 150^{\circ}\text{C} \\ P_D &= 0.36 \text{ W} \\ \Delta V_{BE} &= 0.10 \text{ v from 3 to 30 mA} \\ V_{BE1\min} &= 0.52 \text{ v at 3 mA at } 25^{\circ}\text{C} \\ V_{BE1\max} &= 0.72 \text{ v at 3 mA at } 25^{\circ}\text{C} \\ I_1 &= 0.001 \text{ A} \end{aligned}$$

Keystrokes:**Outputs:**

First store the data

30. **STO** **0**
 .2 **STO** **1**
 70. **STO** **2**
 0. **STO** **3**
 150. **STO** **4**
 .36 **STO** **5**
 .001 **STO** **6**
 .1 **STO** **7**
 .52 **STO** **8**
 .72 **STO** **9**

Then compute maximum and minimum temperatures and currents

A $\longrightarrow$ $148.+00 \text{ *** } T_{\max}$
 $18.0-03 \text{ *** } I_{C\max}$
 $74.8+00 \text{ *** } T_{\min}$
 $12.0-03 \text{ *** } I_{C\min}$

From the transistor's data sheet determine:

$$\begin{aligned} h_{FE\max} &= 600 \text{ at } 150^{\circ}\text{C at } 18 \text{ mA} \\ h_{FE\min} &= 100 \text{ at } 80^{\circ}\text{C at } 12 \text{ mA} \end{aligned}$$

Finish problem

Keystrokes:

600 **ENTER** 100 **R/S** 

Outputs:

45.0+03 T R₁
4.18+03 Z R₂
888.+00 Y R_L
115.+00 X R_E
22.9+00 *** A_P

4. TRANSISTOR AMPLIFIER PERFORMANCE

TRANSISTOR AMPLIFIER PERFORMANCE

$$\theta_{ij} + h_{ij} + i_{ij}$$

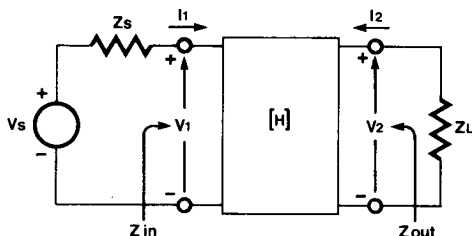
$$\theta_L + R_L$$

$$+A_v$$

$$+A_{vs}$$

$$+Z_{out}$$

This program computes certain small-signal properties of a transistor amplifier given the h-parameter matrix and the source and load impedances. Properties computed are current and voltage gains and input and output impedances.



Equations:

Definition of h-parameter matrix

$$\begin{bmatrix} v_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} h_i & h_r \\ h_f & h_o \end{bmatrix} \begin{bmatrix} i_1 \\ v_2 \end{bmatrix}$$

Current gain

$$A_i = \frac{i_2}{i_1} = \frac{-h_f}{1 + h_o Z_L}$$

Voltage gain

$$A_v = \frac{v_2}{v_1} = \frac{A_i Z_L}{Z_{in}}$$

Voltage gain with source resistor

$$A_{vs} = \frac{v_2}{v_s} = \frac{A_i Z_L}{Z_{in} + Z_s}$$

Input impedance

$$Z_{in} = h_i + h_r Z_L A_i$$

Output impedance

$$Z_{out} = \frac{h_i + Z_S}{h_o h_i + h_o Z_S - h_f h_r}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input h-parameters.			
	Angle	θ_{ij} , deg	ENTER	
	Magnitude	h_{ij}	ENTER	
	Designation	ij	A	
3	Input termination impedances.			
	Angle of source impedance	θ_s , deg	ENTER	
	Magnitude of source impedance	R_s	f B	
	Angle of load impedance	θ_L , deg	ENTER	
	Magnitude of load impedance	R_L	B	
4	Compute			
	Voltage gain		C	A_v
	Current gain		f C	A_i
	Voltage gain with source resistor		D	A_{vs}
	Input impedance		f E	Z_{in}
	Output impedance		E	Z_{out}

Example:

What are the small-signal properties of a transistor which has the following h-parameter matrix and has source and load impedances of 1000 and 10,000 ohms, respectively?

$$[h] = \begin{bmatrix} 1100 & 250E-6 \\ 50 & 25E-6 \end{bmatrix}$$

Keystrokes:

0 **ENTER** 1100 **ENTER** 11 **A**
 0 **ENTER** 250 **EEX** 6 **CHS** **ENTER**
 12 **A**
 0 **ENTER** 50 **ENTER** 21 **A**
 0 **ENTER** 25 **EEX** **CHS** 6 **ENTER**
 22 **A**
 0 **ENTER** 1000 **f** **B**
 0 **ENTER** 10000 **B** **C** —————→

f **C** —————→

D —————→

f **E** —————→

E —————→

Outputs:

0.000+00 *** $\angle A_v$
 -400.0+00 *** $|A_v|$

0.000+00 *** $\angle A_i$
 -40.00+00 *** $|A_i|$

0.000+00 *** $\angle A_{vs}$
 -200.0+00 *** $|A_{vs}|$

0.000+00 *** $\angle Z_{in}$
 1.000+03 *** $|Z_{in}|$

0.000+00 *** $\angle Z_{out}$
 52.50+03 *** $|Z_{out}|$

Notes

5. TRANSISTOR CONFIGURATION CONVERSION



This program converts among h-parameter matrices for common-base, common-emitter, and common-collector transistor configurations.

The program first converts the h-parameter matrix to a y-parameter matrix using the following transformation:

$$[y] = \frac{1}{h_{11}} \begin{bmatrix} 1 & -h_{12} \\ h_{21} & h_{11} h_{22} - h_{12} h_{21} \end{bmatrix}$$

The y-matrix is then transformed into a y'-matrix depending on the conversion desired:

CB → CE or CE → CB

$$\begin{aligned} y'_{11} &= y_{11} + y_{12} + y_{21} + y_{22} \\ y'_{12} &= -(y_{12} + y_{22}) \\ y'_{21} &= -(y_{21} + y_{22}) \\ y'_{22} &= y_{11} \end{aligned}$$

CC → CB

$$\begin{aligned} y'_{11} &= y_{22} \\ y'_{12} &= -(y_{21} + y_{22}) \\ y'_{21} &= -(y_{12} + y_{22}) \\ y'_{22} &= y_{11} + y_{12} + y_{21} + y_{22} \end{aligned}$$

CC → CE or CE → CC

$$\begin{aligned} y'_{11} &= y_{11} \\ y'_{12} &= -(y_{11} + y_{12}) \\ y'_{21} &= -(y_{11} + y_{21}) \\ y'_{22} &= y_{11} + y_{12} + y_{21} + y_{22} \end{aligned}$$

CB → CC

$$\begin{aligned} y'_{11} &= y_{11} + y_{12} + y_{21} + y_{22} \\ y'_{12} &= -(y_{11} + y_{21}) \\ y'_{21} &= -(y_{11} + y_{12}) \\ y'_{22} &= y_{11} \end{aligned}$$

Finally the desired h-parameter matrix is derived from the y'-matrix by the $[h] - [y]$ transformation used above.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input h-parameter matrix (ij = 11, 12, 21, 22).			
	Angle of h-parameter	θ_{ij} , deg	[ENTER]	
	then Magnitude of			
	h-parameter	h_{ij}	[ENTER]	
	then Designation of			
	h-parameter	ij	[A]	
3	Perform desired conversion.			
	CE→CB		[B]	
	CB→CE		[f] [B]	
	CC→CB		[C]	
	CB→CC		[f] [C]	
	CC→CE		[D]	
	CE→CC		[f] [D]	
4	Display converted			
	h-parameter matrix.*		[E]	θ_{11}
				h_{11}
				θ_{12}
				h_{12}
				θ_{21}
				h_{21}
				θ_{22}
				h_{22}
	*This feature may be used at			
	any time to display whatever			
	matrix is in storage.			

Example:

Convert the following common-collector h-parameter matrix to common base.

$$[h_{cc}] = \begin{bmatrix} h_{ic} & h_{rc} \\ h_{fc} & h_{oc} \end{bmatrix} = \begin{bmatrix} 1000 \angle 30 & 100 \times 10^{-6} \angle -45 \\ 60 \angle 30 & 30 \times 10^{-6} \angle 0 \end{bmatrix}$$

Keystrokes:

```
30 ENTER 1000 ENTER 11 A
45 CHS ENTER 100 EEX CHS
6 ENTER 12 A 30 ENTER 60
ENTER 21 A 0 ENTER 30 EEX
CHS 6 ENTER 22 A C E →
```

Outputs:

```
-9.354+00 ***  $\theta_{11}$ 
38.31+03 ***  $h_{11} = h_{ib}$ 
-9.349+00 ***  $\theta_{12}$ 
2.299+03 ***  $h_{12} = h_{rb}$ 
-179.8+00 ***  $\theta_{21}$ 
999.6-03 ***  $h_{21} = h_{fb}$ 
-39.35+00 ***  $\theta_{22}$ 
1.149-03 ***  $h_{22} = h_{ob}$ 
```

Notes

6. PARAMETER CONVERSION

PARAMETER CONVERSION S $\leftrightarrow$ Y,Z,G,H

$\Gamma = \theta_{ij}, M_{ij}$

S $\leftrightarrow$ Y: Z_0

S $\leftrightarrow$ Z: Z_0

S $\leftrightarrow$ G: Z_0

S $\leftrightarrow$ H: Z_0

Two-port S-parameters may be converted to and from any of Y, Z, G or H parameters using a single matrix equation. Appropriate pre- and postconditioning operations must be performed depending on which conversion is desired.

First, the preconditioning operation generates a T matrix. Then occurs the basic transformation

$$T' = (I + T)^{-1} (I - T)$$

$$= \frac{2}{(1 + t_{11})(1 + t_{22}) - t_{12}t_{21}} \begin{bmatrix} 1 + t_{22} & -t_{12} \\ -t_{21} & 1 + t_{11} \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Finally, the postconditioning operation is performed.

The preconditioning operations performed when converting from S are

S $\rightarrow$ Y	S $\rightarrow$ Z	S $\rightarrow$ G	S $\rightarrow$ H
T = S	T = -S	T = $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} S$	T = $\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} S$

and those performed when converting to S are

Y $\rightarrow$ S	Z $\rightarrow$ S	G $\rightarrow$ S	H $\rightarrow$ S
T = $Z_0 Y$	T = Z/Z_0	T = $\begin{bmatrix} Z_0 g_{11} & g_{12} \\ g_{21} & g_{22}/Z_0 \end{bmatrix}$	T = $\begin{bmatrix} h_{11}/Z_0 & h_{12} \\ h_{21} & h_{22} Z_0 \end{bmatrix}$

The postconditioning operations performed when converting from S are

S $\rightarrow$ Y	S $\rightarrow$ Z	S $\rightarrow$ G	S $\rightarrow$ H
Y = T'/Z_0	Z = $Z_0 T'$	G = $\begin{bmatrix} t_{11}'/Z_0 & t_{12}' \\ t_{21}' & t_{22}'/Z_0 \end{bmatrix}$	H = $\begin{bmatrix} t_{11}' Z_0 & t_{12}' \\ t_{21}' & t_{22}'/Z_0 \end{bmatrix}$

and those performed when converting to S are

$Y \rightarrow S$	$Z \rightarrow S$	$G \rightarrow S$	$H \rightarrow S$
$S = T'$	$S = -T'$	$S = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} T'$	$S = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} T'$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input S, Y, Z, G, or H.			
	Angle of element ij	θ_{ij}	ENTER	
	Magnitude of element ij	M_{ij}	ENTER	
	Subscript to element	ij	f A	
3	Select desired conversion.			
	S→Y	Z_0	B	
	Y→S	Z_0	f B	
	S→Z	Z_0	C	
	Z→S	Z_0	f C	
	S→G	Z_0	D	
	G→S	Z_0	f D	
	S→H	Z_0	E	
	H→S	Z_0	f E	
4	Display elements of new matrix.			
	Input element subscript	ij	A	
	Display angle of element ij			θ_{ij}
	Display magnitude of			
	element ij			M_{ij}

Example:

The s-parameter matrix of a 2N3571 transistor is

$$S = \begin{bmatrix} 0.62 \angle -44.0 & 0.0115 \angle 75.0 \\ 9.0 \angle 130 & 0.955 \angle -6.0 \end{bmatrix}$$

What is the h-parameter matrix? Z_0 is 50 Ω .

Keystrokes:

```
44 CHS ENTER .62 ENTER 11
f A 75 ENTER .0115 ENTER
12 f A 130 ENTER 9 ENTER
21 f A 6 CHS ENTER .955 ENTER
22 f A 50 E 11 A →
```

Outputs:

```
-53.88 ***  $\theta_{11}$ 
119.1 ***  $h_{11}$ 
```

```
12 A →
```

```
39.26 ***  $\theta_{12}$ 
18.14-03 ***  $h_{12}$ 
```

```
21 A →
```

```
94.26 ***  $\theta_{21}$ 
-14.19 ***  $h_{21}$ 
```

```
22 A →
```

```
21.17 ***  $\theta_{22}$ 
2.272-03 ***  $h_{22}$ 
```

Notes

7. FOURIER SERIES



Any periodic function may be written as a series of sine and cosine waves by the application of the following formulas.

$$f(t) = \frac{a_0}{2} + \sum_{i=1}^{\infty} \left(a_i \cos \frac{i2\pi t}{T} + b_i \sin \frac{i2\pi t}{T} \right)$$

$$= \frac{a_0}{2} + \sum_{i=1}^{\infty} c_i \sin \left(\frac{i2\pi t}{T} + \theta_i \right)$$

$$a_i = \frac{2}{T} \int_0^T f(t) \cos \frac{i2\pi t}{T} dt, \quad i = 0, 1, 2, \dots$$

$$b_i = \frac{2}{T} \int_0^T f(t) \sin \frac{i2\pi t}{T} dt, \quad i = 1, 2, \dots$$

$$c_i = (a_i^2 + b_i^2)^{1/2}$$

$$\theta_i = \tan^{-1} \left(\frac{a_i}{b_i} \right)$$

T = period of $f(t)$

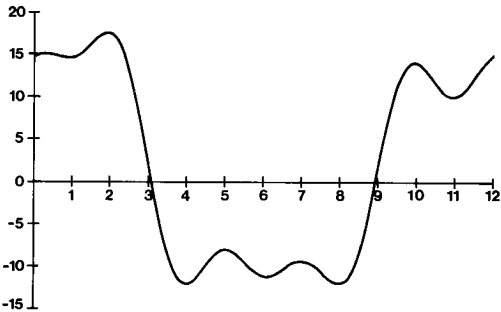
This program computes the Fourier coefficients from discrete versions of the above formulas given a large enough number of samples of the periodic function. Up to ten consecutive pairs of coefficients may be computed at one time from N equally spaced points. The coefficients may be displayed in either rectangular or polar form.

The value of N should be chosen to be more than twice the highest expected multiple of the fundamental frequency present in the wave to be analyzed. A low estimate for N will cause energy above one-half the sampling rate to appear at a lower frequency (a phenomenon known as aliasing).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Initialize		f A	
3	Input			
	Number of samples			
	in one period	N	ENTER	
	Number of frequencies			
	desired	#freqs	A	N
	Order of first coefficient	J	B	J
4	Input $y_k, k = 1, N$	y_k	C	2,..., .111
5	Repeat step 4 until display			
	shows 0.111			
6	Display coefficients for			
	$J \leq i \leq J + \text{\#freqs}$			
	in polar form		f D	i
				θ_i
				c_i
	in rectangular form.		D	i
				b_i
				a_i
7	Compute value of Fourier			
	series at t.	t	E	f(t)

Example:

Compute a discrete Fourier series representation for the waveform shown. Since there are 12 samples, select 7 frequencies (dc term plus 6 harmonics).



t	f(t)
1	14.758
2	17.732
3	2
4	-12.
5	-7.758
6	-11
7	-9.026
8	-12.
9	2
10	14.268
11	10.026
12	15

Keystrokes:

f A 12 ENTER 7 A 0 B →
14.758 C →
17.732 C →
2 C →
12 CHS C →
7.758 CHS C →
11 CHS C →
9.026 CHS C →
12 CHS C →
2 C →
14.268 C →
10.026 C →

Outputs:

1.000
2.000
3.000
4.000
5.000
6.000
7.000
8.000
9.000
10.000
11.000
12.000

15 **C** $\longrightarrow$
D $\longrightarrow$

0.111

0. *** i

0.000 *** b_i4.000 *** a_i

1. ***

1.000 ***

15.000 ***

2. ***

1.000 ***

3.000000001-08 ***

3. ***

1.000 ***

-5.000 ***

4. ***

3.200000001-09 ***

3.333333334-09 ***

5. ***

1.467291667-05 ***

3.000 ***

6. ***

2.359925334-08 ***

0.000 ***

$$\text{Thus } f(t) = 2 + 15 \cos \frac{2\pi t}{12} + \sin \frac{2\pi t}{12}$$

$$+ \sin \frac{4\pi t}{12}$$

$$- 5 \cos \frac{6\pi t}{12} + \sin \frac{6\pi t}{12}$$

$$+ 3 \cos \frac{10\pi t}{12}$$

8. ACTIVE FILTER DESIGN



This program computes element values for the standard active filter circuits shown. The user selects corner frequency f_0 or center frequency f_0 , midband gain A , peaking factor α , and a capacitor C . The program then prints out a list of elements which form the desired filter.

Equations:

$$\alpha = \frac{1}{Q} = 2\zeta, \text{ where } Q \text{ is quality factor and } \zeta \text{ is damping factor.}$$

Low pass filter

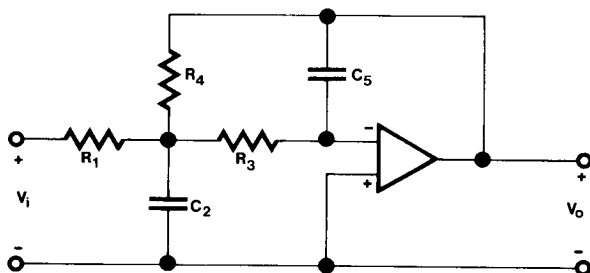
$$C_5 = C$$

$$C_2 = \frac{4C(A + 1)}{\alpha^2}$$

$$R_1 = \frac{\alpha}{4A\pi f_0 C}$$

$$R_3 = \frac{\alpha}{4\pi f_0 C(A + 1)} = \frac{A}{A + 1} R_1$$

$$R_4 = AR_1$$



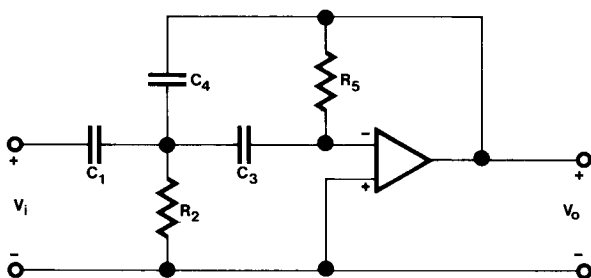
High pass filter

$$C_1 = C_3 = C$$

$$C_4 = \frac{C}{A}$$

$$R_2 = \frac{\alpha}{2\pi f_0 C \left(2 + \frac{1}{A} \right)}$$

$$R_5 = \frac{2A + 1}{\alpha 2\pi f_0 C}$$



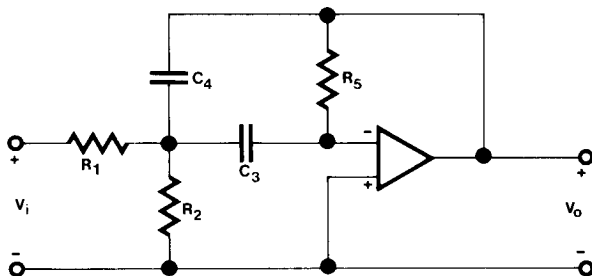
Bandpass filter

$$C_3 = C_4 = C$$

$$R_1 = \frac{1}{A 2\pi f_0 C \alpha}$$

$$R_2 = \frac{1}{\left(\frac{2}{\alpha^2} - A \right) 2\pi f_0 C \alpha}$$

$$R_5 = \frac{2}{\alpha 2\pi f_0 C}$$



STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input filter design specifications.			
	Corner or center frequency	f_0 , Hz	f A	f_0
	Midband gain	A	A	A
	Peaking factor (1/Q)	α	f B	α
	Capacitor value	C, F	B	C
3	Select desired filter characteristic and list elements.			
	Low pass		C	$R_{1,}$
				$C_{2,}$
				$R_{3,}$
				$R_{4,}$
				C_5
	High pass		D	$C_{1,}$
				$R_{2,}$
				$C_{3,}$
				$C_{4,}$
				R_5
	Band pass		E	$R_{1,}$
				$R_{2,}$
				$C_{3,}$
				$C_{4,}$
				R_5

Example 1:

Design a high-pass active filter with the following parameters:

$$f_0 = 10 \text{ Hz}$$

$$A = 10$$

$$\alpha = 1$$

$$C = 1 \mu\text{F}$$

Keystrokes:

10 **f** **A** 10 **A** 1 **f** **B** 1

EEX **CHS** 6 **B** **D** 

Outputs:

1.000-06 *** C_1

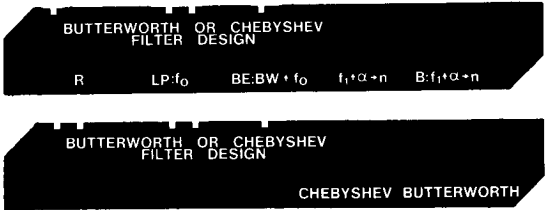
7.579+03 *** R_2

1.000-06 *** C_3

100.0-09 *** C_4

334.2+03 *** R_5

9. BUTTERWORTH OR CHEBYSHEV FILTER DESIGN



This program computes component values for Butterworth or Chebyshev filters between equal terminations. Inputs are termination resistance, bandpass characteristics, attenuation at some out-of-band frequency, and, for the Chebyshev filter, allowable passband ripple.

Before the filter elements can be calculated, a normalized frequency must be computed from the desired cutoff or center frequency and band pass characteristics. The normalized frequency is computed by one of these formulas:

Low Pass

$$\omega_n = \frac{\omega}{\omega_0}$$

High Pass

$$\omega_n = \frac{\omega_0}{\omega}$$

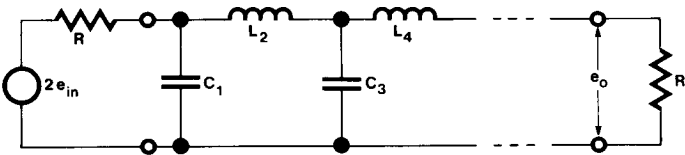
Band Pass

$$\omega_n = \frac{\omega^2 - \omega_0^2}{BW\omega}$$

Band Elimination

$$\omega_n = \frac{\omega BW}{\omega_0^2 - \omega^2}$$

The basic form of the filter is this low-pass prototype



whose elements are given by one of the following sets of formulas:

BUTTERWORTH

$$C_i = \frac{1}{\pi f_c R} \sin \frac{(2i-1)\pi}{2n}, \quad i = 1, 3, 5, \dots, n-1$$

$$L_i = \frac{R}{\pi f_c} \sin \frac{(2i-1)\pi}{2n}, \quad i = 2, 4, 6, \dots, n$$

where

$$n = \text{INT} \left[\frac{1}{2} + \frac{\ln(2 \times 10^{-\Delta\text{dB}/10} - 1)}{2 \ln(\omega/\omega_0)} \right]$$

CHEBYSHEV

$$C_i = \frac{G_i}{2\pi f_c R}, \quad i = 1, 3, 5, \dots, n$$

$$L_i = \frac{R G_i}{2\pi f_c}, \quad i = 2, 4, 6, \dots, n-1$$

where

$$G_1 = \frac{2a_1}{\gamma}$$

$$G_i = \frac{4a_{i-1} a_i}{b_{i-1} G_{i-1}}, \quad i = 2, 3, 4, \dots, n$$

$$\gamma = \sinh \left[\frac{\ln \left(\coth \frac{\epsilon}{40 \log e} \right)}{2n} \right]$$

$$a_i = \sin \frac{(2i-1)\pi}{2n}, \quad i = 1, 2, 3, \dots, n$$

$$b_i = \gamma^2 + \sin^2 \frac{i\pi}{n}, \quad i = 1, 2, 3, \dots, n-1$$

$$\epsilon = \left(10^{\Delta\text{dB}/10} - 1 \right)^{1/2}$$

The filter order is found by using Newton's method to solve for n in the following formula:

$$(\omega + \sqrt{\omega^2 - 1})^{2n} + (\omega + \sqrt{\omega^2 - 1})^{-2n} = \frac{4}{\epsilon^2} (10^{\Delta_{dB}/10} - 1) - 2$$

using

$$n = \frac{\ln \left[\frac{4}{\epsilon^2} (10^{\Delta_{dB}/10} - 1) - 2 \right]}{\ln (\omega + \sqrt{\omega^2 - 1})}$$

as an initial guess.

The resulting value is then increased slightly:

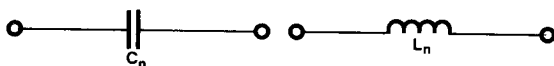
$$n \leftarrow \text{INT}(n + 1)$$

Once the low-pass values have been calculated, if some other bandpass characteristic is desired, the components of the filter are changed by frequency transformation as shown.

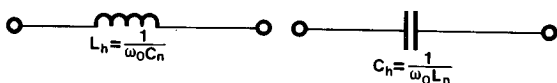
BANDPASS CHARACTERISTIC

CIRCUIT ELEMENTS

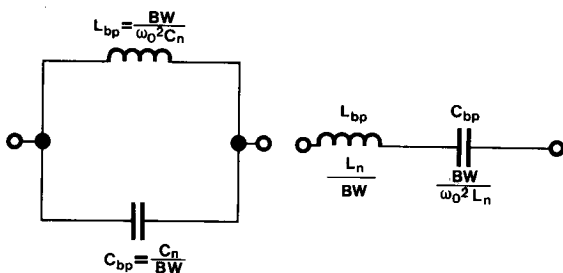
Low pass



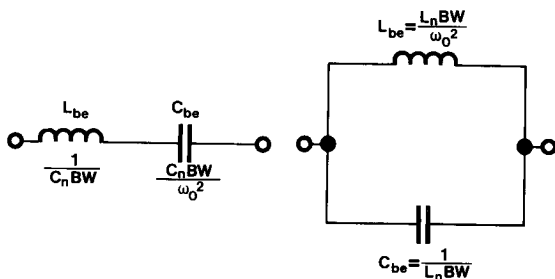
High pass



Band pass



Band elimination



To aid in deciphering the output, capacitors are output with a negative sign. A bit of thought may be necessary to determine whether the L-C's are connected in series or parallel.

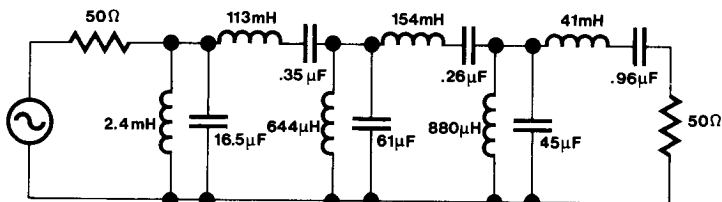
Note:

The program will give erroneous results if asked to compute filter order when ΔdB is small (i.e.: when $\Delta\text{dB} \sim \text{Loss}(\omega_0)$).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load first program (EE1-09A1).			
2	Input termination resistance.	R, Ω	A	R
3	Input frequency information for desired filter characteristic.			
	Low Pass	f_0, Hz	B	
	High Pass	f_0, Hz	f B	
	Band Pass	BW, Hz	ENTER	
		f_0, Hz	f C	
	Band Elimination	BW, Hz	ENTER	
		f_0, Hz	C	
4	For Chebyshev filter, continue with steps 5, 7, and 9. For Butterworth filter, continue with steps 6, 7 and 8.			
5	Input bandpass information and compute Chebyshev filter order.			
	Passband ripple	Ripple, dB	f D	ϵ
	Frequency at which attenuation is specified	f_1, Hz	ENTER	
	Desired attenuation	α, dB	D	n
6	Input bandpass information and compute Butterworth filter order.			
	Frequency at which attenua- tion is specified.	f_1, Hz	ENTER	
	Desired attenuation	α, dB	E	n
7	Load second program (EE1-09A2).			
8	Compute Butterworth filter elements.		E	
9	Compute Chebyshev filter elements.		D	

Example 1:

Design a 100 Hz wide Butterworth filter centered at 800 Hz with a 30 db attenuation at 900 Hz. R_0 is 50Ω . The termination resistance R is 50Ω .

**Keystrokes:**

Load card 1 (EE1-09A1)

50 **A** 100 **ENTER** 800

f **C** 900 **ENTER** 30 **E** →

Load card 2 (EE1-09A2)

E →

Outputs:

6.000+00 *** filter order

1.000+00 *** component 1
-16.48-06 *** capacitor
2.402-03 *** inductor

2.000+00 *** component 2
112.5-03 *** inductor
-351.7-09 *** capacitor

3.000+00 *** component 3
-61.49-06 *** capacitor
643.6-06 *** inductor

4.000+00 *** component 4
153.7-03 *** inductor
-257.5-09 *** capacitor

5.000+00 *** component 5
-45.02-06 *** capacitor
879.2-06 *** inductor

6.000+00 *** component 6
41.19-03 *** inductor
-960.8-09 *** capacitor

10. BODE PLOT OF BUTTERWORTH AND CHEBYSHEV FILTERS



This program provides gain, phase and group delay information for Bode plots of n -pole Butterworth or Chebyshev filters. A frequency transformation feature allows four types of filter characteristics: low pass, high pass, band pass, and band elimination. Frequency steps may be either linear (additive Δf) or logarithmic (multiplicative Δf).

The poles of an n -pole Butterworth filter are given by the following expression.

$$s_k = \sigma_k + j\omega_k = -\sin\left(\frac{2k-1}{3}\frac{\pi}{2}\right) - j\cos\left(\frac{2k-1}{3}\frac{\pi}{2}\right) \quad (k=1, \dots, n)$$

The poles of a Chebyshev filter are derived from Butterworth poles by the following procedure.

Let

$$\beta_k = \frac{1}{n} \sinh^{-1} \frac{1}{\epsilon}$$

Then the new poles are given by

$$s_k = \sigma_k \sinh \beta_k + j \omega_k \cosh \beta_k$$

The gain, phase and delay functions of a filter are given by the following expressions.

The network transfer function is

$$\begin{aligned} H(j\omega) &= \frac{K}{(j\omega - s_1)(j\omega - s_2) \dots (j\omega - s_n)} \\ &= \frac{K}{(M_1 \angle \theta_1)(M_2 \angle \theta_2) \dots (M_n \angle \theta_n)} \\ &= \frac{K}{M(\omega) \angle \theta(\omega)} \end{aligned}$$

in which K is a constant chosen such that

$$|H(j0)| = 1$$

The magnitude of the transfer function is

$$|H(j\omega)| = \frac{K}{\prod_{i=1}^n \sqrt{\sigma_i^2 + (\omega - \omega_i)^2}}$$

and its phase is

$$\arg [H(j\omega)] = -\theta(\omega) = -\sum_{i=1}^n \tan^{-1} \frac{\omega - \omega_i}{-\sigma_i}$$

The normalized group delay is

$$t_g = \frac{d}{d\omega} \{\theta(\omega)\} = \sum_{i=1}^n \frac{\sigma_i}{\sigma_i^2 + (\omega - \omega_i)^2}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Select which filter.			
	Butterworth			
	# poles	n	A	
	Chebyshev			
	# poles	n	ENTER	
	Passband ripple in dB	dB	f A	
3	Select passband characteristic.			
	Low pass-cutoff frequency	f ₀	B	
	High pass-cutoff frequency	f ₀	f B	
	Band pass-Bandwidth	BW	ENTER	
	Center frequency	f ₀	f C	
	Band elimination-Bandwidth	BW	ENTER	
	Center frequency	f ₀	C	
4	Select linear or logarithmic frequency incrementation.		f D	0-lin/1-log
5	Specify band of interest.			
	Minimum frequency	f ₁ , Hz	ENTER	
	Maximum frequency	f ₂ , Hz	ENTER	
	Frequency increment	Δf, Hz or ratio	D	

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
6	Start computing.		E	f
	Magnitude of transfer function			$20\log H(j\omega) , \text{dB}$
	Angle of transfer function			$\arg\{H(j\omega)\}$
	Normalized group delay			t_g
7	Step 6 is repeated auto-			
	matically for the band			
	specified.			

Example 1:

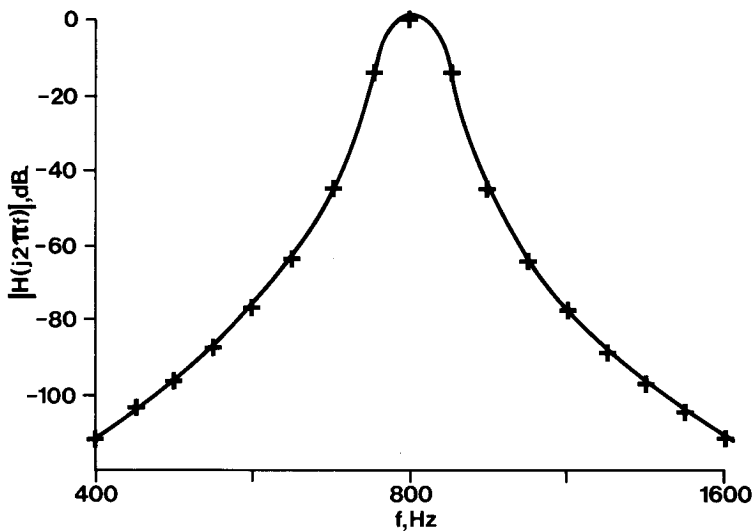
Plot the response of a 6-pole Butterworth band-pass filter with $BW = 100$, $f_0 = 800$. Make a logarithmic plot using steps of $2^{1/8}$ from 400 Hz to 1600 Hz.

Keystrokes:

6 **A** 100 **ENTER** 800 **f C f D** $\longrightarrow$ 1.000 (If 0.000 appears,
400 **ENTER** 1600 **ENTER** press **f D** again.)
2 **$\sqrt{x}$ $\sqrt{x}$ $\sqrt{x}$ D E** $\longrightarrow$

Outputs:

400.000	T	frequency	565.685	T
-129.502	Z	$ H(j2\pi f) $	-90.309	Z
161.536	Y	$\angle H(j2\pi f)$	140.715	Y
0.027	X	group delay, sec.	0.122	X
436.203	T		616.884	T
-121.591	Z		-74.863	Z
158.504	Y		126.993	Y
0.036	X		0.223	X
475.683	T		672.717	T
-112.727	Z		-53.407	Z
154.506	Y		99.228	Y
0.051	X		0.524	X
518.736	T		733.603	T
-102.519	Z		-17.172	Z
148.966	Y		6.544	Y
0.076	X		2.683	X



800.000 T	1037.472 T
0.000 Z	-74.863 Z
-9.682986738 -06 Y	-126.993 Y
3.864 X	0.223 X
872.406 T	1131.371 T
-17.172 Z	-90.309 Z
-6.544 Y	-140.715 Y
2.683 X	0.122 X
951.366 T	etc. for
-53.407 Z	1233.769
-99.228 Y	1345.434
0.524 X	1467.206

Example 2:

Plot the response of a 7-pole Chebyshev band-elimination filter of 5 Hz BW centered at 60 Hz with 3 dB passband ripple. Make a linear plot using steps of 0.5 Hz from 50 Hz to 61 Hz.

Keystrokes:

```

f D → 0.000 (linear plot)
7 ENTER 3 f A 5 ENTER 60
C 50 ENTER 61 ENTER
.5 D E →

```

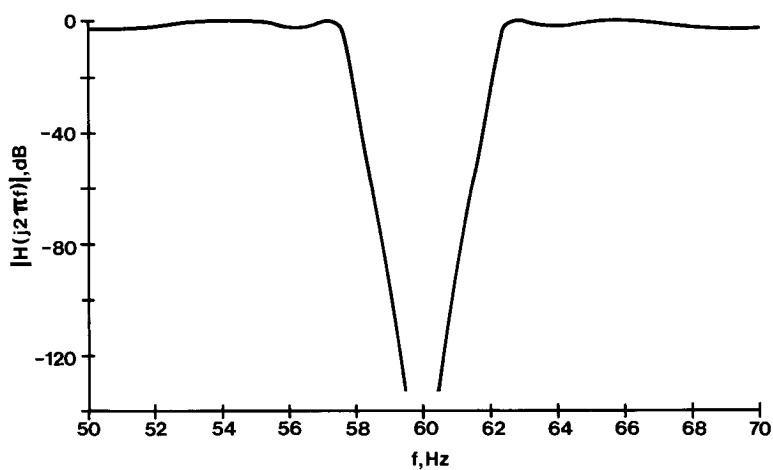
10-05

Outputs:

50.000	T	frequency	53.500	T
-2.997	Z	mag {H(s)}, dB	-1.027	Z
-84.017	Y	arg {H(s)}, degrees	-127.379	Y
4.506	X	group delay, sec.	7.737	X
50.500	T		54.000	T
-2.964	Z		-0.364	Z
-87.457	Y		-143.029	Y
4.559	X		9.239	X
51.000	T		54.500	T
-2.880	Z		0.000	Z
-91.347	Y		-164.525	Y
4.675	X		10.286	X
51.500	T		55.000	T
-2.730	Z		-0.478	Z
-95.842	Y		169.348	Y
4.881	X		9.368	X
52.000	T		55.500	T
-2.491	Z		-1.799	Z
-101.177	Y		143.391	Y
5.216	X		6.957	X
52.500	T		56.000	T
-2.140	Z		-2.932	Z
-107.732	Y		119.424	Y
5.742	X		5.448	X
53.000	T		56.500	T
-1.651	Z		-2.136	Z
-116.126	Y		88.980	Y
6.550	X		7.335	X

57.000 T	59.000 T
-0.479 Z	-88.662 Z
8.481 Y	103.950 Y
13.596 X	0.111 X
57.500 T	59.500 T
-0.066 Z	-133.081 Z
-122.266 Y	96.633 Y
37.279 X	0.024 X
58.000 T	60.000 T
-34.346 Z	-1048.077 Z
127.620 Y	-90.000 Y
1.179 X	1.985653756-15 X
58.500 T	60.500 T
-59.784 Z	-133.598 Z
113.071 Y	-96.577 Y
0.338 X	0.024 X

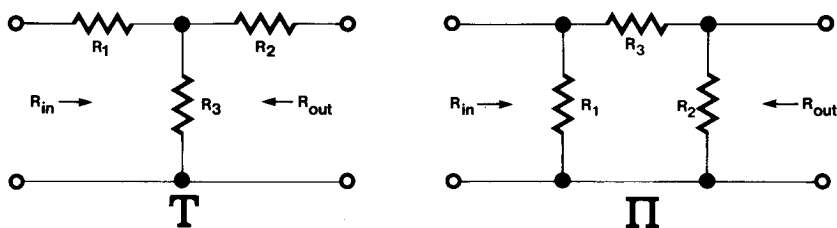
Note symmetry
which indicates
that we can reflect
plot around 60 Hz.



11. RESISTIVE ATTENUATOR DESIGN



Both the T attenuator and the Π attenuator can be used to match between two resistive impedances, R_{in} and R_{out} . This program computes the minimum loss of the attenuator and values for the resistors R_1 , R_2 and R_3 which will yield an attenuator having any desired loss.



The minimum loss in decibels is given by

$$\text{Min Loss} = 10 \log \left(\sqrt{\frac{R_{in}}{R_{out}}} + \sqrt{\frac{R_{in}}{R_{out}}} - 1 \right)^2$$

where $R_{in} \geq R_{out}$

If N is the desired loss of the attenuator expressed as a ratio (loss in dB = $10 \log N$), then for the T attenuator

$$R_3 = \frac{2\sqrt{N R_{in} R_{out}}}{N - 1}$$

$$R_1 = R_{in} \left(\frac{N + 1}{N - 1} \right) - R_3$$

$$R_2 = R_{out} \left(\frac{N + 1}{N - 1} \right) - R_3$$

and for the Π attenuator

$$R_3 = \frac{1}{2} (N - 1) \left(\frac{R_{in} R_{out}}{N} \right)^{1/2}$$

$$\frac{1}{R_1} = \frac{1}{R_{in}} \left(\frac{N + 1}{N - 1} \right) - \frac{1}{R_3}$$

$$\frac{1}{R_2} = \frac{1}{R_{out}} \left(\frac{N + 1}{N - 1} \right) - \frac{1}{R_3}$$

Note: If the desired loss is less than the minimum loss, an error message will be generated.

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input impedance levels.			
	Input circuit	R_{in}, Ω	A	
	Output circuit	R_{out}, Ω	B	
3	Compute minimum loss.		C	min loss, dB
4	Input desired loss and			
	compute resistances.			
	For T attenuator	Loss, dB	D	Loss
				R_1
				R_2
				R_3
	For Π attenuator	Loss, dB	E	Loss
				R_1
				R_2
				R_3

Example 1:

Compute element values for T and Π attenuators matching 75Ω to 50Ω with 6 dB loss.

Keystrokes:

75 **A** 50 **B** **C** $\longrightarrow$
6 **D** $\longrightarrow$

6 **E** $\longrightarrow$

Outputs:

5.719+00 *** min loss
6.000+00 T desired loss
43.34+00 Z R_1
1.572+00 Y R_2
81.97+00 X R_3

6.000+00 T desired loss
2.386+03 Z R_1
86.52+00 Y R_2
45.75+00 X R_3

Example 2:

Compute element values for T and Π attenuators matching 50Ω to 50Ω with 10 dB loss.

Keystrokes:

50 **A** 50 **B** **C** $\longrightarrow$
10 **D** $\longrightarrow$

10 **E** $\longrightarrow$

Outputs:

0.000+00 ***
10.00+00 T desired loss
25.97+00 Z R_1
25.97+00 Y R_2
35.14+00 X R_3

10.00+00 T desired loss
96.25+00 Z R_1
96.25+00 Y R_2
71.15+00 X R_3

Notes

12. SMITH CHART CONVERSIONS

SMITH CHART CONVERSIONS

SWR ↔ ρ ρ ↔ σ R.L. ↔ ρ Γ ↔ Z Z ↔ Γ

The distance between a point on a Smith Chart and its center may be measured by a number of parameters. The first three keys of this program allow conversion among some of the most commonly used ones: standing wave ratio, reflection coefficient, and return loss. The last two keys of this program convert between impedance and reflection coefficient.

The parameters

σ = voltage standing wave ratio

SWR = standing wave ratio expressed in decibels

ρ = reflection coefficient

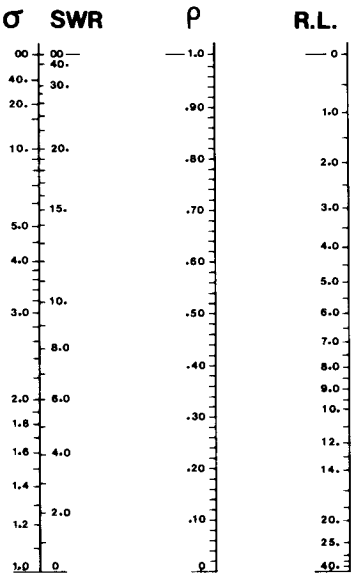
R.L. = return loss

are related as follows:

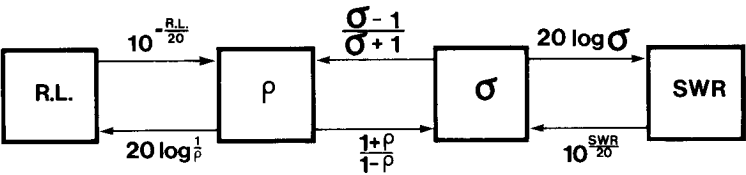
$$SWR = 20 \log \sigma$$

$$R.L. = 20 \log \frac{1}{\rho}$$

$$\sigma = \frac{1 + \rho}{1 - \rho}$$



These relationships are perhaps more clearly seen in this sketch:



For a system having characteristic impedance Z_0 , the impedance and reflection coefficient are related by

$$\Gamma = \rho \angle \phi = \frac{\frac{Z}{Z_0} - 1}{\frac{Z}{Z_0} + 1}$$

and

$$Z = Z_0 \angle \theta = Z_0 \frac{1 + \Gamma}{1 - \Gamma}$$

where

Γ = complex reflection coefficient

$\rho = |\Gamma|$

$\phi = \angle \Gamma$

Z = impedance

$Z = |Z|$

$\theta = \angle Z$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Convert among σ , SWR, ρ , and R.L. as desired.			
	$\sigma \rightarrow \text{SWR}$	σ	f A	SWR
	$\text{SWR} \rightarrow \sigma$	SWR	A	σ
	$\sigma \rightarrow \rho$	σ	f B	ρ
	$\rho \rightarrow \sigma$	ρ	B	σ
	$\rho \rightarrow \text{R.L.}$	ρ	f C	R.L.
	$\text{R.L.} \rightarrow \rho$	R.L.	C	ρ
3	Store characteristic impedance.	Z_0	f D	
4	Convert between Z and Γ as desired.			
	$Z \rightarrow \Gamma$	θ	ENTER	
		Z	E	ϕ, ρ
	$\Gamma \rightarrow Z$	ϕ	ENTER	
		ρ	D	θ, Z

Example 1:

Convert a 6 dB SWR to σ .

Keystrokes:	Outputs:
6 A →	2 σ

Example 2:

Convert a 7 dB return loss to SWR.

Keystrokes:	Outputs:
7 C B f A →	8.35 SWR

Example 3:

A 50Ω system is terminated with an impedance of $62 \angle 37^\circ$. What is the reflection coefficient?

Keystrokes:	Outputs:
50 f D 37 ENTER 62 E →	70.19 *** ϕ 0.35 *** ρ

Example 4:

A reflection coefficient of $.5 \angle 7^\circ$ is observed in a 72Ω system. What is the impedance?

Keystrokes:	Outputs:
72 f D 7 ENTER .5 D →	9.23 *** θ 212.50 *** Z

Notes

13. TRANSMISSION LINE IMPEDANCE

TRANSMISSION LINE IMPEDANCE

$D \cdot d \cdot \epsilon_r$ $d \cdot h \cdot \epsilon_r$ $D \cdot d \cdot h \cdot \epsilon_r$ $D \cdot d \cdot h \cdot \epsilon_r$ $D \cdot d \cdot \epsilon_r$

This program computes high frequency characteristic impedance for five types of transmission line.

Transmission line configuration

Equation for Z_0

open two-wire line

$$Z_0 = \frac{120}{\sqrt{\epsilon}} \ln \left(\frac{2D}{d} \right)$$

single wire near ground

$$Z_0 = \frac{138}{\sqrt{\epsilon}} \log \left(\frac{4h}{d} \right)$$

balanced wires near ground

$$Z_0 = \frac{276}{\sqrt{\epsilon}} \log \left\{ \frac{2D}{d} \left[1 + \left(\frac{D}{2h} \right)^2 \right]^{-1/2} \right\}$$

wires in parallel near ground

$$Z_0 = \frac{69}{\sqrt{\epsilon}} \log \left\{ \frac{4h}{d} \left[1 + \left(\frac{2h}{D} \right)^2 \right]^{+1/2} \right\}$$

coaxial line

$$Z_0 = \frac{60}{\sqrt{\epsilon}} \ln \frac{D}{d}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Compute impedance of open two-wire line.			
	Input wire spacing	D	ENTER	
	wire diameter	d	ENTER	
	relative permittivity	ϵ_r	A	Z_0, Ω
3	Compute impedance of a single wire near ground.			
	Input wire diameter	d	ENTER	
	wire height	h	ENTER	
	relative permittivity	ϵ_r	B	Z_0, Ω
4	Compute impedance of balanced wires near ground.			
	Input wire spacing	D	ENTER	
	wire diameter	d	ENTER	
	wire height	h	ENTER	
	relative permittivity	ϵ_r	C	Z_0, Ω
5	Compute impedance of wires in parallel near ground.			
	Input wire spacing	D	ENTER	
	wire diameter	d	ENTER	
	wire height	h	ENTER	
	relative permittivity	ϵ_r	D	Z_0, Ω
6	Compute impedance of coaxial line.			
	Input inside diameter of outer conductor	D	ENTER	
	outside diameter of inner conductor	d	ENTER	
	relative permittivity	ϵ_r	E	Z_0, Ω

13-03

Example 1:

Compute Z_0 of RG-218/U coaxial cable. ($D = .68$ in., $d = .195$ in., $\epsilon_r = 2.3$ (polyethylene)).

Keystrokes:

.68 **ENTER** .195 **ENTER**
2.3 **E** →

Outputs:

49.42 ***

Example 2:

Compute Z_0 of open 2-wire line with $D = 6$ in., $d = .0808$ in., $\epsilon_r = 1$ (air).

Keystrokes:

6 **ENTER** .0808 **ENTER** 1 **A** →

Outputs:

600.08 ***

Example 3:

Compute Z_0 of an air line consisting of a single .1285 inch wire 6 inches from a ground plane.

Keystrokes:

.1285 **ENTER** 6 **ENTER** 1 **B** →

Outputs:

313.44 ***

Notes

14. MICROSTRIP CALCULATIONS



This program accepts conductor width w , dielectric thickness h , and relative permittivity ϵ_r , and computes relative phase velocity v_r and characteristic impedance Z_c for lossless line. The following formulas are used.

$$\epsilon_{\text{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 10 \frac{h}{w} \right)^{-1/2}$$

$$v_r = \frac{1}{\sqrt{\epsilon_{\text{eff}}}}$$

$$Z_0 = \begin{cases} 60 \ln \left(8 \frac{h}{w} + \frac{w}{4h} \right), & \frac{w}{h} \leq 1 \\ \frac{120\pi}{\frac{w}{h} + 2.42 - 0.44 \frac{h}{w} + \left(1 - \frac{h}{w} \right)^6}, & \frac{w}{h} > 1 \end{cases}$$

$$Z_c = v_r Z_0$$

where

ϵ_r = relative permittivity of dielectric

ϵ_{eff} = effective permittivity of dielectric

h = dielectric thickness

w = width of microstrip

v_r = relative phase velocity of lossless line

Z_0 = characteristic impedance of corresponding air line, Ω

Z_c = characteristic impedance of lossless microstrip, Ω

It then accepts the conductor thickness and computes a normalized conductor loss A .

$$A = \begin{cases} \frac{20}{\ln 10} \frac{h}{w Z_0} \frac{dB}{\Omega}, \text{ uniform current distribution} \\ \frac{10}{\pi \ln 10} \frac{\left(8 \frac{h}{w} - \frac{w}{4h}\right) \left(1 + \frac{h}{w} + \frac{h}{w} \frac{\partial w}{\partial t}\right)}{Z_0 e^{Z_0/60}} \frac{dB}{\Omega}, \frac{w}{h} \leq 1 \\ \frac{Z_0}{720\pi^2 \ln 10} \left[1 + 0.44 \frac{h^2}{w^2} + \frac{6h^2}{w^2} \left(1 - \frac{h}{w}\right)^5\right] \\ \times \left[1 + \frac{w}{h} + \frac{\partial w}{\partial t}\right] \frac{dB}{\Omega}, \frac{w}{h} > 1 \end{cases}$$

where

$$\frac{\partial w}{\partial t} = \begin{cases} \frac{1}{\pi} \ln \frac{4\pi w}{t}, \frac{w}{h} \leq \frac{1}{2\pi} \\ \frac{1}{\pi} \ln \frac{2h}{t}, \frac{w}{h} > \frac{1}{2\pi} \end{cases}$$

Finally, the program accepts conductor resistivity ρ and frequency f and computes copper loss α_c , resistance per unit length R , and unloaded quality factor Q_0 using the following equations.

$$\alpha_0 = \frac{R_s A}{h}$$

$$\mu_0 = 4\pi \times 10^{-9} \text{ H/cm}$$

$$R_s = \sqrt{\pi f \mu_0 \rho}$$

$$R = 2R_s/w$$

$$\alpha_c = \frac{\alpha_0}{v_r}$$

$$Q_0 = \frac{20\pi}{\ln 10} \frac{f}{c v_r \alpha_c}$$

$$c = 3 \times 10^{10} \text{ cm/s}$$

Reference:

M.V. Schneider, "Microstrip Lines for Microwave Integrated Circuits," *Bell System Technical Journal*, 48, No. 5 (May-June 1969).

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input width of microstrip	w, cm	ENTER	
	thickness of dielectric	h, cm	A	w/h
3	Input relative permit-			
	tivity and print relative			
	phase velocity and imped-			
	ance of lossless line.	ϵ_r	B	v_r
				Z_c
4	If a uniform current			
	distribution is desired,			
	skip to step 6.			
5	Input conductor thickness.	t, cm	C	A
6	Input conductor resistivity.	ρ	D	
7	Input frequency and			
	print copper loss,			
	resistance per unit			
	length and unloaded Q.	f, Hz	E	α_c
				R
				Q_0

Example 1:

What are the characteristics of 50-mil microstrip on a 50-mil alumina ($\epsilon_r = 9.5$) substrate at 2GHz? Assume a line thickness of 1 mil and a conductor resistivity of 3 E -6.

Keystrokes:

.05 **ENTER** 2.54 **X** **ENTER** **A**
9.5 **B** $\longrightarrow$

.001 **ENTER** 2.54 **X** **C** 3 **EEX**
CHS 6 **D** 2 **EEX** 9 **E** $\longrightarrow$

Outputs:

391.3-03 *** v_r
49.54+00 *** Z_c

11.01-03 *** α
242.4-03 *** R
422.3+00 *** Q_0

Example 2:

Repeat the above example, but assume a uniform current distribution.

Keystrokes:

.05 **ENTER** 2.54 **×** **ENTER** **A**
 9.5 **B** $\longrightarrow$
 3 **EEX** **CHS** 6 **D** 2 **EEX** 9 **E** $\longrightarrow$

Outputs:

391.3-03 *** v_r
 49.54+00 *** Z_c
 21.25-03 *** α
 242.4-03 *** R
 218.8+00 *** Q_0

15. TRANSMISSION LINE CALCULATIONS

TRANSMISSION LINE CALCULATIONS

$$v_r \cdot R_0$$

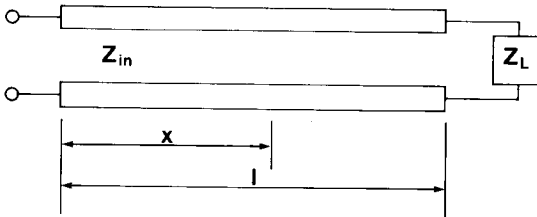
$$l$$

$$G \cdot R$$

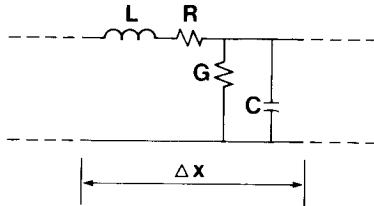
$$\alpha_D \cdot \alpha_C$$

$$Z_L \cdot Z_{in}$$

This program computes the input impedance of lossy transmission line terminated in Z_L . The program provides an exact solution when the distributed line parameters $R_0 (= \sqrt{L/C})$, R , and G are given, and it provides an approximate solution when R_0 , copper loss and dielectric loss are given.



MODEL



The transmission line shown has a lumped model composed of elements L , C , R , and G . From this model the following equations can be derived.

Let

$$R_0 = \sqrt{\frac{L}{C}}$$

$$r = \frac{R}{L} = \frac{vR}{R_0}$$

$$g = \frac{G}{C} = v R_0 G$$

$$\omega = 2\pi f$$

where

L = inductance/unit length

C = capacitance/unit length

R = resistance/unit length

G = conductance/unit length

$v = 3 \times 10^8 v_r$

v_r = relative phase velocity

f = frequency, Hz

Then

$$Z_{in} = Z_0 \left(\frac{1 + \Gamma_L e^{-2\gamma l}}{1 - \Gamma_L e^{-2\gamma l}} \right)$$

where

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

l = line length

Z_L = impedance of termination

Z_0 = characteristic impedance of line = $\text{Re}\{Z_0\} + j \text{Im}\{Z_0\}$

γ = propagation constant of line = $\alpha + j\beta$

Z_0 and γ are computed differently depending on which solution is selected.

$$\text{Re}\{Z_0\} = \frac{R_0}{\sqrt{2(g^2 + \omega^2)}} \left[rg + \omega^2 + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{1/2}$$

$$\text{Im}\{Z_0\} = \frac{\pm R_0}{\sqrt{2(g^2 + \omega^2)}} \left[-(rg + \omega^2) + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{1/2}$$

in which the $+$ sign is chosen when $g \geq r$

and the $-$ sign is chosen when $g < r$

and

$$\alpha = \frac{1}{\sqrt{2} v} \left[rg - \omega^2 + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{1/2}$$

$$\beta = \frac{1}{\sqrt{2} v} \left[\omega^2 - rg + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{1/2}$$

The approximate solution is

$$\operatorname{Re}\{Z_0\} = R_0 \left[1 + \frac{1}{2} \left(\frac{\alpha_c - \alpha_D}{\beta_0} \right) \left(\frac{3\alpha_D + \alpha_c}{\beta_0} \right) \right]$$

$$\operatorname{Im}\{Z_0\} = R_0 \left[\frac{\alpha_D - \alpha_c}{\beta_0} \right]$$

$$\alpha = \alpha_c + \alpha_D$$

$$\beta = \beta_0 \left[1 + \frac{1}{2} \left(\frac{\alpha_c - \alpha_D}{\beta_0} \right)^2 \right]$$

where

$$\alpha_c = \text{Copper loss, nepers/unit length} = \frac{1}{2} \frac{R}{R_0}$$

$$\alpha_D = \text{Dielectric loss, nepers/unit length} = \frac{1}{2} \text{ GR.}$$

$$\beta_0 = \frac{\omega}{v}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Inputs when R and G are known.			
	Frequency	f, Hz	F A	
	Relative phase velocity	v_r	ENTER +	
	Characteristic impedance of lossless line	R_0, Ω	A	
	Line length	l, cm	B	
	Conductance of substrate per unit length	G, S/cm	ENTER +	
	Resistance of line per unit length	R, Ω/cm	C	
	Angle of terminating impedance	$\angle Z_L, \text{deg}$	ENTER +	
	Magnitude of terminating impedance	$ Z_L , \Omega$	E	θ_{in}
				Z_{in}
3	Inputs when α_c and α_D are known.			
	Frequency	f, Hz	F A	
	Relative phase velocity	v_r	ENTER +	
	Characteristic impedance of lossless line	R_0, Ω	A	
	Line length	l, cm	B	
	Dielectric loss per unit length	α_D	ENTER +	
	Copper loss per unit length	α_c	D	
	Angle of terminating impedance	$\angle Z_L, \text{deg}$	ENTER +	
	Magnitude of terminating impedance	$ Z_L , \Omega$	E	θ_{in}
				Z_{in}

Example 1:

A transmission line has the following properties:

$$R = 1.2664 \, \Omega/\text{cm}$$

$$G = 0.000\,041\,87 \text{ Siemens/cm}$$

$$R_0 = 55 \, \Omega$$

$$v_r = 0.85$$

What is the input impedance of 3.5 cm of this line at 2 GHz if it is terminated in $Z_L = 75 \angle -30^\circ$?

Keystrokes:

2 **EEX** 9 **f** **A** .85 **ENTER**

55 **A** 3.5 **B** .00004187

ENTER 1.2664 **C** 30 **CHS**

ENTER 75 **E** $\longrightarrow$

Outputs:

28.48+00 *** $\angle Z_{in}$
48.01+00 *** $|Z_{in}|$

Example 2:

A 4-cm gold ($\rho = 2.3 \, \mu\Omega/\text{cm}$) microstrip line of 50-mil width is on a 50-mil alumina ($\epsilon_r = 9.5$) substrate. Assuming a uniform current distribution and zero dielectric loss, what is the input impedance of the line at 124 MHz when it is terminated in $75 \, \Omega$?

Keystrokes:

Load EE1-14A

.05 **ENTER** 2.54 **x** **ENTER**

A 9.5 **B** $\longrightarrow$

2.3 **EEX** **CHS** 6 **D** 124 **EEX**

6 **E** $\longrightarrow$

Outputs:

391.3-03 *** v_r
49.54+00 *** Z_c

4.632-03 *** α_c
52.84-03 *** R
62.23+00 *** Q_0

Load EE1-15A

124 **EEX** 6 **f** **A** 4 **B** 4.632

EEX **CHS** 3 **ENTER** 0 **D**

0 **ENTER** 75 **E** $\longrightarrow$

-12.06+00 *** $\angle Z_L$
70.06+00 *** $|Z_L|$

Notes

16. UNILATERAL DESIGN: FIGURE OF MERIT, MAXIMUM UNILATERAL GAIN, GAIN CIRCLES



This program computes u , G_u , $G_{\min}$, $G_{\max}$, G_0 , $G_{1\max}$, and $G_{2\max}$ from a transistor's s -parameters. It also computes r_{oi} and ρ_{oi} from $G_i \leq G_{1\max}$ ($i = 1, 2$).

When designing a transistor amplifier with the aid of s -parameters, the often valid assumption that the reverse-transmission parameter s_{12} may be neglected leads to simplified equations. A transistor for which s_{12} is negligible is said to be a "unilateral device." The unilateral figure of merit u may be used to determine the reasonableness of the unilateral assumption:

$$u = \frac{|s_{11} s_{12} s_{21} s_{22}|}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|}$$

Clearly, the unilateral assumption is more nearly correct for u near zero.

The maximum unilateral transducer power gain is given by

$$\begin{aligned} G_u &= \frac{\text{Power delivered to load}}{\text{Power available from source}} \\ &= \frac{|s_{21}|^2}{|(1 - |s_{11}|^2)(1 - |s_{22}|^2)|} \end{aligned}$$

Using the unilateral figure of merit we can place limits on the actual transducer power gain:

$$G_{\min} = G_u \frac{1}{(1 + u)^2}$$

$$G_{\max} = G_u \frac{1}{(1 - u)^2}$$

When input and output impedances are conjugately matched, the transducer power gain is

$$G_u = G_0 \cdot G_1 \cdot G_2$$

where

$$G_u = \text{transducer power gain} = \frac{\text{Power delivered to load}}{\text{Power available from source}}$$

$$G_0 = |s_{21}|^2 = \text{transducer gain for } Z_0 \text{ input and output impedances}$$

$$G_{1\max} = \frac{1}{1 - |s_{11}|^2} = \text{gain contribution from change of source impedance from } Z_0 \text{ to } s_{11}^*$$

$$G_{2\max} = \frac{1}{1 - |s_{22}|^2} = \text{gain contribution from change of load impedance from } Z_0 \text{ to } s_{22}^*$$

$s_{ij}^* = \text{complex conjugate of } s_{ij}.$

For source and load impedances other than s_{11}^* and s_{22}^* , G_1 and G_2 are less than the maximum values given above. The loci of points on a Smith chart representing values of source or load impedance which yield values of G_1 or G_2 less than $G_{1\max}$ or $G_{2\max}$ are circles. The center of a constant gain circle is in the direction of s_{ii}^* ($i = 1, 2$) at a distance

$$r_{oi} = \frac{G_i s_{ii}}{1 + G_i |s_{ii}|^2}$$

from the origin.

The radius of the circle is

$$\rho_{oi} = \frac{\sqrt{1 - G_i(1 - |s_{ii}|^2)}}{1 + G_i |s_{ii}|^2}$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input magnitude of			
	s-parameters for $i = 1, 2,$			
	$j=1, 2.$			
	Magnitude	s_{ij}	ENTER	
	Designation	ij	A	
3	Compute			
			B	u
				G_u
				$G_{\min}$
				$G_{\max}$
				G_0
				$G_{1\max}$
				$G_{2\max}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
4	Input desired gain			
	($\leq G_{1\max}$) and compute loca-			
	tion * of center of gain circle			
	on input plane.	G_1 , dB	C	r_{01}
				ρ_{01}
5	Input desired gain			
	($\leq G_{2\max}$) and compute loca-			
	tion * of center of gain circle			
	on output plane.	G_2 , dB	F C	r_{02}
				ρ_{02}
	*Note: These points are			
	located at a distance r_{0i} from			
	the origin of the Smith chart			
	in the direction of s_{ij} .*			

Example 1:

An HP35876E option 100 transistor operating at 4 GHz has the following s-parameters:

$$S = \begin{bmatrix} .51 \angle 154^\circ & .09 \angle 26^\circ \\ 1.4 \angle 22^\circ & .60 \angle -58^\circ \end{bmatrix}$$

What is the unilateral figure of merit?

What is the maximum unilateral transducer power gain?

What is the range of transducer gain due to the fact that s_{12} is not zero?

What are G_0 , $G_{1\max}$, and $G_{2\max}$?

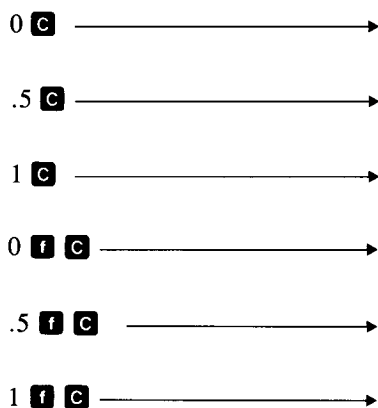
Draw 0 dB, .5 dB, and 1 dB constant gain circles on input and output planes.

Keystrokes:

.51 **ENTER** 11 **A** .09 **ENTER**
 12 **A** 1.4 **ENTER** 21 **A**
 .6 **ENTER** 22 **A B** $\longrightarrow$

Outputs:

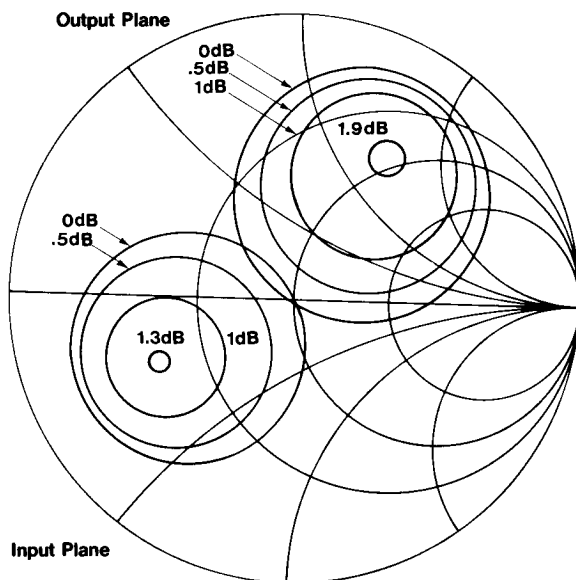
0.08 *** u
 6.17 *** G_u
 5.49 *** $G_{\text{actual min}}$

6.91 *** $G_{\text{actual max}}$ 2.92 *** G_0 1.31 *** $G_{1\text{max}}$ 1.94 *** $G_{2\text{max}}$ 0.40 *** r_{01} 0.40 *** ρ_{01} 0.44 *** r_{01} 0.32 *** ρ_{01} 0.48 *** r_{01} 0.20 *** ρ_{01} 0.44 *** r_{02} 0.44 *** ρ_{02} 0.48 *** r_{02} 0.38 *** ρ_{02} 0.52 *** r_{02} 0.30 *** ρ_{02}

input plane

output plane

	r_{01}	ρ_{01}		r_{02}	ρ_{02}
0 dB	.40 $\angle -154^\circ$	.40		.44 $\angle 58^\circ$	.44
.5 dB	.44 $\angle -154^\circ$	.32		.48 $\angle 58^\circ$	.38
1 dB	.48 $\angle -154^\circ$	.20		.52 $\angle 58^\circ$	.30



17. BILATERAL DESIGN: STABILITY FACTOR, MAXIMUM GAIN, OPTIMUM MATCHING

BILATERAL DESIGN: K, G_{max} , Γ_{opt}

$\Theta_{ij}^* s_{ij}^* \Gamma_{ij} \rightarrow K, G_{\text{max}}, \Gamma_{\text{ml}}$

Sometimes s_{12} is not sufficiently small that it may be neglected in transistor amplifier design. In this case it is necessary to compute a stability factor K and use different design approaches depending on its value. The stability factor is defined by the equation

$$K = \frac{1 + |\Delta|^2 - |s_{11}|^2 - |s_{22}|^2}{2 |s_{21} s_{12}|}$$

where

s_{ij} are s-parameters

and

$$\Delta = s_{11} s_{22} - s_{21} s_{12}$$

For $K < 1$ the amplifier is potentially unstable and the designer must choose input and output matching networks very carefully (see program EE1-18A). For $K > 1$ the amplifier is unconditionally stable and this program may be used to compute the maximum gain available and the load and source reflection coefficients which yield the maximum gain.

Maximum gain is computed using the relation

$$G_{\text{max}} = \frac{|s_{21}|}{|s_{12}|} (K \pm \sqrt{K^2 - 1})$$

in which the plus sign is used when the quantity

$$B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |\Delta|^2$$

is negative and the minus sign is used when B_1 is positive.

The second portion of this program computes values of source and load reflection coefficients required to conjugately match the transistor using the equations

$$\Gamma_{\text{ms}} = C_1^* \left[\frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2|C_1|^2} \right]$$

$$\Gamma_{\text{ml}} = C_2^* \left[\frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2|C_2|^2} \right]$$

where

$$C_1 = s_{11} - \Delta s_{22}^*$$

C_1^* = complex conjugate of C_1

$$C_2 = s_{22} - \Delta s_{11}^*$$

C_2^* = complex conjugate of C_2

$$B_1 = 1 + |s_{11}|^2 - |s_{22}|^2 - |\Delta|^2$$

$$B_2 = 1 + |s_{22}|^2 - |s_{11}|^2 - |\Delta|^2$$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Input s-parameter matrix (ij=11, 12, 21, 22).			
	Angle of s_{ij}	θ_{ij} , deg	ENTER	
	Magnitude of s_{ij}	$ s_{ij} $	ENTER	
	Subscript	ij	A	$ s_{ij} $
3	Compute stability factor and maximum gain.*		B	K $G_{\max}$, dB
4	Compute angle and magnitude of source reflection coefficient.		f C	θ_{ms} $ \Gamma_{ms} $
5	Compute angle and magnitude of load reflection coefficient.		C	θ_{ml} $ \Gamma_{ml} $
	*If $k < 1$, this calculation causes an error.			

Example:

Design a maximum-gain amplifier using a transistor having the following s-parameters.

$$s_{11} = 0.277 \angle -59^\circ$$

$$s_{12} = 0.078 \angle 93.0^\circ$$

$$s_{21} = 1.920 \angle 64^\circ$$

$$s_{22} = 0.848 \angle -31^\circ$$

Keystrokes:

59 **CHS** **ENTER** .277 **ENTER**
 11 **A** 93 **ENTER** .078 **ENTER**
 12 **A** 64 **ENTER** 1.92 **ENTER**
 21 **A** 31 **CHS** **ENTER** .848 **ENTER**
 22 **A** **B** $\longrightarrow$

f **C** $\longrightarrow$

C $\longrightarrow$

Outputs:

1.033+00 *** K
 12.81+00 *** $G_{\max}$
 135.4+00 *** $\angle \Gamma_{ms}$
 729.8-03 *** $|\Gamma_{ms}|$
 33.85+00 *** $\angle \Gamma_{ml}$
 951.1-03 *** $|\Gamma_{ml}|$

Notes

18. BILATERAL DESIGN: GAIN AND STABILITY CIRCLES, LOAD AND SOURCE MAPPING

BILATERAL DESIGN: GAIN AND
STABILITY CIRCLES

$$G_p = \angle \Gamma_L \cdot \Gamma_L \cdot \rho \quad \Gamma_L = \Gamma_{ms} \quad i = \angle \Gamma_{S1} \cdot \Gamma_{S1} \cdot \rho_{S1}$$

If it is desired to build an amplifier having gain less than the maximum possible for the transistor to be used, a gain circle is constructed. This circle shows all possible loads for the output that yield the desired power gain. When a load on this gain circle is selected, the load and source mapping routine may be used to compute the new source reflection coefficient required.

This program computes the center

$$\Gamma_{02} = \left[\frac{G}{1 + D_2 G} \right] C_2^*$$

and radius

$$\rho_{02} = \frac{(1 - 2K |s_{12} s_{21}| G + |s_{12} s_{21}|^2 G^2)^{1/2}}{1 + D_2 G}$$

where

$$G = \frac{G_p}{G_0}$$

G_p = desired gain

G_0 = maximum transducer gain = $|s_{21}|^2$

$$C_2 = s_{22} - \Delta s_{11}^*$$

$$D_2 = |s_{22}|^2 - |\Delta|^2$$

$$\Delta = s_{22} s_{11} - s_{21} s_{12}$$

When a two-port network is terminated in a load having reflection coefficient Γ_L , the source reflection coefficient for a conjugate input match becomes

$$\Gamma_{ms} = \left[s_{11} + \frac{s_{12} s_{21}}{\frac{1}{\Gamma_L} - s_{22}} \right]^*$$

Similarly, when the source reflection coefficient of a two-port network is Γ_s , the output reflection coefficient for a conjugate output match becomes

$$\Gamma_{ml} = \left[s_{22} + \frac{s_{12} s_{21}}{\frac{1}{\Gamma_s} - s_{11}} \right]^*$$

This routine accepts Γ_L or Γ_s and computes the corresponding source or load reflection coefficient. A typical use is to determine which area defined by a stability circle is the stable or unstable region (for stable operation, Γ_L must be such that $|\Gamma_{ms}| < 1$ and Γ_s must be such that $|\Gamma_{ml}| < 1$).

For the potentially unstable amplifier (stability factor $K < 1$), it is necessary to avoid values of source and load reflection coefficients which could cause oscillations. The boundaries between stable and unstable regions are circles on the input and output planes.

The centers of the stability circles are located at:

$$r_{si} = \frac{C_i^*}{|s_{ii}|^2 - |\Delta|^2}$$

where

r_{s1} = location of center of stability circle on input plane

r_{s2} = location of center of stability circle on output plane

$$C_1 = s_{11} - \Delta s_{22}^*$$

$$C_2 = s_{22} - \Delta s_{11}^*$$

$$\Delta = s_{11} s_{22} - s_{21} s_{12}$$

The radii of the stability circles are:

$$\rho_{s1} = \frac{|s_{12} s_{21}|}{|s_{ii}|^2 - |\Delta|^2}$$

where

ρ_{s1} = radius of stability circle on input plane

ρ_{s2} = radius of stability circle on output plane

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	First run EE1-17A, then			
	load this program.			
2	Perform any or all of the			
	following steps in any order.			
3	Input desired gain less than			
	$G_{\max}$ and compute location			
	and radius of gain circle.	G_p , dB	A	$\angle r$
				r
				ρ
4	Input load reflection coefficient			
	and compute new source			
	reflection coefficient.	$\angle \Gamma_L$, deg	ENTER	
		$ \Gamma_L $	B	$\angle \Gamma_{ms}$
				$ \Gamma_{ms} $
5	Input source reflection coef-			
	ficient and compute new load			
	reflection coefficient.	$\angle \Gamma_s$, deg	ENTER	
		$ \Gamma_s $	F B	$\angle \Gamma_{ml}$
				$ \Gamma_{ml} $
6	Compute location and radius			
	of stability circles on input			
	(i=1) or output (i=2) planes.	i	C	$\angle r_{si}$
				$ r_{si} $
				ρ_{si}

Example 1:

A gain of 10 dB is desired from an amplifier using a transistor whose s-parameter matrix is

$$S = \begin{bmatrix} .277 \angle -59^\circ & .078 \angle 93^\circ \\ 1.92 \angle 64^\circ & .848 \angle -31^\circ \end{bmatrix}$$

Where is the center of the 10 dB gain circle and what is its radius?

Keystrokes:

Load EE1-17A

59 **CHS** **ENTER** .277 **ENTER** 11

A 93 **ENTER** .078 **ENTER** 12

A 64 **ENTER** 1.92 **ENTER** 21

A 31 **CHS** **ENTER** .848 **ENTER**

22 **A** **B** $\longrightarrow$

f **C** $\longrightarrow$

C $\longrightarrow$

Load EE1-18A

10 **A** $\longrightarrow$

Outputs:

1.033+00 *** K

12.81+00 *** $G_{\max}$

135.4+00 *** θ_{ms}

729.8-03 *** Γ_{ms}

33.85+00 *** θ_{ml}

951.1-03 *** Γ_{ml}

33.85+00 *** $\angle r_{02}$

781.2-03 *** $|r_{02}|$

214.2-03 *** ρ_{02}

Example 2:

We have determined that the 10 dB gain circle is located at $r_{02} = .781 \angle 33.85^\circ$ with a radius of $\rho_{02} = .214$. If we pick a load reflection coefficient of $(|r_{02}| - \rho_{02}) \angle r_{02} = .567 \angle 33.85^\circ$, what source reflection coefficient is required?

Keystrokes:

Continuing from Example 1,

33.85 **ENTER** .567 **B** $\longrightarrow$

Outputs:

93.33+00 *** $\angle \Gamma_{ms}$

276.0-03 *** $|\Gamma_{ms}|$

Example 3:

Construct stability circles for a transistor having the following s-matrix.

$$S = \begin{bmatrix} .385 \angle -55^\circ & .045 \angle 90^\circ \\ 2.7 \angle 78^\circ & .89 \angle -26.5^\circ \end{bmatrix}$$

Keystrokes

Load EE1-17A

55 **CHS** **ENTER** .385 **ENTER** 11

A 90 **ENTER** .045 **ENTER** 12

A 78 **ENTER** 2.7 **ENTER** 21 **A**

26.5 **CHS** **ENTER** .89 **ENTER**

22 **A** **B** $\longrightarrow$

CLX (Clear "Error")

Load EE1-18A

1 **C** $\longrightarrow$

2 **C** $\longrightarrow$

Outputs:

909.5-03 *** K

"Error" signifies $K < 1$

122.4+00 *** $\angle r_{s1}$
 -8.371+00 *** $|r_{s1}|$
 -9.271+00 *** ρ_{s1}

29.88+00 *** $\angle r_{s2}$
 1.178+00 *** $|r_{s2}|$
 192.6-03 *** ρ_{s2}

Program Listings

The following listings are included for your reference. A table of keycodes and keystrokes corresponding to the symbols used in the listings can be found in Appendix E of your Owners Handbook.

Program	Page
1a. Network Transfer Functions—Input	L01-01
1b. Network Transfer Functions—Output	L01-03
2. Reactive L-Network Impedance Matching	L02-01
3. Class A Transistor Amplifier Bias Optimization	L03-01
4. Transistor Amplifier Performance	L04-01
5. Transistor Configuration Conversion	L05-01
6. Parameter Conversion: $S \Rightarrow Y, Z, G, H$	L06-01
7. Fourier Series	L07-01
8. Active Filter Design	L08-01
9a. Butterworth or Chebyshev Filter Design	L09-01
9b. Butterworth or Chebyshev Filter Design	L09-03
10. Bode Plot of Butterworth and Chebyshev Filters	L10-01
11. Resistive Attenuator Design	L11-01
12. Smith Chart Conversions	L12-01
13. Transmission Line Impedance	L13-01
14. Microstrip Transmission Line Calculations	L14-01
15. Transmission Line Calculations	L15-01
16. Unilateral Design: Figure of Merit, Maximum Unilateral Gain, Gain Circles	L16-01
17. Bilateral Design: Stability Factor, Maximum Gain, Optimum Matching	L17-01
18. Bilateral Design: Gain and Stability Circles, Load and Source Mapping	L18-01

Network Transfer Functions—Input

001 #LBLA	Input f	057 1/X	
002 CLR6		058 9	
003 2		059 0	
004 x		060 CHS	
005 P;		061 GT02	Pass $(\omega C)^{-1} \angle -90$ to LBL 2.
006 x		062 #LBLA	
007 ST00	Store ω	063 CSB0	
008 1		064 CHS	
009 ST01		065 X $\leftrightarrow$ Y	Pass $\frac{1-\omega^2 LC}{\omega C} \angle -90$ to LBL 2.
010 ST07	$[u] \leftarrow \begin{bmatrix} 1 \angle 0 & 0 \\ 0 & 1 \angle 0 \end{bmatrix} [u]$	066 1/X	
011 CLX		067 X $\leftrightarrow$ Y	
012 RTN		068 #LBL2	
013 #LBLB		069 CSB7	
014 0		070 RCL0	
015 GT01	Pass R $\angle 0$ to LBL 1.	071 RCLB	
016 #LBLC		072 RCL9	
017 RCL0		073 1/X	
018 x		074 RCLA	
019 9		075 CHS	
020 0		076 CSB9	
021 GT01	Pass $\omega L \angle 90$ to LBL 1.	077 ST05	
022 #LBLD		078 R4	
023 RCL0		079 ST06	
024 x		080 RCL0	
025 1/X		081 RCLD	
026 9		082 RCL9	
027 0		083 1/X	
028 CHS		084 RCLA	
029 GT01	Pass $(\omega C)^{-1} \angle -90$ to LBL 1.	085 CHS	
030 #LBLB		086 CSB9	
031 X $\leftrightarrow$ Y	Pass $\frac{\omega L}{1-\omega^2 LC} \angle 90$ to LBL 1.	087 ST07	
032 CSB0		088 R4	
033 #LBL1		089 ST08	
034 CSB7		090 CLX	
035 RCLC		091 RTN	
036 ST02	$[u] \leftarrow \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} [u]$	092 #LBL7	
037 RCLB		093 ST0A	
038 ST01		094 X $\leftrightarrow$ Y	
039 RCL0		095 ST09	
040 ST04		096 RCL5	
041 RCLD		097 RCL6	
042 ST03		098 CSB9	
043 CLX		099 RCL2	
044 RTN		100 RCL1	
045 #LBL6		101 CSB8	
046 0		102 ST0B	
047 GT02	Pass R $\angle 0$ to LBL 2.	103 R4	
048 #LBLC		104 ST0C	
049 RCL0		105 RCLA	
050 x		106 RCL9	
051 9		107 RCL7	
052 0		108 RCL0	
053 GT02	Pass $\omega L \angle 90$ to LBL 2.	109 CSB9	
054 #LBLE		110 RCL4	
055 RCL0		111 RCL3	
056 x		112 CSB8	

REGISTERS									
0 ω	1 $ u_{11} $	2 $\angle u_{11}$	3 $ u_{12} $	4 $\angle u_{12}$	5 $ u_{21} $	6 $\angle u_{21}$	7 $ u_{22} $	8 $\angle u_{22}$	9 $ Z $
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A $\angle Z$	B $ u_{11 \text{ new}} $	C $\angle u_{11 \text{ new}}$	D $ u_{12 \text{ new}} $	E $\angle u_{12 \text{ new}}$	F	G	H	I	J

113	STOD							
114	R↓							
115	STOE							
116	RTN							
117	*LBL8							
118	→R							
119	R↓							
120	R↓							
121	→R							
122	X↔Y							
123	R↓							
124	+							
125	R↓							
126	+							
127	R↑							
128	+P							
129	RTN							
130	*LBL9							
131	R↓							
132	x							
133	R↓							
134	+							
135	R↑							
136	RTN							
137	*LBL0							
138	x							
139	LSTX							
140	RCL0							
141	x							
142	X↔Y							
143	LSTX							
144	X↔							
145	x							
146	1							
147	-							
148	CHS							
149	÷							
150	9							
151	0							
152	RTN							
153	R/S							

LABELS					FLAGS	SET STATUS			
A f	B Series R	C Series L	D Series C	E Series tank	0	FLAGS		TRIG	DISP
a	b Shunt R	c Shunt L	d Shunt C	e Shunt L-C	1	ON	OFF		
0 Used	1 Used	2 Used	3	4	2	0	☒	DEG ☒	FIX ☐
						1	☐	GRAD ☐	SCI ☐
						2	☐	RAD ☐	ENG ☒
5	6	7 Used	8 CADD	9 CMULT	3	3	☒		n <u>3</u>

Network Transfer Functions—Output

001	*LBL4	21 11	Input Z_L	057	RCL6	36 06	IF flag 0 THEN go to LBL 0 ELSE Display y and x alternately.	
002	STO5	35 09		058	RCL5	36 05		
003	XZY	-41		059	RCL8	36 08		
004	STO4	35 11		060	RCL7	36 07		
005	CLX	-51		061	GSB6	23 06		
006	R/S	51		062	1/X	52		
007	*LBL6	21 12		063	X ²	53		
008	GSB4	23 04		064	RCL0	36 13		
009	RCLB	36 12		065	÷	-24		
010	1/X	52		066	F0?	16 23 00		
011	RCL1	36 46		067	PRTX	-14		
012	CHS	-22		068	RTN	24		
013	GSB9	23 09	069	*LBL5	21 05	Print y and x.		
014	GT05	22 05	070	F0?	16 23 00			
015	*LBL0	21 13	071	GT00	22 00			
016	RCL2	36 02	072	*LBL1	21 01			
017	RCL1	36 01	073	XZY	-41			
018	RCL4	36 04	074	R/S	51			
019	RCL3	36 03	075	GT01	22 01			
020	GSB6	23 06	076	*LBL0	21 00			
021	RCL4	36 11	077	XZY	-41			
022	RCL9	36 09	078	PRTX	-14			
023	R↑	16-31	079	XZY	-41			
024	CHS	-22	080	PRTX	-14			
025	R↑	16-31	081	RTN	24			
026	1/X	52	082	*LBL4	21 04	Compute and store $Z_L \mathbf{q}_{21} + \mathbf{q}_{22}$.		
027	XZY	-41	083	RCL6	36 06			
028	GSB9	23 09	084	RCL5	36 05			
029	GT05	22 05	085	RCL8	36 08			
030	*LBLD	21 14	086	RCL7	36 07			
031	RCL6	36 06	087	GSB6	23 06			
032	RCL5	36 05	088	STOE	35 12			
033	RCL8	36 08	089	R4	-31			
034	RCL7	36 07	090	STO1	35 46			
035	GSB6	23 06	091	RCL2	36 02			
036	1/X	52	092	RCL1	36 01			
037	XZY	-41	093	RCL4	36 04			
038	CHS	-22	094	RCL3	36 03	Compute $Z_L \mathbf{q}_{11} + \mathbf{q}_{12}$.		
039	XZY	-41	095	*LBL6	21 06			
040	CHS	-22	096	STOE	35 15			
041	GT05	22 05	097	R4	-31			
042	*LBL6	21 15	098	STOD	35 14			
043	GSB4	23 04	099	R4	-31			
044	RCLB	36 12	100	RCL9	36 09			
045	1/X	52	101	RCL4	36 11			
046	RCL1	36 46	102	GSB9	23 09			
047	CHS	-22	103	RCLD	36 14			
048	GSB9	23 09	104	RCL6	36 15			
049	+R	44	105	GSB8	23 08			
050	RCL4	36 11	106	RTN	24			
051	RCL5	36 09	107	*LBL0	21 16 13	INPUT: $\angle A$ A $\angle B$ B OUTPUT: $\angle Z_L A + B$ $Z_L A + B$		
052	+R	44	108	RCL2	36 02			
053	XZY	-41	109	RCL1	36 01			
054	R4	-31	110	RCL4	36 04			
055	÷	-24	111	RCL3	36 03			
056	STOC	35 13	112	GSB6	23 06			
REGISTERS							Compute I_2/V_1	
0	1	2	3	4	5			6
	$ q_{11} $	$\angle q_{11}$	$ q_{12} $	$\angle q_{12}$	$ q_{21} $			$\angle q_{21}$
S0	S1	S2	S3	S4	S5			S6
A	$\angle Z_L$	Denom	Used	$\angle B$	B			$\angle Denom$

IF flag 0
THEN go to LBL 0
ELSE
Display y and x
alternately.

Print y and x.

Compute and store
 $Z_L q_{21} + q_{22}$.

Compute $Z_L q_{11} + q_{12}$

INPUT: $\angle A$
|A|
 $\angle B$
|B|

OUTPUT: $\angle Z_L A + B$
| $Z_L A + B$ |

Compute I_2/V_1

113	1/X	52			
114	XZY	-41			
115	CHS	-22			
116	XZY	-41			
117	CHS	-22			
118	GT05	22 05			
119	*LBL#	21 16 14			
120	RCL6	36 06	Compute V_2/I_1		
121	RCL5	36 05			
122	RCL8	36 08			
123	RCL7	36 07			
124	GSB6	23 06			
125	RCL4	36 11			
126	RCL5	36 05			
127	R#	16-31			
128	CHS	-22			
129	R#	16-31			
130	1/X	52			
131	XZY	-41			
132	GSB9	23 09			
133	GT05	22 05			
134	*LBL8	21 08			
135	+R	44	Subroutine to add complex numbers.		
136	R+	-31			
137	R+	-31			
138	+R	44			
139	XZY	-41			
140	R+	-31			
141	+	-55			
142	R+	-31			
143	+	-55			
144	R#	16-31			
145	+P	34			
146	RTN	24			
147	*LBL9	21 09			
148	R+	-31	Subroutine to multiply complex numbers.		
149	x	-35			
150	R+	-31			
151	+	-55			
152	R#	16-31			
153	RTN	24			
154	R/S	51			

LABELS					FLAGS	SET STATUS		
A Z _L	B →Z _{in}	C →V ₂ /V ₁	D →I ₂ /I ₁	E →P ₂ /P ₁	0 PRINT	FLAGS		TRIG
a	b	c →I ₂ /V ₁	d →V ₂ /I ₁	e	1	ON OFF		DISP
0 Print y & x	1	2	3	4 Z ₁₁ + Z ₂₂	2	0 ☐ ☐	DEG ☐	FIX ☐
5 Display	6 Z _L A + B	7	8 CADD	9 CMULT	3	1 ☐ ☐	GRAD ☐	SCI ☐
						2 ☐ ☐	RAD ☐	ENG ☐
						3 ☐ ☐		n <u>3</u>

Reactive L-Network Impedance Matching

001 *LBLA		057 *LBLD							
002 ST01	Store R_L	058 CSB2	Exchange Z_S and Z_L .						
003 R4		059 CSB1	Compute $X_{1(+)}$.						
004 ST02	Store X_L	060 CSB5	Compute X_2 .						
005 R/S	-----	061 CSBE							
006 *LBLB	Store R_S	062 CSB5							
007 ST03		063 +							
008 R4		064 CSB2	Save X_2 in LSTx.						
009 ST04	Store X_S	065 LSTX	Exchange Z_S and Z_L .						
010 R/S	-----	066 RTN	Recover X_2 .						
011 *LBL1	Subroutine to compute	067 *LBLd	Exchange Z_S and Z_L .						
012 RCL2	$X_{1(+)} \text{ and } X_{1(-)}$.	068 CSB2	Compute $X_{1(-)}$.						
013 X*		069 CSB1							
014 RCL1		070 RCL5							
015 X*		071 CSB5							
016 +		072 CSBE							
017 RCL3		073 CSB5	Compute X_2						
018 x		074 +							
019 RCL1		075 CSB2	Save X_2 in LSTx.						
020 RCL3		076 LSTX	Exchange Z_S and Z_L .						
021 -		077 RTN	Recover X_2 .						
022 ÷		078 *LBLB	-----						
023 LSTX		079 ST07	Subroutine to compute						
024 1/X		080 RCL2	X_2 .						
025 RCL3		081 +							
026 x		082 RCL3							
027 RCL2		083 x							
028 x		084 RCL7							
029 X*		085 RCL4							
030 LSTX		086 +							
031 R4		087 RCL1							
032 +		088 x							
033 1/X		089 -							
034 R†		090 RCL1							
035 X*Y		091 ÷							
036 -		092 RTN							
037 ST05		093 *LBL2							
038 LSTX		094 RCL1	Subroutine to exchange						
039 ENT†		095 RCL3	Z_S and Z_L .						
040 +		096 ST01							
041 +		097 X*Y							
042 ST06		098 ST03							
043 RTN		099 RCL2							
044 *LBLC	Compute $X_{1(+)}$	100 RCL4							
045 CSB1		101 ST02							
046 CSB5		102 X*Y							
047 CSBE		103 ST04							
048 CSB5	Compute X_2	104 RTN							
049 RTN	-----	105 *LBL5							
050 *LBLc	Compute $X_{1(-)}$	106 F0?	DISPLAY ROUTINE						
051 CSB1		107 PRTX	IF flag 0						
052 RCL5		108 F0?	THEN PRINT						
053 CSB5		109 RTN							
054 CSBE		110 R/S	ELSE						
055 CSB5	Compute X_2	111 RTN	DISPLAY.						
056 RTN		112 R/S							
REGISTERS									
0	1	2	3	4	5	6	7	8	9
	R_L	X_L	R_S	X_S	$X_{1(-)}$	$X_{1(+)}$	X_1		
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B	C	D	E	F	G	H	I	J

LABELS					FLAGS	SET STATUS		
A $X_L \uparrow R_L$	B $X_S \uparrow R_S$	C 	D 	E	0 PRINT	FLAGS	TRIG	DISP
a	b	c	d	e	1	0 ☒ ON ☐ OFF	DEG ☒	FIX ☒
0	1 X_1	2 $Z_S \uparrow Z_L$	3 X_2	4	2	1 ☐ 	GRAD ☐	SCI ☐
5 Display	6	7	8	9	3	2 ☐ 	RAD ☐	ENG ☐
						3 ☐ 	n <u>2</u>	

Class A Transistor Amplifier Bias Optimization

001	*LBLA			057	STOE				
002	RCL9	Transfer $V_{BE_{max}}$ to secondary register.		058	1				
003	PFS			059	RCL1				
004	STO9			060	X?				
005	PFS			061	-				
006	RCL4			062	2				
007	2			063	$\div$				
008	5			064	RCL1				
009	-	Compute θ_{JA}		065	x				
010	RCL5			066	RCL5			Compute T_{min}	
011	$\div$			067	x				
012	STO5			068	RCL0				
013	RCL0			069	x				
014	X?			070	RCL3				
015	x	Compute R_{L1}		071	+				
016	RCL4			072	GSB3				
017	RCL2			073	CHS				
018	-			074	1				
019	4			075	RCL1			Compute V_{BEN}	
020	.			076	-				
021	4			077	GSB4				
022	x			078	PFS				
023	$\div$			079	RCL9				
024	STOC			080	+				
025	.			081	PFS				
026	1	Compute R_{E1}		082	STO9				
027	x			083	RCL5				
028	STOD			084	X>Y?			IF $V_{BEX} > V_{BEN}$	
029	*LBL0	Begin iterative loop.		085	GT02			THEN reduce R_E to 0	
030	RCL0			086	-			and increment R_L	
031	2			087	RCL1			ELSE	
032	$\div$			088	$\div$			Compute a new value	
033	ENT1			089	RCL1			for R_E .	
034	ENT1			090	$\div$				
035	RCLC			091	RCLD				
036	RCLD			092	X<Y?				
037	+	Compute I_{cq}		093	STOD				
038	$\div$			094	XCH				
039	STO1			095	.				
040	RCL5			096	5				
041	x			097	X<Y?			IF $\Delta R_E \geq .5\%$	
042	x	Compute T_{max}		098	GT00			THEN repeat loop	
043	RCL2			099	F1?			IF flag 1	
044	+			100	GT01			THEN finish problem	
045	RCL4			101	SF1			ELSE repeat loop	
046	X<Y?			102	GT00			once more to print.	
047	X>Y?	IF $T_{max} > T_{jmax}$		103	*LBL1				
048	GT01	THEN increase R_L		104	CF1				
049	GSB3	ELSE compute V_{BEX} .		105	R/S			Stop to accept h_{FE} 's	
050	CHS			106	STOE				
051	RCL1			107	X<Y?			Store h_{FEmin}	
052	1			108	STO4			Store h_{FEmax}	
053	+			109	RCL1				
054	GSB4			110	2				
055	RCL8			111	x				
056	+			112	RCL1				

REGISTERS									
0 V_{CC}	1 ΔI_{cq}	2 $T_{Amax} \cdot R_B$	3 $T_{Amin} \cdot V_{BB}$	4 T_{jmax}	5 P_D, θ_{JA}	6 I_1	7 ΔV_{BE}	8 V_{BEmin}	9 V_{BEN}
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9 V_{BEmax}
A h_{FEmax}	B h_{FEmin}	C R_{Ln}	D R_{En}	E V_{BEX}	F	G	H	I I_{cq}	

Transistor Amplifier Performance

001 #LBLA		057 RCL3							
002 2		058 RCL4							
003 x		059 CSB9							
004 2		060 RCL2							
005 1	Compute storage location.	061 RCL1							
006 -		062 CSB8							
007 ST01		063 ST08							
008 R4	Store h_{ij}	064 XZY							
009 ST0i		065 ST01							
010 ISZ1		066 F1?	IF flag 1						
011 R4		067 CSB5	THEN PRINT or						
012 ST0i	Store θ_{ij}	068 XZY	DISPLAY.						
013 RTN	-----	069 F1?	IF flag 1						
014 #LBLB		070 CSB5	THEN PRINT or						
015 ST07	Store R_L	071 F1?	DISPLAY.						
016 XZY		072 SPC							
017 ST08	Store θ_L	073 RTN							
018 RTN	-----	074 #LBLD	Compute A_{vs}						
019 #LBLb		075 CF1							
020 ST05	Store R_S	076 CSBc	Compute Z_{in} without						
021 XZY		077 SF1	printing.						
022 ST06	Store θ_S	078 RCL6							
023 RTN	-----	079 RCL5							
024 #LBLc	Compute A_i	080 CSB8							
025 CSB7		081 1/X							
026 XZY		082 XZY							
027 CSB5		083 CHS							
028 XZY		084 XZY							
029 CSB5		085 RCL9							
030 SPC		086 RCL4							
031 RTN		087 CSB9							
032 #LBLC	Compute A_v	088 RCL7							
033 CF1		089 RCL8							
034 CSBc	Compute Z_{in} without	090 CSB9							
035 SF1	printing.	091 XZY							
036 1/X		092 CSB5							
037 XZY		093 XZY							
038 CHS		094 CSB5							
039 XZY		095 SPC							
040 RCL7		096 RTN							
041 RCL8		097 #LBL E	Compute Z_{out}						
042 CSB9		098 RCL2							
043 RCL9		099 RCL1							
044 RCL4		100 RCL6							
045 CSB9		101 RCL5							
046 XZY		102 CSB8							
047 CSB5		103 1/X							
048 XZY		104 XZY							
049 CSB5		105 CHS							
050 SPC		106 XZY							
051 RTN		107 RCLB							
052 #LBL e	Compute Z_{in}	108 RCLC							
053 CSB7		109 CSB9							
054 RCL7		110 RCL3							
055 RCL8		111 RCL4							
056 CSB9		112 CSB9							
REGISTERS									
0 $ Z_{in} $	1 $h_{11} = h_i$	2 θ_{11}	3 $h_{12} = h_r$	4 θ_{12}	5 R_S	6 θ_S	7 R_L	8 θ_L	9 $ A_i $
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A $\angle A_i$	B $h_{21} = h_f$	C θ_{21}	D $h_{22} = h_o$	E θ_{22}	F $\angle Z_{in}$				

113	CHS			169	R↓	Subroutine to multiply complex numbers.
114	RCLF			170	×	
115	RCLD			171	R↓	
116	GSBB			172	+	
117	1/X			173	R↑	
118	X↔Y			174	RTH	
119	CHS			175	R↔S	
120	GSBS					
121	X↔Y					
122	GSBS					
123	SPC					Subroutine to compute A_i .
124	RTH					
125	*LBL5					
126	F0?					
127	PRTX					
128	F0?					
129	RTH					
130	R↔S					
131	RTH					
132	*LBL7					Subroutine to add complex numbers.
133	RCLF					
134	RCLD					
135	RCL7					
136	RCLB					
137	GSBB					
138	0					
139	ENT↑					
140	1					
141	GSBB					
142	1/X					Subroutine to multiply complex numbers.
143	X↔Y					
144	CHS					
145	X↔Y					
146	RCLB					
147	CHS					
148	RCLC					
149	GSBB					
150	STO9					
151	X↔Y					
152	STO9					Subroutine to multiply complex numbers.
153	X↔Y					
154	RTH					
155	*LBL8					
156	→P					
157	R↓					
158	R↓					
159	→R					
160	X↔Y					
161	R↓					
162	+					Subroutine to multiply complex numbers.
163	R↓					
164	+					
165	R↑					
166	→P					
167	RTH					
168	*LBL9					

IF flag 0
THEN PRINT
IF flag 0
THEN RETURN
ELSE DISPLAY.

Subroutine to compute A_i .

Subroutine to add complex numbers.

LABELS

FLAGS

SET STATUS

A θ_{ij} th $_{ij}$ t $_{ij}$	B $\theta_{L1} R_L$	C $\rightarrow A_v$	D $\rightarrow A_{vs}$	E $\rightarrow Z_{out}$	0 PRINT	SET STATUS		
a	b $\theta_{s1} R_s$	c $\rightarrow A_i$	d	e $\rightarrow Z_{in}$	1 NO PRINT	FLAGS	TRIG	DISP
0	1	2	3	4	2	0 ON OFF ☒ ☐	DEG ☒	FIX ☐
						1 ☒ ☐	GRAD ☐	SCI ☐
						2 ☐ ☒	RAD ☐	ENG ☒
5 DISPLAY	6	7 A_i	8 CADD	9 CMULT	3	3 ☐ ☒		n <u>3</u>

Transistor Configuration Conversion

001 *LBLA	057 RCLE		
002 2	058 RCLD		
003 X	059 GSB8		$V_{12}' = -(V_{12} + V_{22})$
004 2	060 CMS		
005 1	061 ST03		
006 -	062 XZ04		
007 ST01	063 ST04		
008 R4	064 XZ04		
009 ST01	065 RCLC		
010 ISZ1	066 RCLB		
011 R4	067 GSB8		
012 ST01	068 RCLE		
013 RTN	069 RCLD		
014 *LBLC	070 GSB8		$V_{11}' = -V_{22} + (V_{21}' + V_{12}')$
015 GSB8	071 CMS		$+ V_{11}$
016 *LBL3	072 RCL2		$= V_{11} + V_{12} + V_{21} + V_{22}$
017 RCL1	073 RCL1		
018 RCLD	074 GSB8		
019 ST01	075 ST01		
020 R4	076 R4		
021 ST0D	077 ST02		
022 RCL3	078 RTN		
023 RCLB	079 *LBL4		CE → CC
024 ST03	080 *LBLD		CC → CE
025 R4	081 GSB8		Compute new y-matrix.
026 ST0E	082 GSB7		Transform [y] to [h].
027 RCL2	083 RTN		
028 RCLE	084 *LBLC		CB → CC
029 ST02	085 GSB8		Compute new y-matrix.
030 R4	086 ST03		Transform
031 ST0E	087 *LBL0		Transform [h] to [y]'
032 RCL4	088 GSB7		
033 RCLC	089 RCL2		
034 ST04	090 RCL1		
035 R4	091 RCL4		
036 ST0C	092 RCL3		$V_{12}' = -(V_{11} + V_{12})$
037 GSB7	093 GSB8		
038 RTN	094 CMS		
039 *LBL6	095 ST03		
040 *LBLB	096 R4		
041 GSB8	097 ST04		
042 GSB7	098 RCL2		
043 RTN	099 RCL1		
044 *LBL0	100 RCLC		
045 GSB7	101 RCLB		
046 RCLC	102 GSB8		$V_{21}' = -(V_{11} + V_{21})$
047 RCLB	103 CMS		
048 RCLE	104 ST0E		
049 RCLD	105 XZ04		
050 GSB8	106 ST0C		
051 CMS	107 XZ04		
052 ST0B	108 RCL4		
053 R1	109 RCL3		
054 ST0C	110 GSB8		$V_{22}' = V_{11} + V_{12} + V_{21} + V_{22}$
055 RCL4	111 RCL2		
056 RCL3	112 RCL1		

REGISTERS									
0	1	2	3	4	5	6	7	8	9
	h_{11}	θ_{11}	h_{12}	θ_{12}		$ \Delta $	$\angle \Delta$		
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B	C	D	E	F	G	H	I	J
	h_{21}	θ_{21}	h_{22}	θ_{22}					

113 GSB8		169 ST00	
114 CHS		170 R↓	
115 RCLE		171 ST0E	
116 RCLD		172 RTN	
117 GSB8		173 *LBL9	
118 ST00		174 +R	
119 R↓		175 R↓	
120 ST0E		176 R↓	
121 RTN		177 +R	
122 *LBL7	Subroutine to convert	178 X↔Y	
123 RCL2	$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$	179 R↓	
124 RCL1	into	180 +	
125 RCLD	$\frac{1}{a_{11}} \begin{bmatrix} 1 & -a_{12} \\ a_{21} & \det a \end{bmatrix}$	181 R↓	
126 RCLE		182 +	
127 GSB9		183 R↑	
128 ST06		184 +P	
129 R↓		185 RTN	
130 ST07		186 *LBL9	
131 RCL4		187 R↓	
132 RCL3		188 x	
133 RCLB		189 R↓	
134 RCLC		190 +	
135 GSB9		191 R↑	
136 CHS		192 +R	
137 RCL7	Compute det a	193 +P	
138 RCL6		194 RTN	
139 GSB8		195 *LBL5	
140 ST06		196 RCL2	
141 R↓		197 GSB5	
142 ST07		198 RCL1	
143 RCL2		199 GSB5	
144 CHS		200 RCL4	
145 ST02	$a_{11} \leftarrow \frac{1}{a_{11}}$	201 GSB5	
146 RCL1		202 RCL3	
147 1/X		203 GSB5	
148 ST01		204 RCLC	
149 RCL3		205 GSB5	
150 CHS		206 RCLB	
151 RCL4		207 GSB5	
152 GSB9	$a_{12} \leftarrow \frac{-a_{12}}{a_{11}}$	208 RCLE	
153 ST03		209 GSB5	
154 R↓		210 RCLD	
155 ST04		211 *LBL5	
156 RCL2		212 F0?	
157 RCL1		213 PRTX	
158 RCLB		214 F0?	
159 RCLC		215 RTN	
160 GSB9	$a_{21} \leftarrow \frac{a_{21}}{a_{11}}$	216 R/S	
161 ST08		217 RTN	
162 R↓		218 R/S	
163 ST00			
164 RCL2			
165 RCL1			
166 RCL6	$a_{22} \leftarrow \frac{\det a}{a_{11}}$		
167 RCL7			
168 GSB9			

LABELS				FLAGS		SET STATUS		
A $\theta_{ij} \rightarrow \theta_{ij}$	B CB ← CE	C CB ← CC	D CE ← CC	E PRINT [h]	0 PRINT	FLAGS		
a	b CB → CE	c CB → CC	d CE → CC	e	1	ON OFF		
0 [h] → [y]'	1	2	3	4	2	0 ☐ ☐	DEG ☐	FIX ☐
5 DISPLAY	6	7 [h] ↔ [y]	8 CADD	9 CMULT	3	1 ☐ ☒	GRAD ☐	SCI ☐
						2 ☐ ☒	RAD ☐	ENG ☒
						3 ☐ ☒		n <u>3</u>

Subroutine to add
complex numbers.

Subroutine to multiply
complex numbers.

Print [h]

IF flag 0
THEN PRINT
ELSE DISPLAY.

Parameter Conversion: $S \rightleftharpoons Y, Z, G, H$

001 *LBL0	057 GSB6	075 ST=1	$\xi = Z_0$
002 GSB0	058 RCL0	076 ST=1	$[Z] = Z_0 [T']$
003 R4	059 CT01	077 x	-----
004 ST01	060 *LBL4	078 ST00	$G \rightarrow S$
005 ISZ1	061 ST00	079 RTN	$[T] = \begin{bmatrix} Z_0 & g_{11} & g_{12} \\ g_{21} & & g_{22}/Z_0 \end{bmatrix}$
006 R4	062 ST=1	080 *LBLD	-----
007 ST01	063 1/X	081 ST00	Compute $[T']$
008 RTN	064 RCL0	082 1	$\xi = -1$
009 *LBLA	065 x	083 CHS	-----
010 GSB0	066 ST00	084 *LBL4	$[T] \leftarrow \begin{bmatrix} 1 & 0 \\ 0 & \xi \end{bmatrix} [T]$
011 RCL1	067 GSB6	085 RCLB	-----
012 ISZ1	068 1	086 XZY	$S \rightarrow G$
013 RCL1	069 1	087 x	$\xi = -1$
014 GSB5	070 CHS	088 ST00	$[T] = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [S]$
015 XZY	071 *LBL4	089 RTN	-----
016 *LBL5	072 RCLB	090 *LBLD	Compute $[T']$
017 F00	073 x	091 ST00	$G = \begin{bmatrix} t_{11}' & & \\ Z_0 & & t_{12}' \\ t_{21}' & & Z_0 t_{22}' \end{bmatrix}$
018 PRTX	074 ST00	092 RTN	-----
019 F00	075 LSTX	093 CHS	$H \rightarrow S$
020 RTN	076 RCLD	094 GSB4	$[T] = \begin{bmatrix} h_{11} & & \\ Z_0 & & h_{12} \\ h_{21} & & h_{22} Z_0 \end{bmatrix} [H]$
021 R4	077 x	095 GSB6	-----
022 RTN	078 ST00	096 RCL0	Compute $[T']$
023 *LBL0	079 RTN	097 ST=1	$\xi = -1$
024 2	080 *LBLD	098 RCLD	-----
025 x	081 ST00	099 x	$[T] \leftarrow \begin{bmatrix} \xi & 0 \\ 0 & 1 \end{bmatrix} [T]$
026 2	082 1	100 CHS	-----
027 1	083 CHS	101 *LBL3	$S \rightarrow H$
028 -	084 GSB4	102 ST=1	$\xi = -1$
029 ST01	085 GSB6	103 ST=1	$T = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} [S]$
030 RTN	086 RCL0	104 RTN	-----
031 *LBL6	087 ST=1	105 *LBL5	Compute $[T']$
032 ST00	088 RCLD	106 ST00	$\xi = -1$
033 GSB1	089 x	107 1	-----
034 CT06	090 ST00	108 CHS	$[T] = \begin{bmatrix} \xi & 0 \\ 0 & 1 \end{bmatrix} [T]$
035 *LBLB	091 RTN	109 GSB3	-----
036 ST00	092 *LBL6	110 GSB6	$S \rightarrow Z$
037 GSB6	093 ST00	111 RCL0	$\xi = -1$
038 RCL0	094 ST=1	112 ST=1	$[T] = -[S]$
039 1/X	095 RCLD		-----
040 *LBL1	096 x		
041 GSB3	097 ST00		
042 GSB4	098 GSB6		
043 RTN	099 1		
044 *LBL6	100 CHS		
045 ST00	101 *LBL3		
046 1/X	102 ST=1		
047 GSB1	103 ST=1		
048 GSB6	104 RTN		
049 1	105 *LBL5		
050 CHS	106 ST00		
051 CT01	107 1		
052 *LBLC	108 CHS		
053 ST00	109 GSB3		
054 1	110 GSB6		
055 CHS	111 RCL0		
056 GSB1	112 ST=1		

REGISTERS

0 Z_0	1 M_{11}, T_{11}'	2 $\theta_{11}, \angle T_{11}'$	3 M_{12}, T_{12}'	4 $\theta_{12}, \angle T_{12}'$	5 2/D	6 $\angle 2/D$	7	8	9
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B M_{21}, T_{21}'	C $\theta_{21}, \angle T_{21}'$	D M_{22}, T_{22}'	E $\theta_{22}, \angle T_{22}'$					pointer

113 1/X					169 XZY				
114 RCLD					170 ST04				
115 x					171 RCLC				
116 ST0D					172 RCLB				
117 RTN					173 CMS				
118 *LBL6					174 GSB2				
119 RCL2					175 ST0B				
120 RCL1					176 XZY				
121 GSB7					177 ST0C				
122 ST05					178 RCL1				
123 XZY					179 RCLD				
124 ST06					180 ST01				
125 RCLE					181 XZY				
126 RCLD					182 ST0D				
127 GSB7					183 RCL2				
128 RCL5					184 RCLE				
129 RCL6					185 ST02				
130 GSB9					186 XZY				
131 ST05					187 ST0E				
132 XZY					188 RTN				
133 ST06					189 *LBL5				
134 RCL4					190 RCL5				
135 RCL3					191 RCL6				
136 RCLB					192 GSB9				
137 RCLC					193 0				
138 GSB9					194 ENT↑				
139 CMS					195 1				
140 RCL6					196 CMS				
141 RCL5					197 GT0B				
142 GSB6					198 *LBL7				
143 2					199 0				
144 ÷					200 ENT↑				
145 1/X					201 1				
146 ST05					202 *LBL8				
147 XZY					203 +R				
148 CMS					204 R↓				
149 ST06					205 R↓				
150 RCLE					206 +R				
151 RCLD					207 XZY				
152 GSB7					208 R↓				
153 GSB5					209 +				
154 ST0D					210 R↓				
155 XZY					211 +				
156 ST0E					212 R↑				
157 RCL2					213 +P				
158 RCL1					214 RTN				
159 GSB7					215 *LBL2				
160 GSB5					216 RCL5				
161 ST01					217 RCL6				
162 XZY					218 *LBL9				
163 ST02					219 R↓				
164 RCL4					220 x				
165 RCL3					221 R↓				
166 CMS					222 +				
167 GSB2					223 R↑				
168 ST03					224 RTN				

$$[H] = \begin{bmatrix} t_{11}' Z_0 & t_{12}' \\ t_{21}' & \frac{t_{22}'}{Z_0} \end{bmatrix}$$

Subroutine to compute [T'].

t_{21}'

Rearrange t_{11}' and t_{22}'

Subroutine to multiply by 2/D and add -1 Δ 0.

Subroutine to add 1 Δ 0.

Subroutine to add complex numbers.

Subroutine to multiply by 2/D.

Subroutine to multiply complex numbers.

$\frac{2}{D}$
 t_{11}'
 t_{22}'
 t_{12}'

LABELS					FLAGS	SET STATUS		
A ij→θ _{ij} M _{ij}	B S→Y	C S→Z	D S→G	E S→H	0 PRINT	ON OFF		DISP
a θ _{ij} ↑M _{ij} ↑ij	b Y→S	c Z→S	d G→S	e H→S	1	0 ☐ ☐	DEG ☐	FIX ☐
0 ij→pointer	1 Used	2 Used	3 Used	4 Used	2	1 ☐ ☐	GRAD ☐	SCI ☐
5 DISPLAY	6 T'	7 +1 Δ 0	8 CADD	9 CMULT	3	2 ☐ ☐	RAD ☐	ENG ☐
						3 ☐ ☐		n 3

Fourier Series

001 *LBL0	START	057 9	ELSE						
002 CLRG		058 1/X	DISPLAY 0.111.						
003 P=S		059 RTN	-----						
004 CLRG		060 *LBL0	DISPLAY new k.						
005 RAD		061 R/S	-----						
006 RTN		062 GT00	PRINT POLAR						
007 *LBLA	Nt# freqs	063 *LBLd							
008 2		064 SF1							
009 x		065 RCLB							
010 ST00		066 ST01							
011 XZY		067 GT02							
012 ST00		068 *LBLD	PRINT RECTANGULAR						
013 RTN		069 CF1	-----						
014 *LBLB	J	070 RCLB	BEGIN loop 2.						
015 ST00	Store J	071 ST01							
016 1		072 *LBL2							
017 ST00	INITIALIZE k	073 RCL1							
018 RTN		074 RCLB							
019 *LBLC	Yk	075 -							
020 ST00	Store Yk	076 2							
021 RCLB		077 CHS							
022 ST01	INITIALIZE pointer	078 ÷							
023 *LBL1	BEGIN loop 1.	079 RCLD							
024 CLX		080 +							
025 RCL0		081 FIX							
026 RCL1		082 DSP0							
027 RCLB		083 CSB5							
028 -		084 DSP3							
029 2		085 RCL1							
030 CHS		086 DSZ1							
031 ÷		087 RCL1							
032 RCLD		088 F10	IF print polar						
033 +		089 GT03	THEN GO TO LBL 3						
034 RCLB		090 2	ELSE						
035 ÷		091 RCLB	Prepare to print						
036 x		092 ÷	rectangular.						
037 2		093 x							
038 x		094 XZY							
039 P1		095 LSTX							
040 x		096 x							
041 XZY		097 *LBL4							
042 +R		098 XZY							
043 ST+1		099 CSB5							
044 XZY		100 R1							
045 DSZ1		101 CSB5							
046 ST+1		102 F00							
047 RCLC		103 SPC							
048 ENT1		104 DSZ1							
049 DSZ1	IF pointer ≠ 0	105 GT02	IF pointer ≠ 0						
050 GT01	THEN REPEAT loop 1.	106 RTN	THEN REPEAT loop 2.						
051 1	ELSE INCREMENT k.	107 *LBL3							
052 ST+0		108 XZY	Convert (a, b) to (c, θ)						
053 RCLB		109 +P							
054 RCL0		110 2							
055 XZY?	IF k ≤ N	111 RCLB							
056 GT00	THEN GO TO LBL 0	112 ÷							
REGISTERS									
0 k, t	1 b	2 a	3 b	4 a	5 b	6 a	7 b	8 a	9 b
S0 a	S1 b	S2 a	S3 b	S4 a	S5 b	S6 a	S7 b	S8 a	S9 b
A a	B 2 x # freqs	C Yk	D J	E N	F	G	H	I pointer	

113	x					169	PRTX	THEN PRINT
114	GT04					170	F0?	ELSE DISPLAY
115	*LBL6					171	RTN	
116	CF2					172	R/S	
117	STOP					173	RTN	
118	RCLP					174	R/S	
119	ST01							
120	CLX							
121	*LBL6							
122	RCL1							
123	RCLB							
124	-							
125	2							
126	CHS							
127	÷							
128	RCLD							
129	+							
130	X=0?							
131	SF2							
132	2							
133	x							
134	Pi							
135	x							
136	RCLP							
137	x							
138	RCLP							
139	÷							
140	1							
141	F2?							
142	GSB0							
143	+R							
144	RCL1							
145	x							
146	X2Y							
147	DSZ1							
148	RCL1							
149	x							
150	+							
151	RCLP							
152	÷							
153	2							
154	x							
155	+							
156	DSZ1							
157	GT06							
158	GSB5							
159	F0?							
160	SPC							
161	RTN							
162	*LBL0							
163	CLX							
164	.							
165	5							
166	RTN							
167	*LBL5							
168	F0?							

LABELS					FLAGS	SET STATUS		
A N1#freqs	B J	C Yk	D RECT	E t→f(t)	0 PRINT	FLAGS	TRIG	DISP
a START	0	c	d POLAR	e	1 POLAR	ON OFF		
0 Used	1 Loop	2 Loop	3 →P	4 PRINT	2 Used	0 ☒ ☐	DEG ☐	FIX ☒
5 DISPLAY	6 Loop	7	8	9	3	1 ☐ ☒	GRAD ☐	SCI ☐
						2 ☐ ☒	RAD ☒	ENG ☐
						3 ☐ ☒		n 3

Active Filter Design

001 *LBLA		057 RTN	
002 ST00	Store f_0	058 *LBLD	HIGH PASS
003 RTN	-----	059 RCL3	Display C_1
004 *LBLA		060 CSB5	
005 ST01	Store A	061 RCL0	
006 RTN	-----	062 x	
007 *LBLB		063 2	
008 ST02	Store α	064 x	
009 RTN	-----	065 Pi	
010 *LBLB		066 x	
011 ST03	Store C	067 ST04	
012 RTN	-----	068 RCL2	
013 *LBLC	LOW PASS	069 XZY	
014 RCL2		070 ÷	
015 2		071 2	
016 ÷		072 RCL1	
017 RCL1		073 1/X	
018 ÷		074 +	
019 2		075 ÷	
020 Pi		076 CSB5	Display R_2
021 x		077 RCL3	
022 RCL0		078 CSB5	Display C_3
023 x		079 RCL1	
024 RCL3		080 ÷	
025 x		081 CSB5	Display C_4
026 ST04		082 RCL1	
027 ÷		083 2	
028 ST05		084 x	
029 CSB5	Display R_1	085 1	
030 RCL3		086 +	
031 4		087 RCL2	
032 x		088 ÷	
033 RCL1		089 RCL4	
034 1		090 ÷	
035 +		091 CSB5	Display R_3
036 x		092 RTN	-----
037 RCL2		093 *LBLB	BAND PASS
038 X ²		094 RCL3	
039 ÷		095 RCL0	
040 CSB5		096 x	
041 RCL2	Display C_2	097 2	
042 2		098 x	
043 ÷		099 Pi	
044 RCL1		100 x	
045 1		101 ST04	
046 +		102 RCL1	
047 ÷		103 x	
048 RCL4		104 RCL2	
049 ÷		105 x	
050 CSB5		106 1/X	
051 RCL1	Display R_3	107 CSB5	
052 RCL5		108 2	
053 x		109 RCL2	
054 CSB5	Display = R_4	110 X ²	
055 RCL3		111 ÷	
056 CSB5	Display C_5	112 RCL1	Display R_1
REGISTERS			
0 f_0	1 A	2 α	3 C
4 $2\pi f_0 C$	5 R_{1LP}	6	7
8	9		
S0	S1	S2	S3
S4	S5	S6	S7
S8	S9		
A	B	C	D
E	F	G	H
I	J	K	L

113	-							
114	RCL4							
115	x							
116	RCL2							
117	x							
118	1/X							
119	GSB5	Display R ₂						
120	RCL3							
121	GSB5	Display C ₃						
122	GSB5	Display C ₄						
123	2							
124	RCL2							
125	÷							
126	RCL4							
127	÷							
128	GSB5	Display R ₅						
129	RTN							
130	*LBL5	-----						
131	F0?	DISPLAY ROUTINE						
132	PRTX	IF flag 0						
133	F0?	THEN PRINT						
134	RTN	ELSE						
135	R/S	DISPLAY.						
136	RTN							
137	R/S							

LABELS					FLAGS	SET STATUS		
A	B	C	D	E	0	FLAGS	TRIG	DISP
A	C	LP	HP	BP	PRINT	ON OFF		
f ₀	α	c	d	e	1	0 ☒ ☐	DEG ☒	FIX ☐
0	1	2	3	4	2	1 ☐ ☒	GRAD ☐	SCI ☐
5 DISPLAY	6	7	8	9	3	2 ☐ ☒	RAD ☐	ENG ☒
						3 ☐ ☒		n <u>3</u>

Butterworth or Chebyshev Filter Design

001 #LBL5		057 LN	
002 1		058 XZY	
003 0		059 ÷	
004 ÷		060 STOE	
005 10 ^x	Compute order of	061 #LBL6	Newton's method root
006 2	Butterworth filter.	062 RCL5	finder.
007 x		063 RCL7	
008 1		064 RCL5	
009 -		065 Y ^x	
010 LN		066 STOA	
011 STOB		067 ENT↑	
012 XZY		068 1/X	
013 GSB9		069 +	
014 GSB7		070 RCL6	
015 RCL8		071 -	
016 XZY		072 RCL4	
017 LN		073 ENT↑	
018 ABS		074 1/X	
019 ÷		075 -	
020 1		076 ÷	
021 +		077 RCL7	
022 2		078 LN	
023 ÷		079 ÷	
024 INT		080 2	
025 STOE		081 ÷	
026 RTN		082 -	
027 #LBLA	Store R	083 STOE	
028 STC5		084 LSTY	
029 RTN		085 ABS	
030 #LBLD		086 .	
031 1		087 0	
032 6		088 1	
033 ÷	Compute order of	089 XZY	
034 10 ^x	Chebyshev filter.	090 STOE	
035 1		091 RCL5	
036 -		092 2	
037 4		093 ÷	
038 x		094 1	
039 RCL6		095 +	
040 X ²		096 INT	
041 ÷		097 STOE	
042 2		098 RTN	
043 -		099 #LBL9	
044 STOB		100 2	Subroutine to multiply
045 XZY		101 x	by 2 π .
046 GSB9		102 P1	
047 GSB7		103 2	
048 ENT↑		104 RTN	
049 X ²		105 #LBL7	
050 1		106 STOA	Subroutine to compute
051 -		107 RCLD	normalized frequency.
052 1/X		108 STOI	
053 +		109 GTOI	
054 STOI		110 #LBL4	
055 LN		111 GSB3	Band Elimination.
056 RCL8		112 GTOE	

REGISTERS									
0	1	2	3 Used	4 Ripple, dB	5 R	6 ϵ	7 ω_0	8 BW	9 i
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A ω	B Used	C ω_n	D 1 LP 2 HP	3 BP 4 BE	E n	F counter			

117	*LBL2	High pass.	159	ST07	35	07
114	GSR1		170	RTN	24	
115	*LBL0		171	R-S	51	
116	1/X					
117	CHS					
118	ST05					
119	*LBL1	Low Pass				
120	RCLA					
121	RCL7					
122	-					
123	ST05					
124	*LBL3	Band Pass				
125	RCLA					
126	X ²					
127	RCL7					
128	X ²					
129	-					
130	RCLA					
131	-					
132	RCL8					
133	-					
134	*LBL5					
135	ABS					
136	ST00					
137	RTN					
138	*LBL6					
139	ST04					
140	1					
141	-					
142	-	dB Ripple→ε				
143	10 ²					
144	1					
145	-					
146	1/X					
147	ST06					
148	RTN	High Pass				
149	*LBL6					
150	2					
151	ST08	Band Pass				
152	*LEL0					
153	3					
154	ST01	Band Elimination				
155	*LEL0					
156	4					
157	*LEL1					
158	GSR0					
159	R4					
160	GSR9					
161	ST08					
162	RTN	Low Pass				
163	*LBL8					
164	1					
165	*LEL0					
166	ST00					
167	R4					
168	GSR9					

LABELS					FLAGS	SET STATUS			
A	R	B LP: f ₀	C BE: BWt f ₀	D f ₁ t _a →n	E f ₁ t _a →n	0 PRINT	FLAGS	TRIG	DISP
a		b HP: f ₀	c BP: BWt f ₀	d dB Ripple→ε	e	1	ON OFF	DEG ☒	FIX ☐
0	Used	1	Used	3	Used	2	0 ☐ 80 ☐	GRAD ☐	SCI ☐
5	Used	6	Used	7	Used	3	1 ☐ 80 ☐	RAD ☐	ENG ☒
							2 ☐ 80 ☒		n <u>3</u>

Butterworth or Chebyshev Filter Design

001 #LBL8	BUTTERWORTH	057 RCL8							
002 RCLE		058 ÷							
003 STOI	INITIALIZE counter	059 GSB6							
004 SF1	-----	060 GSB5							
005 #LBL8	BEGIN loop 8.	061 LSTX							
006 RCLE		062 ÷							
007 RCL1	Butterworth equations	063 1/X							
008 -		064 RCL7							
009 1		065 X ²							
010 +		066 ÷							
011 STOI	Store i	067 GSB6							
012 2		068 CMS							
013 x		069 GT00							
014 1		070 #LBL4	Band Elimination						
015 -		071 X ² I							
016 Pi		072 R4							
017 x		073 RCL8							
018 2		074 x							
019 ÷	(2i - 1) π/2n	075 RCL7							
020 RCLE		076 X ²							
021 ÷		077 ÷							
022 SIN		078 GSB6							
023 2		079 GSB5							
024 x	-----	080 LSTX							
025 #LBL9		081 ÷							
026 STOI		082 RCL7							
027 RCL5		083 X ²							
028 1		084 x							
029 CMS		085 1/X							
030 RCL9		086 GSB6							
031 GSB5	DISPLAY i	087 CMS							
032 Y*	R (-1) ⁱ	088 #LBL0							
033 Y*		089 GSB5							
034 x		090 F0?							
035 RCLD	Branch to appropriate	091 SPC							
036 X ² I	routine for frequency	092 F1?							
037 GTOI	transformation.	093 GTOI	IF Butterworth						
038 #LBL1	-----	094 DSZI	THEN REPEAT loop 8						
039 X ² I	Low Pass	095 GTOI	ELSE REPEAT loop 7.						
040 R4		096 RTN							
041 RCL7		097 #LBL1							
042 ÷		098 DSZI							
043 GSB6		099 GTOI							
044 GT00		100 RTN							
045 #LBL2	-----	101 #LBL6	Subroutine to change sign						
046 X ² I	High Pass	102 1	of capacitors.						
047 R4		103 CMS							
048 RCL7		104 RCL9							
049 x		105 Y*							
050 1/X		106 x							
051 GSB6		107 RTN							
052 CMS		108 #LBLD							
053 GT00		109 1	CHEBYSHEV						
054 #LBL3	Band Pass	110 STOI							
055 X ² I		111 CF1							
056 R4		112 RCL4							
REGISTERS									
0	1	2	3	4 Ripple, dB	5 R	6 ε	7 ω ₀	8 BW	9 i
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A G ₁ , G _{i-1}	B a ₁ , a _i	C γ ²	D 1 LP 2 HP	E 3 BP 4 BE	F n	G counter			

113	-4		169	+	
114	0		170	P;	
115	÷		171	x	
116	1		172	2	
117	e ^x		173	÷	
118	LOG		174	RCLE	
119	÷		175	÷	
120	ENT↑		176	SIN	
121	+		177	STOB	
122	e ^y	Chebyshev setup	178	x	
123	1		179	4	
124	X ² Y		180	x	
125	+		181	RCLA	
126	LSTX		182	÷	
127	1		183	RCLC	
128	-		184	RCLE	
129	÷		185	RCLJ	
130	RCLE		186	-	
131	STOI		187	P;	
132	2		188	x	
133	x		189	RCLE	
134	1/X		190	÷	
135	Y ^x		191	SIN	
136	ENT↑		192	X ²	
137	1/X		193	+	
138	-		194	÷	
139	2		195	CTO9	
140	÷		196	*LBL5	
141	X ²		197	FB?	
142	STOC		198	PPTX	
143	P;		199	FB?	
144	2		200	RTN	
145	÷		201	R/S	
146	RCLE		202	RTN	
147	÷		203	R/S	
148	SIN				
149	STOB				
150	2				
151	x				
152	RCLC				
153	FX				
154	÷				
155	CTO9				
156	*LBL7				
157	RCLB				
158	RCLE				
159	RCLJ				
160	-				
161	1				
162	+				
163	STO9				
164	1				
165	-				
166	2				
167	x				
168	1				

DISPLAY ROUTINE
IF flag 0
THEN PRINT

ELSE
DISPLAY.

BEGIN loop 7.

Chebyshev equations

LABELS					FLAGS	SET STATUS		
A	B	C	D	E	PRINT	FLAGS	TRIG	DISP
a	b	c	d	e	1 Butterworth	0 ☒ ON ☐ OFF	DEG ☐	FIX ☐
0 Used	1 Used	2 Used	3 Used	4 Used	2	1 ☐ ☒	GRAD ☐	SCI ☐
5 DISPLAY	6 Used	7 Loop	8 Loop	9 Used	3	2 ☐ ☒	RAD ☒	ENG ☒
						3 ☐ ☒		n <u>3</u>

Code Plot of Butterworth and Chebyshev Filters

001 *LBL0		057 RCL0									
002 1		058 STD1									
003 0	Convert dB ripple to ϵ .	059 GSB7	----- Compute ω_N -----								
004 +		060 *LBL8									
005 10*		061 RAD	BEGIN loop 8.								
006 1		062 GSB6	Compute s_k								
007 -		063 RCL1									
008 1X		064 RCL9									
009 ST06	Store ϵ	065 +									
010 R4		066 RCL2									
011 CF0	Chebyshev	067 +P									
012 ST0E	Store n	068 ST+4	Gain								
013 RTN	-----	069 XZY									
014 *LBLA		070 ST-5	Phase								
015 SF0		071 RCL2									
016 ST0E	Butterworth	072 RCL1									
017 RTN	Store n	073 +P									
018 *LBL6	-----	074 STX4									
019 2	High Pass	075 +P	Gain normalization								
020 GT00	-----	076 RCL9									
021 *LBL0		077 +									
022 3	Band Pass	078 RCL2									
023 GT01	-----	079 +P									
024 *LBL0		080 XZ									
025 4	Band Elimination	081 XZY									
026 *LBL1		082 R4									
027 GSB0	Store filter characteristic	083 +									
028 R4	and ω_0 .	084 ST+3	Time delay								
029 GSB9		085 DSZ1	WHILE counter $\neq 0$								
030 ST08	Store $2\pi \times BW$	086 GT0E	REPEAT loop 8.								
031 RTN	-----	087 RCLA	-----								
032 *LBL6		088 1									
033 1	Low Pass	089 GSB9									
034 *LBL0		090 +									
035 ST00	Store filter characteristic.	091 RCL4	Frequency								
036 R4		092 LOG									
037 GSB9	Multiply by 2π .	093 2									
038 ST07	Store ω_0	094 0									
039 RTN	-----	095 X									
040 *LBLD		096 RND	Gain, dB								
041 ST08	Store Δf	097 RCL5									
042 GSB9		098 1									
043 ST0C	Store $\Delta\omega$	099 +P									
044 R4		100 DEG									
045 GSB9		101 +P									
046 ST08	Store ω_2	102 CLX	Phase, degrees								
047 R4		103 RCL3	Delay								
048 GSB9		104 PRST	Print f, H , θ , t								
049 ST0A	Store ω_1	105 RCL6									
050 RTN	-----	106 RCLA									
051 *LBL0	Initialize registers	107 F10									
052 0		108 GT08	IF flag 1								
053 ST02		109 RCL0	THEN GO TO LBL 0								
054 ST05		110 +	ELSE								
055 1		111 GT03	$\omega \leftarrow \omega + \Delta\omega$								
056 ST04		112 *LBL0									
REGISTERS											
0 Δf	1 $-Im\{s_k\}$	2 $-Re\{s_k\}$	3 delay	4 $-II\{H(\omega)\}$	5 $\Sigma\theta(\omega)$	6 ϵ	7 ω_0	8 BW	9 ω_N		
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9		
A ω_1, ω		B ω_2		C $\Delta\omega$		D 1 LP 2 HP		3 BP 4 BE		E n	I counter

113 RCL0		169 LSTX	
114 X	$\omega \leftarrow \omega \times \Delta f$	170 CHS	
115 *LBL3		171 e ^x	
116 STOA	Store new ω	172 +	
117 X $\leftarrow$ Y?	IF $\omega \leq \omega_3$	173 ENT*	
118 GTOE	THEN REPEAT loop E	174 ENT*	
119 RTN	ELSE stop.	175 LSTX	
120 *LBL7	-----	176 2	
121 RCL0	Subroutine to compute ω_N .	177 x	
122 X $\leftarrow$ Y		178 -	
123 GT01	GO TO case i.	179 STX2	
124 *LBL4	BE	180 RJ	
125 GSB3		181 STX1	
126 GT00		182 2	
127 *LBL2	HP	183 ST+2	
128 GSB1		184 ST+1	
129 *LBL0		185 RTN	
130 1/X		186 *LBL1	
131 CHS		187 RCL1	
132 GT05		188 2	
133 *LBL1	LP	189 Y	
134 X $\leftarrow$ Y		190 1	
135 RCL6		191 -	
136 RCL7		192 RCLE	
137 ÷		193 ÷	
138 GT05		194 GSB9	
139 *LBL3	BP	195 4	
140 X $\leftarrow$ Y		196 +	
141 RCL9		197 1	
142 X ²		198 +P	
143 RCL7		199 ST01	
144 X ²		200 X $\leftarrow$ Y	
145 -		201 ST02	
146 RCL6		202 RTN	
147 ÷		203 *LBL4	
148 RCL9		204 1	
149 ÷		205 F10	
150 *LBL5		206 CLN	
151 ST05	Store ω_N	207 SF1	
152 RTN	-----	208 X $\leftarrow$ 0	
153 *LBL6	Subroutine to compute s_k .	209 CF1	
154 F00	IF Butterworth	210 RTN	
155 GT01	THEN GO TO LBL 1	211 *LBL9	
156 GSB1	ELSE get Butterworth pole	212 2	
157 1	and modify it.	213 x	
158 RCL6		214 Pi	
159 1/X		215 x	
160 +P		216 RTN	
161 X $\leftarrow$ Y		217 R/S	
162 R1			
163 LSTX			
164 +			
165 LN			
166 RCLE			
167 ÷			
168 e ^x			

LABELS					FLAGS		SET STATUS		
A B'WORTH n	B LP: f ₀	C BE: BWtf ₀	D f ₁ f ₂ tΔf	E "PLOT"	0 B'WORTH	FLAGS	TRIG	DISP	
a CHEBn t d BR	b HP: f ₀	c BP: BWtf ₀	d LIN - LOG	e	1 LOG	ON OFF	DEG ☐	FIX ☒	
0 Used	1 Used	2 Used	3 Used	4 Used	2	1 ☒ ☐	GRAD ☐	SCI ☐	
5 Used	6 Used	7 Used	8 Loop	9 Used	3	2 ☐ ☒	RAD ☒	ENG ☐	
						3 ☐ ☒		n <u>3</u>	

Resistive Attenuator Design

001 *LBLA	Store R_{in}	057 x							
002 ST01		058 -							
003 RTN		059 CHS							
004 *LBLB	Store R_{out}	060 ST05							
005 ST02		061 1							
006 RTN		062 RCL4							
007 *LBLC		063 +							
008 RCL1		064 LSTX							
009 RCL2		065 1							
010 ÷		066 -							
011 ENT↑	Compute min loss.	067 ÷							
012 ENT↑		068 RCL2							
013 1		069 x							
014 -		070 RCL7							
015 JX		071 -							
016 XZY		072 ST06							
017 JX		073 GT01							
018 +		074 *LBLD	II calculation						
019 X²		075 RCL3	IF min loss > desired loss						
020 LOG		076 X/Y?	THEN ERROR						
021 1		077 GT09	ELSE						
022 0		078 XZY	Compute R_1, R_2, R_3						
023 x		079 1							
024 GSBS		080 0							
025 ST03		081 ÷							
026 RTN		082 10*							
027 *LBLE	T calculation	083 ST04							
028 RCL3		084 1/X							
029 X/Y?	IF min loss > desired loss	085 RCL1							
030 GT09	THEN ERROR	086 x							
031 XZY	ELSE	087 RCL2							
032 1	Compute R_1, R_2, R_3	088 x							
033 0		089 JX							
034 ÷		090 RCL4							
035 10*		091 1							
036 ST04		092 -							
037 RCL1		093 x							
038 x		094 2							
039 RCL2		095 ÷							
040 x		096 ST07							
041 JX		097 1							
042 2		098 RCL4							
043 x		099 +							
044 RCL4		100 LSTX							
045 1		101 1							
046 -		102 -							
047 ÷		103 ÷							
048 ST07		104 RCL1							
049 1		105 ÷							
050 RCL4		106 RCL7							
051 +		107 1/X							
052 LSTX		108 -							
053 1		109 1/X							
054 -		110 ST05							
055 ÷		111 1							
056 RCL1		112 RCL4							
REGISTERS									
0	1 R_{in}	2 R_{out}	3 min loss	4 N	5 R_1	6 R_2	7 R_3	8	9
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B	C	D	E	F	G	H	I	J

Smith Chart Conversions

001 #LBL0	$\rho \rightarrow R, L$	057 RTN							
002 1/X	-----	058 #LBL7							
003 #LBL0		059 ENT+	Input: $\angle a$						
004 LOG		060 R4	$ a $						
005 2	$\sigma \rightarrow \text{SWR}$	061 R4	k						
006 0		062 +P							
007 x		063 R+	Subroutine to compute						
008 RTN	-----	064 -							
009 #LBL0	R, L $\rightarrow \rho$	065 ST06							
010 CHS		066 R4	$\frac{a \angle a + k \angle 0}{a \angle a - k \angle 0}$						
011 #LBLA	-----	067 R4							
012 2		068 +							
013 0		069 +							
014 +	SWR $\rightarrow \sigma$	070 +P							
015 10Y	-----	071 R+							
016 RTN		072 RCL0							
017 #LBLk		073 +P							
018 1/X	$\sigma \rightarrow \rho$	074 R4							
019 CHS	-----	075 X=Y							
020 #LBL0		076 R+							
021 1		077 +							
022 X=Y		078 R4							
023 +		079 -							
024 1	$\rho \rightarrow \sigma$	080 R+	Output: ang						
025 LSTX		081 RTN	mag						
026 -		082 P/S	-----						
027 +									
028 RTN	-----								
029 #LBLd	Store Z_0								
030 ST01	-----								
031 RTN									
032 #LBLD	$\Gamma \rightarrow Z$								
033 :									
034 GSB7									
035 RCL1									
036 CHS									
037 x									
038 +R									
039 +P									
040 ST09									
041 #LBL0	$Z \rightarrow \Gamma$								
042 RCL1	-----								
043 CHS									
044 GSB7									
045 #LBL9	Print results								
046 X=Y									
047 GSB5									
048 X=Y									
049 GSB5									
050 RTN	-----								
051 #LBL5	Print routine								
052 F0?									
053 PRTX									
054 F0?									
055 RTN									
056 R+S									
REGISTERS									
0	1 Z_0	2	3	4	5	6 Used	7	8	9
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B	C	D	E	F	G	H	I	J

Transmission Line Impedance

001 #LBLA		057 7	
002 ST00	Open two-wire line.	058 6	
003 R4		059 x	
004 ÷		060 RCL0	
005 2		061 JX	
006 x		062 ÷	
007 LN		063 GT05	
008 1		064 #LBLD	Wires in parallel near ground.
009 2		065 ST00	
010 0		066 R4	
011 x		067 ST01	
012 RCL0		068 R4	
013 JX		069 ST02	
014 ÷		070 R4	
015 GT05		071 ST03	
016 #LBLB	Single wire near ground.	072 RCL1	
017 ST00		073 ÷	
018 R4		074 1/X	
019 4		075 2	
020 x		076 x	
021 ÷		077 X2	
022 1/X		078 1	
023 LOG		079 +	
024 1		080 JX	
025 3		081 RCL1	
026 8		082 x	
027 x		083 RCL2	
028 RCL0		084 ÷	
029 JX		085 4	
030 ÷		086 x	
031 GT05		087 LOG	
032 #LBLC		088 6	
033 ST00	Balanced wires near ground.	089 9	
034 R4		090 x	
035 ST01		091 RCL0	
036 R4		092 JX	
037 ST02		093 ÷	
038 R4		094 GT05	
039 ST03		095 #LBL5	Coaxial line
040 RCL1		096 ST00	
041 ÷		097 R4	
042 2		098 ÷	
043 ÷		099 LN	
044 X2		100 6	
045 1		101 0	
046 +		102 x	
047 JX		103 RCL0	
048 1/X		104 JX	
049 2		105 ÷	
050 x		106 #LBL5	DISPLAY ROUTINE
051 RCL3		107 F0?	IF flag 0
052 x		108 PRN	THEN PRINT
053 RCL2		109 RTN	ELSE
054 ÷		110 R/S	DISPLAY.
055 LOG			
056 2			
REGISTERS			
0 e _r	1 h	2 d	3 D
4	5	6	7
8	9		
S0	S1	S2	S3
S4	S5	S6	S7
S8	S9		
A	B	C	D
E	F	G	H
I	J	K	L

--	--	--	--

LABELS					FLAGS	SET STATUS		
A	B	C	D	E	0 PRINT	FLAGS	TRIG	DISP
					1	ON OFF 0 ☒ ☐ 1 ☐ ☒ 2 ☐ ☒ 3 ☐ ☒	DEG ☒ GRAD ☐ RAD ☐	FIX ☒ SCI ☐ ENG ☐ n <u>2</u>
a	b	c	d	e	2			
0	1	2	3	4	3			
5 DISPLAY	6	7	8	9				

Microstrip Transmission Line Calculations

001 *LBL4		057 RCL8							
002 SF1		058 +							
003 ST07	Store h	059 ÷							
004 X=Y		060 2							
005 ST06	Store w	060 P1							
006 SF0		061 x							
007 X/Y	IF w > h	062 X=Y							
008 CF0	THEN clear flag 0	063 ÷							
009 ÷		064 GT02	----- Compute Z ₀ for w ≤ h.						
010 ST09	Store h/w	065 *LBL1							
011 1/X		066 8							
012 ST08	Store w/h	067 RCL8							
013 1		068 ÷							
014 0		069 LSTX							
015 LN		070 4							
016 ST00	Store ln 10	071 ÷							
017 RTN	-----	072 +							
018 *LBL8		073 LN							
019 1		074 *LBL2	-----						
020 X=Y		075 6							
021 +		076 0							
022 LSTX	Compute ε _{eff}	077 x							
023 1		078 ST06	Store Z ₀						
024 -		079 x							
025 1		080 ST01	Store Z _c						
026 0		081 X=Y							
027 RCL8		082 PRTX	Print v _r						
028 ÷		083 X=Y							
029 1		084 PRTX	Print Z _c						
030 +		085 RTN	-----						
031 JX		086 *LBLD	IF uniform assumption						
032 ÷		087 JX	THEN GO TO 1.						
033 +		088 F10							
034 2		089 GT01							
035 ÷		090 *LBL4							
036 JX		091 RCL4							
037 1/X		092 x							
038 ST02	Store v _r	093 RCL7							
039 F00	IF w ≤ h	094 ÷							
040 GT01	THEN GO TO 1.	095 2							
041 1		096 x							
042 RCL9		097 P1							
043 -		098 ÷							
044 6	Compute Z ₀ for w > h	099 ST02	Store partial result.						
045 YX		100 RTN	-----						
046 .		101 *LBL1							
047 4		102 2							
048 4		103 0							
049 RCL8		104 RCL8							
050 ÷		105 ÷							
051 -		106 RCL9							
052 2		107 x							
053 .		108 RCL4							
054 4		109 ÷							
055 2		110 ST04							
056 +		111 R4	-----						
		112 GT04							
REGISTERS									
0 ln 10	1 Z _c	2 v _r	3 α _c	4 A	5 f/10 ⁹	6 w	7 h	8 w/h	9 h/w
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A Z ₀		C		D		E		I	

Transmission Line Calculations

001 #LBLA		057 RCL6							
002 EEX		058 +							
003 1		059 ST04							
004 0		060 RCL6							
005 ÷		061 RCL8							
006 ST09	Store f/10 ¹⁰	062 -							
007 2		063 ST02							
008 P1		064 RCL5							
009 x		065 RCL3							
010 x		066 ÷							
011 ST08	Store ω'	067 STX1							
012 RTN	-----	068 RCL5							
013 #LBLA		069 RCL3							
014 ST01	Store R ₀	070 x							
015 XZY		071 STX7							
016 ST02	Store v _r	072 RTN							
017 RTN	-----	073 #LBLD							
018 #LBLB		074 XZY							
019 ST0A	Store ℓ	075 ST08	Store α _D						
020 2		076 R4							
021 x		077 ST03	Store α _C						
022 3		078 RCL4							
023 RCL2		079 RCL2							
024 x		080 RCL9							
025 ST03	Store 3 v _r	081 P1							
026 ÷		082 x							
027 ST07	Store 2ℓ/3 v _r	083 1							
028 RTN	-----	084 .							
029 #LBLC		085 5							
030 RCL3		086 ÷							
031 x		087 XZY							
032 RCL1		088 ÷							
033 ÷		089 ST06							
034 ST05	Store 3 v _r R/R ₀	090 x							
035 R4		091 2							
036 RCL1		092 x							
037 x		093 ST07							
038 STX3	R ₃ ← 3 v _r R ₀ G	094 RCL8							
039 RCL8		095 1							
040 RCL5		096 0							
041 +P		097 LN							
042 IX		098 2							
043 ST05		099 0							
044 XZY		100 ÷							
045 2		101 RCL6							
046 ÷		102 ÷							
047 ST06		103 STX3							
048 RCL8		104 STX8							
049 RCL3		105 RCL8							
050 +P		106 RCL3							
051 IX		107 -							
052 ST03		108 ENT+							
053 XZY		109 ST05							
054 2		110 RCL8							
055 ÷		111 3							
056 ST08		112 x							
REGISTERS									
0	1 R ₀ , Z ₀	2 v _r	3 Used	4 Used	5 Used	6 Used	7 2ℓ/3 v _r , 2β ₀ ℓ	8 ω', α _D	9 f/10 ¹⁰
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	ℓ	B	C	D	E	F	G	H	I

113	RCL3			169	CHS		
114	+			170	x		
115	x			171	XZY		
116	2			172	CHS		
117	+			173	XZY		
118	CHS			174	+R		
119	1			175	1		
120	+			176	+		
121	+P			177	+P		
122	STX1			178	RCL7		
123	XZY			179	x		
124	ST02			180	1/X		
125	RCL5			181	XZY		
126	X ²			182	RCL8		
127	2			183	-		
128	÷			184	CHS		
129	1			185	XZY		
130	+			186	+R		
131	RCL3			187	1		
132	RCL8			188	-		
133	+			189	+P		
134	+P			190	1/X		
135	STX7			191	2		
136	XZY			192	x		
137	ST04			193	XZY		
138	RTN			194	CHS		
139	*LBL5			195	XZY		
140	ST05			196	+R		
141	XZY			197	1		
142	ST06			198	+		
143	RCL4			199	+P		
144	RCL7			200	RCL1		
145	+R			201	x		
146	CHS			202	XZY		
147	e ^y			203	RCL2		
148	ST07			204	+		
149	XZY			205	GSB5		
150	1			206	XZY		
151	8			207	GSB5		
152	0			208	RTN		
153	x			209	*LBL5		
154	P1			210	F0?		
155	÷			211	PRTX		
156	ST08			212	F0?		
157	RCL6			213	RTN		
158	RCL2			214	R/S		
159	-			215	RTN		
160	RCL5			216	R/S		
161	RCL1						
162	±						
163	+R						
164	1						
165	+						
166	+P						
167	1/X						
168	2						

LABELS					FLAGS	SET STATUS		
A v _r ↑R ₀	B g	C GTR	D α ₀ ↑α _C	E Z _L →Z _m	0 PRINT	FLAGS	TRIG	DISP
a f	b	c	d	e	1	ON OFF		
0	1	2	3	4	2	0 ☐ ☐	DEG ☒	FIX ☐
5 DISPLAY	6	7	8	9	3	1 ☐ ☒	GRAD ☐	SCI ☐
						2 ☐ ☒	RAD ☐	ENG ☒
						3 ☐ ☒		n <u>3</u>

 DISPLAY ROUTINE
 IF flag 0
 THEN PRINT
 ELSE
 DISPLAY.

Unilateral Design: Figure of Merit, Maximum
Unilateral Gain, Gain Circles

001 #LBLA		057 +	
002 2		058 RCLD	
003 x		059 X ²	
004 2		060 CHS	
005 1	Input [S]	061 GSB1	
006 -		062 GSB2	
007 STOI		063 GSB5	Display G ₂ max
008 R1		064 RTN	-----
009 STOI		065 #LBL5	DISPLAY ROUTINE
010 RTN		066 F0?	IF flag 0
011 #LBLF		067 PRTX	THEN PRINT
012 RCL1		068 F0?	
013 RCL3	Compute	069 RTN	ELSE
014 x	u, G _u , G _{min} , G _{max}	070 R/S	DISPLAY.
015 RCLB	G ₀ , G ₁ max, G ₂ max.	071 RTN	-----
016 x		072 #LBL1	Subroutine to compute
017 RCLD		073 1	
018 x		074 +	$\frac{1}{1+x}$
019 1		075 1/X	-----
020 RCL1		076 RTN	Subroutine to re-compute
021 X ²		077 #LBL3	G _u .
022 -		078 RCLB	
023 1		079 X ²	
024 RCLD		080 RCLF	
025 X ²		081 +	
026 -		082 #LBL2	
027 x		083 LOG	Subroutine to convert to
028 STOE		084 1	decibels.
029 +		085 0	
030 STOE	Display u	086 x	-----
031 GSB5		087 RTN	Subroutine to compute
032 GSB3	Display G _u	088 #LBL4	
033 GSB5		089 1	$\frac{1}{(1+x)^2}$
034 RCL7		090 +	-----
035 GSB4		091 X ²	Compute r _{o1} , p _{o1}
036 GSB2		092 1/X	
037 GSB3		093 RTN	-----
038 +		094 #BLC	Compute r _{o2} , p _{o2}
039 GSB5	Display G _{min}	095 1	
040 RCL7		096 STOE	
041 CHS		097 #BLC	
042 GSB4		098 2	
043 GSB2		099 3	
044 GSB3		100 #LBL6	
045 +		101 STOI	
046 GSB5	Display G _{max}	102 X ²	
047 RCLB		103 1	
048 X ²		104 0	
049 GSB2		105 +	
050 GSB5	Display G ₀	106 10 ^x	
051 RCL1		107 STOE	
052 X ²		108 RCL1	
053 CHS		109 x	
054 GSB1		110 LSTX	
055 GSB2		111 X ²	
056 GSB5	Display G ₁ max	112 RCLF	

REGISTERS									
0 Used	1 s ₁₁	2	3 s ₁₂	4	5 G ₁	6 s ₂₁ ² /G _u	7 u	8 r	9 ρ
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B s ₂₁	C	D s ₂₂	E	F	G	H	I	pointer

Bilateral Design: Stability Factor, Maximum Gain, Optimum Matching

001 #LBLA			057 XZY						
002 2			058 ST07						Store $\angle \Delta$
003 x	Compute pointer		059 RCLD						
004 $\frac{2}{1}$			060 RCL1						
005 $\frac{1}{1}$			061 GSB7						
006 -			062 RCL6						
007 ST01			063 X ²						
008 R4			064 1						
009 ST01	Store s _{ij}		065 +						
010 ISZ7			066 RCL1						
011 R4			067 X ²						
012 ST01	Store θ_{ij}		068 -						
013 RTN			069 RCLD						
014 #LBLB	-----		070 X ²						
015 RCL2			071 -						
016 RCLE	Compute K, G _{max}		072 2						
017 +			073 ÷						
018 1			074 RCL3						
019 +R			075 RCLB						
020 RCL1			076 x						
021 RCLD			077 ABS						
022 x			078 ÷						
023 x			079 ST09						
024 XZY			080 GSB5						Display K
025 LSTX			081 ENT1						
026 x			082 x						
027 RCL3			083 LSTX						
028 RCLB			084 XZY						
029 x			085 1						
030 ST09			086 -						
031 CLX			087 1X						
032 RCL4			088 RCL5						
033 RCLC			089 x						
034 +			090 CHS						
035 RCL9			091 +						
036 ST07			092 RCLB						
037 CLX			093 x						
038 1			094 RCL3						
039 +R			095 ÷						
040 ST06			096 ABS						
041 R4			097 LOC						
042 RCL7			098 1						
043 x			099 0						
044 LSTX			100 x						
045 STx6			101 GSB5						Display G _{max}
046 CLX			102 RTN						-----
047 RCL6			103 #LBLC						Compute Γ_{ms}
048 R4			104 RCL7						
049 -			105 RCL6						
050 R4			106 RCLD						
051 +			107 RCLE						
052 CHS			108 CHS						
053 R4			109 GSB9						
054 XZY			110 CHS						
055 +P			111 RCL2						
056 ST06	Store $\angle \Delta$		112 RCL1						
REGISTERS									
0 C	1 s ₁₁	2 θ_{11}	3 s ₁₂	4 θ_{12}	5 sgn	6 Used	7 Used	8 Used	9 Used
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
A	B s ₂₁	C θ_{21}	D s ₂₂	E θ_{22}	I pointer				

113 GSB0		169 X=0?	
114 ST00		170 1	
115 XZY		171 ABS	
116 ST0A		172 LSTX	
117 RCLD		173 +	
118 RCL1		174 ST05	
119 GSB7		175 RTN	
120 CTO1		176 #LBL8	
121 #LBLC	Compute Γ_{ml}	177 +R	
122 RCL7		178 R4	
123 RCL6		179 R4	
124 RCL1		180 +R	
125 RCL2		181 XZY	
126 CHS		182 R4	
127 GSB9		183 +	
128 CHS		184 R4	
129 RCL5		185 +	
130 RCLD		186 R4	
131 GSB8		187 +P	
132 ST00		188 RTN	
133 XZY		189 #LBL9	
134 ST0A		190 R4	
135 RCL1		191 x	
136 RCLD		192 R4	
137 GSB7		193 +	
138 #LBL1		194 R4	
139 RCL8		195 RTN	
140 RCL0		196 #LBL5	
141 =		197 F0?	
142 2		198 PRTX	
143 +		199 F0?	
144 ENT4		200 RTN	
145 X2		201 R/S	
146 1		202 RTN	
147 -		203 R/S	
148 TX			
149 RCL5			
150 x			
151 -			
152 RCL4			
153 CHS			
154 GSB5	Display $\angle I'$		
155 XZY	Display (I')		
156 GSB5			
157 RTN			
158 #LBL7			
159 X2			
160 XZY			
161 X2			
162 -			
163 1			
164 +			
165 RCL6	Compute $\text{sgn}(B)$.		
166 X2			
167 -			
168 ST08			

LABELS					FLAGS	SET STATUS		
A $\theta_{ij} t_{ij} t_{ij}$	B $\rightarrow K, G_{max}$	C $\rightarrow \Gamma_{ml}$	D	E	0 PRINT	FLAGS	TRIG	DISP
a	b	c $\rightarrow \Gamma_{ms}$	d	e	1	ON OFF		
						0 ☒ ☐	DEG ☒	FIX ☐
	1 Used	2	3	4	2	1 ☐ ☒	GRAD ☐	SCI ☐
5 DISPLAY	6	7 Used	8 CADD	9 CMULT	3	2 ☐ ☒	RAD ☐	ENG ☒
						3 ☐ ☒		n <u>3</u>

Bilateral Design: Gain and Stability Circles, Load and Source Mapping

001 #LBLA		057 x	
002 1		058 1	
003 0		059 +	
004 ÷		060 ÷	Display ρ
005 10 ²		061 #LBL5	-----
006 RCLB		062 F00	DISPLAY ROUTINE
007 X ²		063 PRTX	IF flag 0
008 ÷		064 F00	THEN PRINT
009 ST01	Store G_p	065 RTN	ELSE
010 RCL7		066 R/S	DISPLAY.
011 RCL6		067 RTN	-----
012 RCL1		068 #LBLC	
013 CHS		069 ST01	Store pointer
014 RCL2		070 GT01	
015 CHS		071 #LBL1	Compute input stability
016 GSB9		072 RCL1	circles.
017 RCL1		073 CHS	
018 RCLD		074 RCLD	
019 GSB8		075 RCL6	
020 ST00		076 RCL7	
021 X ² Y		077 GSB9	
022 CHS		078 CHS	
023 GSB5	Display L_r	079 RCL2	
024 RCLD		080 RCL1	
025 X ²		081 GSB8	
026 RCL6		082 X ² Y	
027 X ²		083 CHS	Display L_{r1}
028 -		084 GSB5	
029 ST0A		085 X ² Y	
030 RCL1		086 RCL1	
031 x		087 X ²	
032 LSTX		088 RCL6	
033 X ² Y		089 X ²	
034 1		090 -	
035 +		091 ÷	
036 ÷		092 GSB5	Display $ r_{s1} $
037 RCL0		093 GT03	-----
038 x		094 #LBL2	Compute output stability
039 GSB5	Display r	095 RCL2	circles.
040 RCL1		096 CHS	
041 RCL3		097 RCL1	
042 x		098 RCL6	
043 RCLB		099 RCL7	
044 x		100 GSB9	
045 ENT+		101 CHS	
046 ENT?		102 RCL1	
047 RCL9		103 RCLD	
048 ENT?		104 GSB8	
049 +		105 X ² Y	
050 -		106 CHS	
051 x		107 GSB5	Display L_{r2}
052 1		108 X ² Y	
053 +		109 RCLD	
054 FX		110 X ²	
055 RCL7		111 RCL6	
056 RCL4		112 X ²	
REGISTERS			
0 C ₂	1 s ₁₁	2 θ_{11}	3 s ₁₂
4 θ_{12}	5 sgn(B)	6 A	7 Δ
8 B	9 K		
S0	S1	S2	S3
S4	S5	S6	S7
S8	S9		
A D ₂	B s ₂₁	C θ_{21}	D s ₂₂
E θ_{22}	I G _p		

113	-			169	RCLB		
114	÷			170	RCLC		
115	GSB5	Display $ r_{s2} $		171	GSB9		
116	*LBL3			172	RTN		
117	LSTX			173	*LBL8		
118	1/X			174	→R		
119	RCL3			175	R↓		
120	x			176	R↓		
121	RCLB			177	→R		
122	x			178	X↔Y		
123	GSB5	Display ρ_{ij}		179	R↓		
124	RTN			180	+		
125	*LBLB	$\Gamma_L \rightarrow \Gamma_{ms}$		181	R↓		
126	1/X			182	+		
127	X↔Y			183	R↑		
128	CMS			184	→P		
129	X↔Y			185	RTN		
130	RCLC			186	*LBL9		
131	RCLD			187	R↓		
132	GSB7			188	x		
133	RCL2			189	R↓		
134	RCL1			190	+		
135	GSB8			191	R↑		
136	X↔Y			192	RTN		
137	CMS			193	R/S		
138	GSB5						
139	X↔Y						
140	GSB5						
141	RTN						
142	*LBL6	$\Gamma_s \rightarrow \Gamma_{ml}$					
143	1/X						
144	X↔Y						
145	CMS						
146	X↔Y						
147	RCL2						
148	RCL1						
149	GSB7						
150	RCLC						
151	RCLD						
152	GSB8						
153	X↔Y						
154	CMS						
155	GSB5						
156	X↔Y						
157	GSB5						
158	RTN						
159	*LBL7	Subroutine to compute					
160	CMS						
161	GSB8						
162	1/X	$\frac{s_{12} s_{21}}{1 - s_{ij}}$					
163	X↔Y						
164	CMS						
165	X↔Y						
166	RCL3						
167	RCL4						
168	GSB9						

LABELS					FLAGS	SET STATUS		
A $G_D \rightarrow Lr, r, \rho$	B $\Gamma_L \rightarrow \Gamma_{ms}$	C $i \rightarrow Lr, r, \rho$	D	E	0 PRINT	FLAGS	TRIG	DISP
a	b $\Gamma_s \rightarrow \Gamma_{ml}$	c	d	e	1	ON OFF	DEG ☒	FIX ☐
0	1 Used	2 Used	3	4 Used	2	1 ☐ ☒	GRAD ☐	SCI ☐
5 DISPLAY	6	7 Used	8 CADD	9 CMULT	3	2 ☐ ☒	RAD ☐	ENG ☒
						3 ☐ ☒		n <u>3</u>

Appendix A

MAGNETIC CARD

SYMBOLS AND CONVENTIONS

SYMBOL OR CONVENTION	INDICATED MEANING
White mnemonic: x A	White mnemonics are associated with the user-definable key they are above when the card is inserted in the calculator's window slot. In this case the value of x could be input by keying it in and pressing A.
Gold mnemonic: y x f E x ↑ y A	Gold mnemonics are similar to white mnemonics except that the gold f key must be pressed before the user-definable key. In this case y could be input by pressing f E. ↑ is the symbol for ENTER. In this case ENTER is used to separate the input variables x and y. To input both x and y you would key in x, press ENTER, key in y and press A.
X A	The box around the variable x indicates input by pressing STO A.
(x) A	Parentheses indicate an option. In this case, x is not a required input but could be input in special cases.
→ x A	→ is the symbol for calculate. This indicates that you may calculate x by pressing key A.
→ x, y, z A	This indicates that x, y, and z are calculated by pressing A once. The values would be printed in x, y, z order.
→ x; y; z A	The semi-colons indicate that after x has been calculated using A, y and z may be calculated by pressing R/S.
→ "x", y A	The quote marks indicate that the x value will be "paused" or held in the display for one second. The pause will be followed by the display of y.
↔ x A	The two-way arrow ↔ indicates that x may be either output or input when the associated user-definable key is pressed. If numeric keys have been pressed between user-definable keys, x is stored. If numeric keys have not been pressed, the program will calculate x.

SYMBOLS AND CONVENTIONS (Continued)

SYMBOL OR CONVENTION	INDICATED MEANING
P? A	The question mark indicates that this is a mode setting, while the mnemonic indicates the type of mode being set. In this case a print mode is controlled. Mode settings typically have a 1.00 or 0.00 indicator displayed after they are executed. If 1.00 is displayed, the mode is on. If 0.00 is displayed, it is off.
START A	The word START is an example of a command. The start function should be performed to begin or start a program. It is included when initialization is necessary.
DEL A	This special command indicates that the last value or set of values input may be deleted by pressing A.
→ x; ... A	Three dots (...) indicate that additional output follows. See User Instructions for complete description of variables output.

Notes



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A ● C D E

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