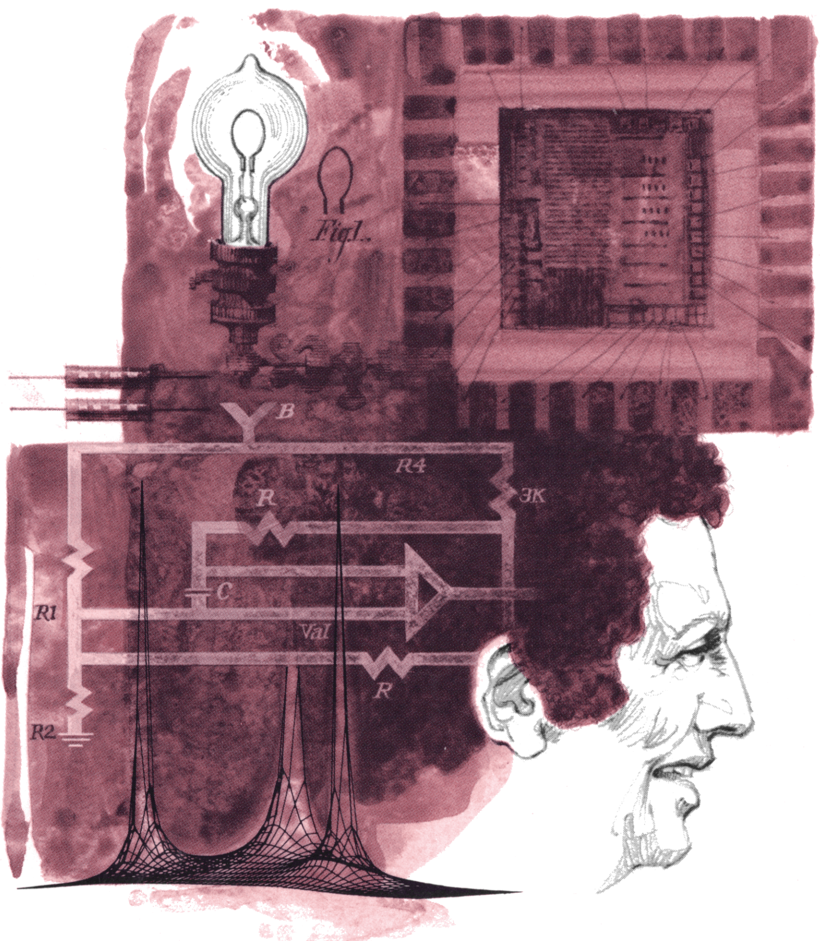
HEWLETT-PACKARD

HP-67/HP-97

E.E. Pac I



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HEWLETT hp PACKARD

WE NEED YOUR HELP

To provide better calculator support for people like you, we need your help. Your timely inputs will enable us to provide high quality software in the future and improve the existing application pacs for your calculator. Your early reply will be extremely helpful in this effort.

1. Pac name ______________________________

2. How important was the availability of this pac in making your decision to buy a Hewlett-Packard calculator? ☐ Would not buy without it. ☐ Important ☐ Not important

3. Did you buy this pac and your calculator at the same time? ☐ Yes ☐ No

4. In deciding to buy this application pac, which three programs seemed most useful to you? Program numbers 1.______ 2.______ 3.______

5. Which three programs in this application pac seemed least useful to you? Program numbers 1.______ 2.______ 3.______

6. What program(s) would you add to this pac?

____

____

____

7. In the list below and "please" select up to three application areas for which you purchased this pac. Please indicate the order of importance by 1, 2, 3 (1 represents the most important area).

Engineering
- ___ 01 Chemical
- ___ 02 Civil/Structural
- ___ 03 Electrical/Electronic
- ___ 04 Industrial
- ___ 05 Mechanical
- ___ 06 Surveying
- ___ 10 Other (Specify) ______

Science
- ___ 31 Biology
- ___ 32 Chemistry
- ___ 33 Earth Sciences
- ___ 34 Mathematics
- ___ 35 Medical Sciences
- ___ 36 Physics
- ___ 37 Statistics
- ___ 39 Other (Specify) ______

Business
- ___ 51 Accounting
- ___ 52 Banking
- ___ 53 Insurance
- ___ 54 Investment Analysis
- ___ 55 Real Estate
- ___ 56 Securities
- ___ 57 Sales
- ___ 58 Marketing
- ___ 59 Other (Specify) ______

Other
- ___ 71 Architecture
- ___ 72 Aviation
- ___ 73 Computer Science
- ___ 74 Education
- ___ 75 Navigation
- ___ 79 Other (Specify) ______

Thank you for your time and cooperation.

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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 keystrokes 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.

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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 up to two 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.

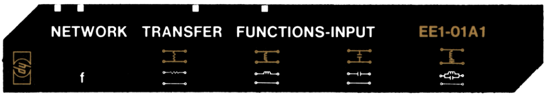
Every program with this feature has flag 0 "set", initially. Thus, the user who is content to have his data output by PRINT/PAUSE simply loads the program and begins execution. The user who desires that the machine stop to display each result must press [CLF] [0] (CLEAR FLAG 0) after loading the program.

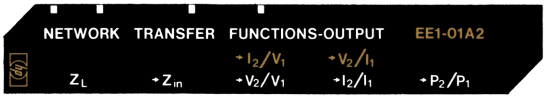
The HP-97 users may also want to keep a permanent record of the values input to a certain program. A convenient way to do this is to set the Print Mode switch to NORMAL before running the program. In this mode, all input values and their corresponding user-definable keys will be listed on the printer,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

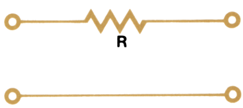
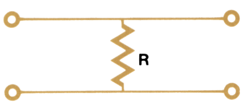
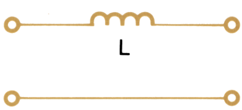
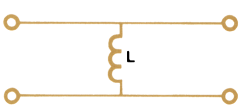
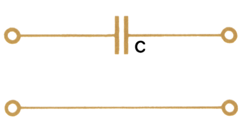
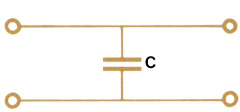
NETWORK TRANSFER FUNCTIONS





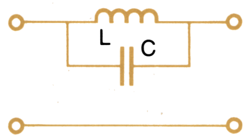
This program computes various transfer functions of a ladder network composed of any number of standard elements. The ladder is built up one element at a time by selecting shunt or series elements from the following menu.

MENU OF CIRCUIT ELEMENTS

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

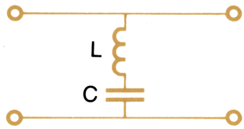
* ч is the Cyrillic letter "cha".

Series tank



$$\text{ч} = \begin{bmatrix} 1\angle 0 & \dfrac{\omega L}{1-\omega^2 LC}\angle 90 \\ 0 & 1\angle 0 \end{bmatrix}$$

Shunt L-C



$$\text{ч} = \begin{bmatrix} 1\angle 0 & 0 \\ \dfrac{\omega C}{1-\omega^2 LC}\angle 90 & 1\angle 0 \end{bmatrix}$$

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

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \text{ч}_{11} & \text{ч}_{12} \\ \text{ч}_{21} & \text{ч}_{22} \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

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

$$Z_{in} = \frac{\text{ч}_{11} Z_L + \text{ч}_{12}}{\text{ч}_{21} Z_L + \text{ч}_{22}}$$

Power Gain

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

Voltage transfer ratio

$$\frac{V_2}{V_1} = \frac{Z_L}{\text{ч}_{11} Z_L + \text{ч}_{12}}$$

Forward transfer admittance

$$\frac{I_2}{V_1} = \frac{-1}{\text{ч}_{11} Z_L + \text{ч}_{12}}$$

Current transfer ratio

$$\frac{I_2}{I_1} = \frac{-1}{\text{ч}_{21} Z_L + \text{ч}_{22}}$$

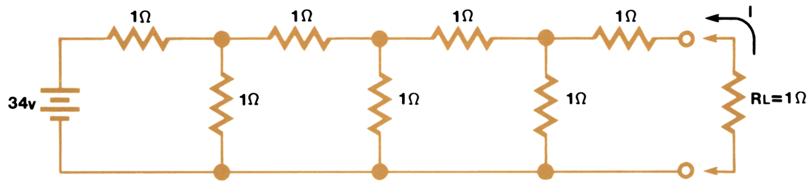
Forward transfer impedance

$$\frac{V_2}{I_1} = \frac{Z_L}{\text{ч}_{21} Z_L + \text{ч}_{22}}$$

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] →	0.000 00

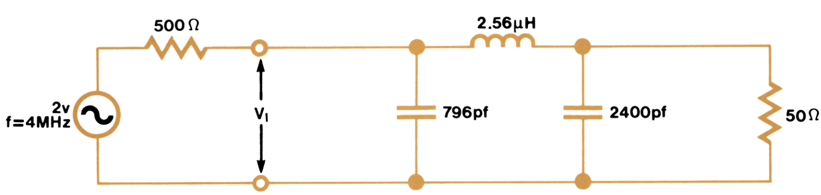
Note:

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] →	0.000 00
Load card EE1-01A2	
0 [ENTER↑] 1 [A] [f] [C] →	0.000+00 *** Angle of transfer admittance
	−29.41−03 *** Magnitude of transfer admittance
34 [×] →	-1.000+00 Current in load resistor
[B] →	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.

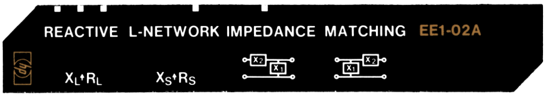
Keystrokes:	Outputs:
Load EE1-01A1	
4 EEX 6 A 2400 EEX CHS	
12 f D 2.56 EEX CHS 6 C	
796 EEX CHS 12 f D →	0.000 00
Load EE1-01A2	
0 ENTER↑ 50 A B →	984.0−03 *** Angle of input impedance
	497.7 00 *** Magnitude of input impedance

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

Keystrokes:	Outputs:
Load EE1-01A1	
4 EEX 6 A 500 B →	0.000 00
Load EE1-01A2	
.984 ENTER↑ 497.7 A C →	493.1−03 *** Angle of voltage ratio
	498.9−03 ***
2 × →	997.7−03 Magnitude of V_1

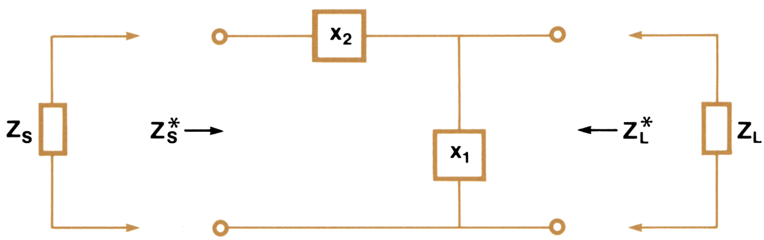
Notes

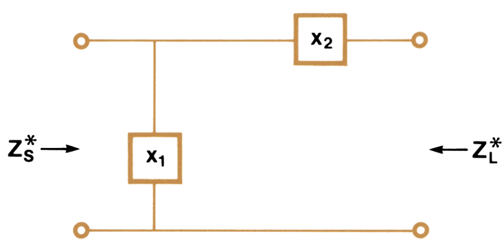
2. REACTIVE L-NETWORK IMPEDANCE MATCHING



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:

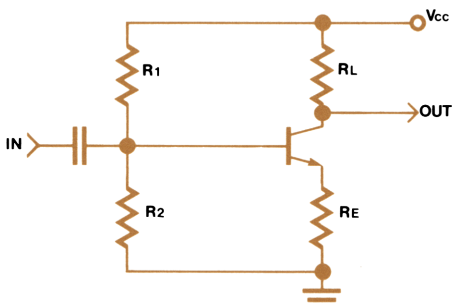
What reactive L-networks could be used to match $Z_L = 50 + j50$ to $Z_S = 25 + j50$?

Keystrokes:	**Outputs:**
50 ENTER↑ 50 A 50 ENTER↑	
25 B f C →	−36.60 *** X_1
	−6.70 *** X_2
C →	136.60 *** X_1
	−93.30 *** X_2
f D →	−161.24 *** X_1
	−111.24 *** X_2
D →	−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:

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

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}).

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

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

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

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

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_{Cmax}, T_{min}, and I_{Cmin} are displayed.

Then values for

h_{FEmax} = maximum worst-case current gain at T_{max} or T_{min} and I_{Cmax} or I_{Cmin}

and

h_{FEmin} = minimum worst-case current gain at T_{max} or T_{min} and I_{Cmax} or I_{Cmin}

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:

$$R_B = \frac{h_{FEmax}\, h_{FEmin} \left[R_{E(n+1)}\,(I_{Cmax} - I_{Cmin}) + V_{BEX} - V_{BEN}\right]}{h_{FEmax}\, I_{Cmin} - h_{FEmin}\, I_{Cmax}}$$

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

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:

$$A_P = \frac{R_B\, R_L\, h_{FEmin}}{R_E\,(R_B + h_{FEmin}\, R_E)}$$

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

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}, °C	STO 2	
	Minimum ambient			
	temperature	T_{Amin}, °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 ±20%.

From the transistor's data sheet, determine:

T_{Jmax} = 150°C
P_D = 0.36 W
ΔV_{BE} = 0.10 v from 3 to 30 mA
V_{BE1min} = 0.52 v at 3 mA at 25°C
V_{BE1max} = 0.72 v at 3 mA at 25°C
I_1 = 0.001 A

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 →	148.0+00 *** T_{max}
	18.0–03 *** I_{Cmax}
	74.8+00 *** T_{min}
	12.0–03 *** I_{Cmin}

From the transistor's data sheet determine:

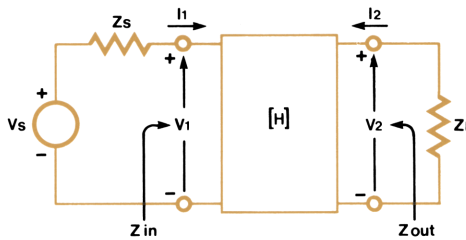
h_{FEmax} = 600 at 150°C at 18 mA
h_{FEmin} = 100 at 80°C at 12 mA

Finish problem

Keystrokes:	**Outputs:**		
600 ENTER↑ 100 R/S →	45.0+03	T	R_1
	4.18+03	Z	R_2
	888.+00	Y	R_L
	115.+00	X	R_E
	22.9+00	***	A_P

4. TRANSISTOR AMPLIFIER PERFORMANCE

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:

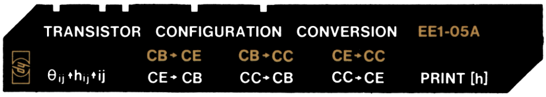
What are the small-signal properties of a transistor which has the following h-parameter matrix and has source and load impedances of 1000 and 10,000 ohms, respectively?

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

Keystrokes:	Outputs:
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 →	0.000+00 *** $\angle A_v$
	-400.0+00 *** $\lvert A_v \rvert$
f C →	0.000+00 *** $\angle A_i$
	-40.00+00 *** $\lvert A_i \rvert$
D →	0.000+00 *** $\angle A_{vS}$
	-200.0+00 *** $\lvert A_{vS} \rvert$
f E →	0.000+00 *** $\angle Z_{in}$
	1.000+03 *** $\lvert Z_{in} \rvert$
E →	0.000+00 *** $\angle Z_{out}$
	52.50+03 *** $\lvert Z_{out} \rvert$

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

$y'_{11} = y_{11} + y_{12} + y_{21} + y_{22}$

$y'_{12} = -(y_{12} + y_{22})$

$y'_{21} = -(y_{21} + y_{22})$

$y'_{22} = y_{11}$

CC → CB

$y'_{11} = y_{22}$

$y'_{12} = -(y_{21} + y_{22})$

$y'_{21} = -(y_{12} + y_{22})$

$y'_{22} = y_{11} + y_{12} + y_{21} + y_{22}$

CC → CE or CE → CC

$y'_{11} = y_{11}$

$y'_{12} = -(y_{11} + y_{12})$

$y'_{21} = -(y_{11} + y_{21})$

$y'_{22} = y_{11} + y_{12} + y_{21} + y_{22}$

CB → CC

$y'_{11} = y_{11} + y_{12} + y_{21} + y_{22}$

$y'_{12} = -(y_{11} + y_{21})$

$y'_{21} = -(y_{11} + y_{12})$

$y'_{22} = y_{11}$

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:

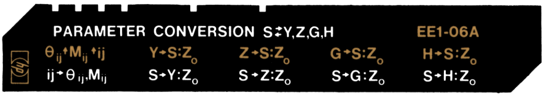
30 ENTER↑ 1000 ENTER↑ 11 A
45 CHS ENTER↑ 100 EEX CHS
6 ENTER↑ 12 A 30 ENTER↑ 60
ENTER↑ 21 A 0 ENTER↑ 30 EEX
CHS 6 ENTER↑ 22 A C E →

Outputs:

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

Notes

6. PARAMETER CONVERSION



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

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

and those performed when converting to S are

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

The postconditioning operations performed when converting from S are

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

and those performed when converting to S are

Y → S	Z → S	G → S	H → 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:	**Outputs:**
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 →	−53.88 *** θ_{11}
	119.1 *** h_{11}
12 A →	39.26 *** θ_{12}
	18.14−03 *** h_{12}
21 A →	94.26 *** θ_{21}
	−14.19 *** h_{21}
22 A →	21.17 *** θ_{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.

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

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

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

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

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

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

$$T = \text{period of } f(t)$$

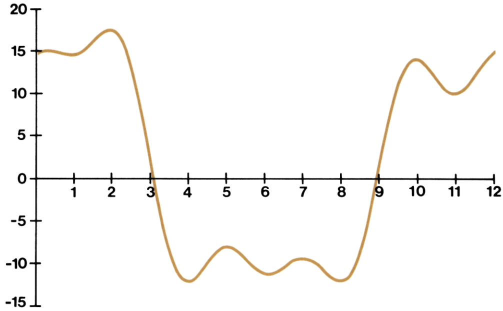
This program computes the Fourier coefficients from discrete versions of the above formulas given a large enough number of samples of the periodic function. Up to ten consecutive pairs of coefficients may be computed at one time from N equally spaced points. The coefficients may be displayed in either 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			
	$J \leqslant i \leqslant J + \#freqs$			
	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:	Outputs:
f A 12 ENTER↑ 7 A 0 B →	1.000
14.758 C →	2.000
17.732 C →	3.000
2 C →	4.000
12 CHS C →	5.000
7.758 CHS C →	6.000
11 CHS C →	7.000
9.026 CHS C →	8.000
12 CHS C →	9.000
2 C →	10.000
14.268 C →	11.000
10.026 C →	12.000

15 **C** ⟶ 0.111

D ⟶ 0. *** i

0.000 *** b_i

4.000 *** 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:

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

Low pass filter

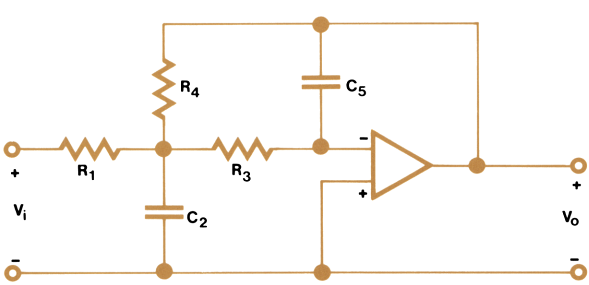
$$C_5 = C$$

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

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

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

$$R_4 = AR_1$$



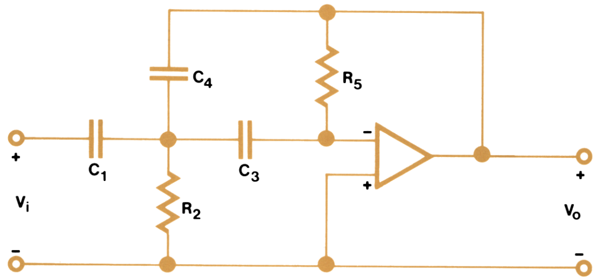
High pass filter

$$C_1 = C_3 = C$$

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

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

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



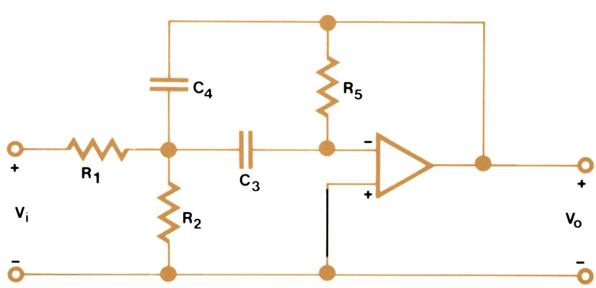
Bandpass filter

$$C_3 = C_4 = C$$

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

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

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



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 character-			
	istic 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:

$f_0 = 10$ Hz

$A = 10$

$\alpha = 1$

$C = 1\ \mu F$

Keystrokes:	**Outputs:**
10 [f] [A] 10 [A] 1 [f] [B] 1	
[EEX] [CHS] 6 [B] [D] →	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

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

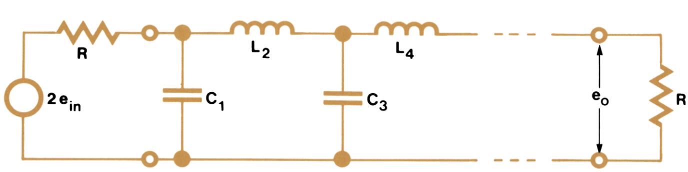
Band Pass

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

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

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

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

where

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

CHEBYSHEV

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

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

where

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

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

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

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

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

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

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

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

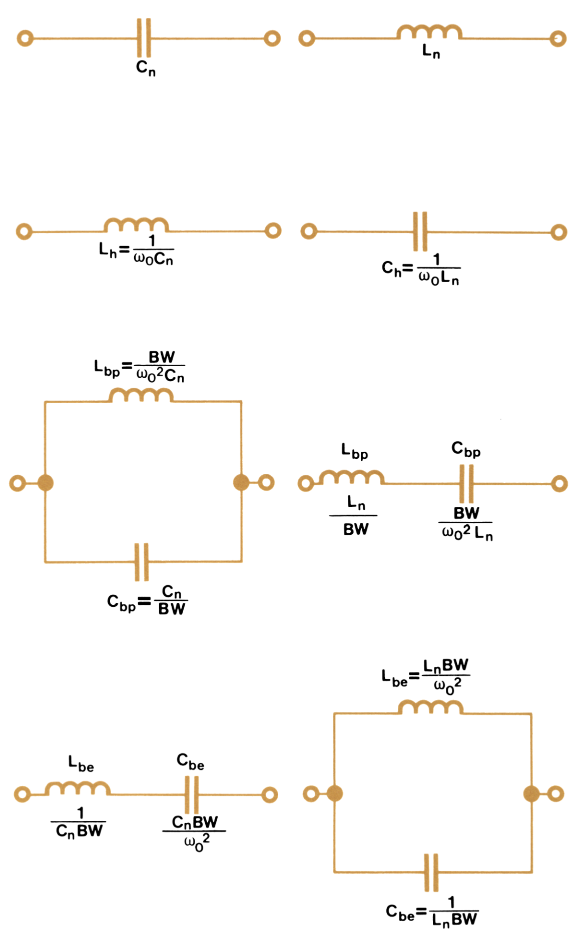
as an initial guess.

The resulting value is then increased slightly:

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

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.

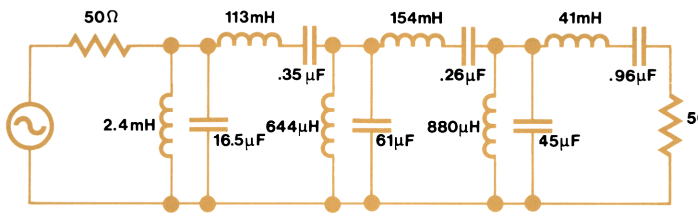
Note:

The program will give erroneous results if asked to compute filter order when ΔdB is small (i.e.: when ΔdB $\sim$ Loss (ω_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:	**Outputs:**
Load card 1 (EE1-09A1)	
50 A 100 ENTER↑ 800	
f C 900 ENTER↑ 30 E →	6.000+00 *** filter order
Load card 2 (EE1-09A2)	
E →	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.

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

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

$$H(j\omega) = \frac{K}{(j\omega - s_1)(j\omega - s_2)\ldots(j\omega - s_n)}$$

$$= \frac{K}{(M_1 \angle \theta_1)(M_2 \angle \theta_2)\ldots(M_n \angle \theta_n)}$$

$$= \frac{K}{M(\omega) \angle \theta(\omega)}$$

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

$$\arg [H(j\omega)] = -\theta(\omega) = -\sum_{i=1}^{n} \tan^{-1} \frac{\omega - \omega_i}{-\sigma_1}$$

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			20log|H(jω)|,dB
	Angle of transfer function			arg{H(jω)}
	Normalized group delay			t_g
7	Step 6 is repeated auto-			
	matically for the band			
	specified.			

Example 1:

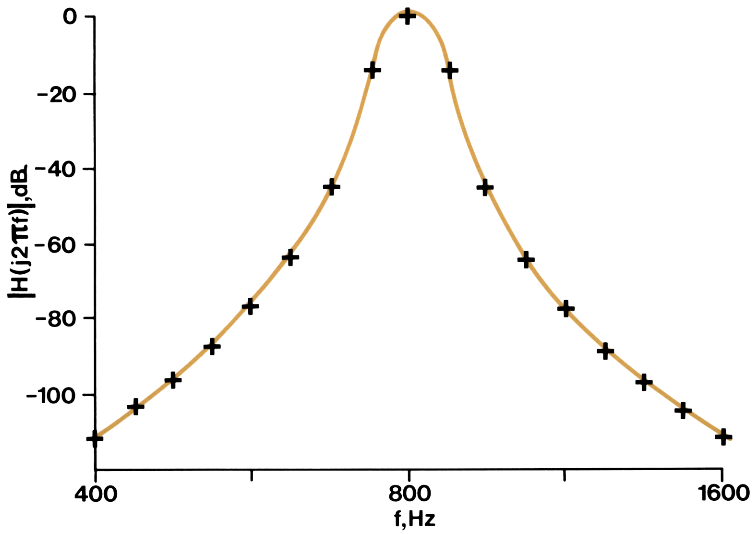
Plot the response of a 6-pole Butterworth band-pass filter with BW = 100, f_0 = 800. Make a logarithmic plot using steps of $2^{1/8}$ from 400 Hz to 1600 Hz.

Keystrokes:

6 A 100 ENTER↑ 800 f C
f D 400 ENTER↑ 1600 ENTER↑
2 √x √x √x D E ⟶

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↑

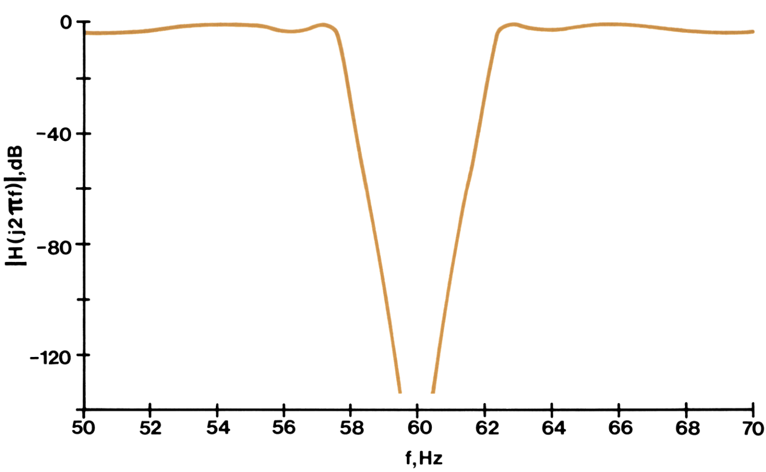
.5 D E ——→

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

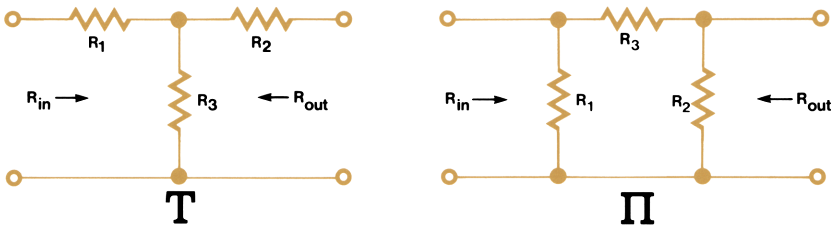
57.000	T	59.000	T
−0.479	Z	−88.662	Z
8.481	Y	103.950	Y
13.596	X	0.111	X
57.500	T	59.500	T
−0.066	Z	−133.081	Z
−122.266	Y	96.633	Y
37.279	X	0.024	X
58.000	T	60.000	T
−34.346	Z	−1048.077	Z
127.620	Y	−90.000	Y
1.179	X	1.985653756−15	X
58.500	T	60.500	T
−59.784	Z	−133.598	Z
113.071	Y	−96.577	Y
0.338	X	0.024	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 $R_{in} \geqslant R_{out}$

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:	Outputs:		
75 A 50 B C →	5.719+00	***	min loss
6 D →	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 E →	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:	Outputs:		
50 A 50 B C →	0.000+00	***	
10 D →	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 E →	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

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

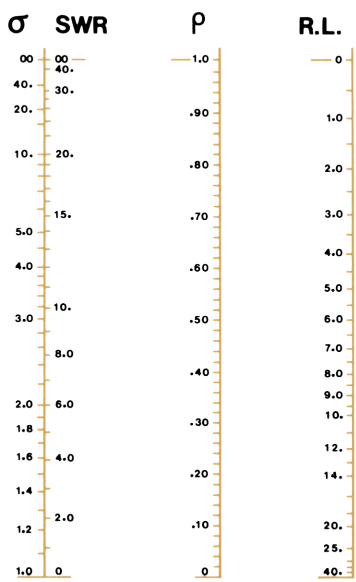
R.L. = return loss

are related as follows:

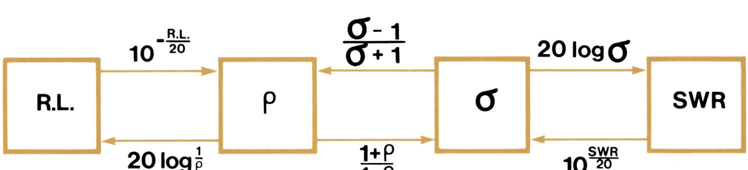
$$\text{SWR} = 20 \log \sigma$$

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

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



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

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

and

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

where

Γ = complex reflection coefficient

$\rho = |\Gamma|$

$\phi = \angle \Gamma$

$\mathbf{Z}$ = impedance

$Z = |\mathbf{Z}|$

$\theta = \angle \mathbf{Z}$

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
1	Load program.			
2	Convert among σ, SWR, ρ,			
	and R.L. as desired.			
	$\sigma \to$ SWR	σ	f A	SWR
	SWR $\to \sigma$	SWR	A	σ
	$\sigma \to \rho$	σ	f B	ρ
	$\rho \to \sigma$	ρ	B	σ
	$\rho \to$ R.L.	ρ	f C	R.L.
	R.L. $\to \rho$	R.L.	C	ρ
3	Store characteristic			
	impedance.	Z_0	f D	
4	Convert between Z and Γ			
	as desired.			
	$Z \to \Gamma$	θ	ENTER↑	
		Z	E	ϕ, ρ
	$\Gamma \to Z$	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 ∠37°. 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 ∠7° 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

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

Example 1:

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

Keystrokes:	Outputs:
.68 ENTER↑ .195 ENTER↑	
2.3 E ⟶	49.42 ***

Example 2:

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

Keystrokes:	Outputs:
6 ENTER↑ .0808 ENTER↑ 1 A ⟶	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:	Outputs:
.1285 ENTER↑ 6 ENTER↑ 1 B ⟶	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.

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

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

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

$$Z_c = v_r Z_0$$

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.

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

where

$$\frac{\partial w}{\partial t} = \begin{cases} \dfrac{1}{\pi} \ln \dfrac{4\pi w}{t}, & \dfrac{w}{h} \leqslant \dfrac{1}{2\pi} \\[2ex] \dfrac{1}{\pi} \ln \dfrac{2h}{t}, & \dfrac{w}{h} > \dfrac{1}{2\pi} \end{cases}$$

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:	Outputs:
.05 ENTER↑ 2.54 × ENTER↑ A	
9.5 B →	391.3–03 *** v_r
	49.54+00 *** Z_c
.001 ENTER↑ 2.54 × C 3 EEX	
CHS 6 D 2 EEX 9 E →	11.01–03 *** α
	242.4–03 *** R
	422.3+00 *** Q_0

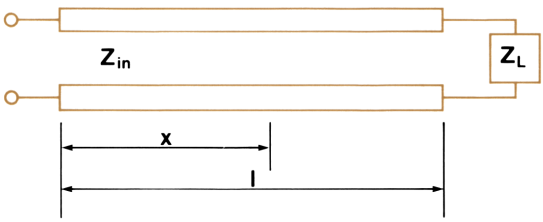
Example 2:

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

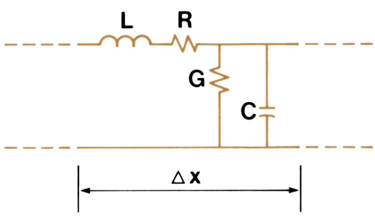
Keystrokes:	**Outputs:**
.05 ENTER↑ 2.54 × ENTER↑ A	
9.5 B ⟶	391.3−03 *** v_r
	49.54+00 *** Z_c
3 EEX CHS 6 D 2 EEX 9 E ⟶	21.25−03 *** α
	242.4−03 *** R
	218.8+00 *** Q_0

15. TRANSMISSION LINE CALCULATIONS

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 = $\mathrm{Re}\{Z_0\} + j\,\mathrm{Im}\{Z_0\}$

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

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

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

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

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

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

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

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

$$\alpha = \alpha_C + \alpha_D$$

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

where

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

α_D = Dielectric loss, nepers/unit length = $\frac{1}{2}$ 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	$\angle Z_L$, deg	ENTER↑	
	Magnitude of terminating			
	impedance	$\|Z_L\|$, Ω	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	$\angle Z_L$, deg	ENTER↑	
	Magnitude of terminating			
	impedance	$\|Z_L\|$, Ω	E	θ_{in}
				Z_{in}

Example 1:

A transmission line has the following properties:

$R = 1.2664\ \Omega/cm$

$G = 0.000\ 041\ 87$ 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 $Z_L = 75\ \angle -30°$?

Keystrokes:	Outputs:
2 EEX 9 f A .85 ENTER↑	
55 A 3.5 B .00004187	
ENTER↑ 1.2664 C 30 CHS	
ENTER↑ 75 E ⟶	28.48+00 *** $\angle Z_{in}$
	48.01+00 *** $\lvert Z_{in} \rvert$

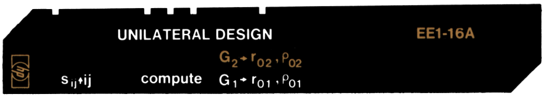
Example 2:

A 4-cm gold ($\rho = 2.3\ \mu\Omega/cm$) 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 Ω?

Keystrokes:	Outputs:
Load EE1-14A	
.05 ENTER↑ 2.54 × ENTER↑	
A 9.5 B ⟶	391.3−03 *** v_r
	49.54+00 *** Z_c
2.3 EEX CHS 6 D 124 EEX	
6 E ⟶	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 ⟶	−12.06+00 *** $\angle Z_L$
	70.06+00 *** $\lvert Z_L \rvert$

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_{1max}, and G_{2max} from a transistor's s-parameters. It also computes r_{oi} and ρ_{oi} from $G_i \leqslant G_{imax}$ (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

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

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

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

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

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

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

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

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

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_{1max} or G_{2max} 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_{1max}
				G_{2max}

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS	OUTPUT DATA/UNITS
4	Input desired gain			
	($\leq G_{1max}$) and compute loca-			
	tion * of center of gain circle			
	on input plane.	G_1, dB	C	r_{01}
				ρ_{01}
5	Input desired gain			
	($\leq G_{2max}$) 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_{ii}.*			

Example 1:

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

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

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_{1max}, and G_{2max}?

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

Keystrokes:

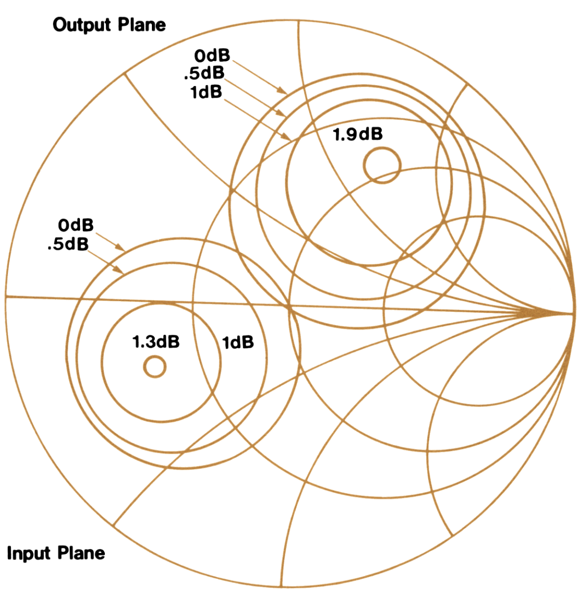
.51 ENTER↑ 11 A .09 ENTER↑
12 A 1.4 ENTER↑ 21 A
.6 ENTER↑ 22 A B ⟶

Outputs:

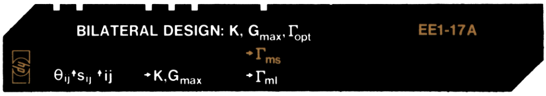
0.08 *** u
6.17 *** G_u
5.49 *** $G_{actual\ min}$

Keys	Output
	6.91 *** $G_{actual\ max}$
	2.92 *** G_0
	1.31 *** G_{1max}
	1.94 *** G_{2max}
0 [C] →	0.40 *** r_{o1}
	0.40 *** ρ_{o1}
.5 [C] →	0.44 *** r_{o1}
	0.32 *** ρ_{o1}
1 [C] →	0.48 *** r_{o1}
	0.20 *** ρ_{o1}
0 [f] [C] →	0.44 *** r_{o2}
	0.44 *** ρ_{o2}
.5 [f] [C] →	0.48 *** r_{o2}
	0.38 *** ρ_{o2}
1 [f] [C] →	0.52 *** r_{o2}
	0.30 *** ρ_{o2}

	input plane		output plane	
	r_{o1}	ρ_{o1}	r_{o2}	ρ_{o2}
0 dB	$.40 \angle -154°$	.40	$.44 \angle 58°$	.44
.5 dB	$.44 \angle -154°$	.32	$.48 \angle 58°$	.38
1 dB	$.48 \angle -154°$	.20	$.52 \angle 58°$	.30



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



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

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

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

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

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

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.

$s_{11} = 0.277 \angle -59°$

$s_{12} = 0.078 \angle 93.0°$

$s_{21} = 1.920 \angle 64°$

$s_{22} = 0.848 \angle -31°$

Keystrokes:	Outputs:
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 ⟶	1.033+00 *** K
	12.81+00 *** G_{max}
f C ⟶	135.4+00 *** $\angle \Gamma_{ms}$
	729.8−03 *** $\lvert\Gamma_{ms}\rvert$
C ⟶	33.85+00 *** $\angle \Gamma_{ml}$
	951.1−03 *** $\lvert\Gamma_{ml}\rvert$

Notes

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

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

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

and radius

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

where

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

G_p = desired gain

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

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

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

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

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

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

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:

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

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

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

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

Keystrokes:	Outputs:
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 →	1.033+00 *** K
	12.81+00 *** G_{max}
f C →	135.4+00 *** θ_{ms}
	729.8−03 *** Γ_{ms}
C →	33.85+00 *** θ_{ml}
	951.1−03 *** Γ_{ml}
Load EE1-18A	
10 A →	33.85+00 *** $\angle r_{02}$
	781.2−03 *** $\lvert r_{02} \rvert$
	214.2−03 *** ρ_{02}

Example 2:

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

Keystrokes:	Outputs:
Continuing from Example 1,	
33.85 ENTER↑ .567 B →	93.33+00 *** $\angle \Gamma_{ms}$
	276.0−03 *** $\lvert \Gamma_{ms} \rvert$

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	**Outputs:**
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 ⟶	909.5−03 *** K
	''Error'' signifies K < 1
CL X (Clear ''Error'')	
Load EE1-18A	
1 C ⟶	122.4+00 *** $\angle r_{s1}$
	−8.371+00 *** $\|r_{s1}\|$
	−9.271+00 *** ρ_{s1}
2 C ⟶	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.

Network Transfer Functions—Input

Key	Comment
*LBLA	Input f
CLRG	
2	
x	
Pi	
x	
ST00	Store ω
1	
ST01	
ST07	$[\psi] = \begin{bmatrix} 1\angle 0 & 0 \\ 0 & 1\angle 0 \end{bmatrix}$
CLX	
RTN	
*LBLB	
0	
GTO1	Pass $R\angle 0$ to LBL 1.
*LBLC	
RCL0	
x	
9	
0	
GTO1	Pass $\omega L \angle 90$ to LBL 1.
*LBLD	
RCL0	
x	
1/X	
9	
0	
CHS	
GTO1	Pass $(\omega C)^{-1} \angle -90$ to LBL 1.
*LBLE	
X⇄Y	
GSB0	Pass $\dfrac{\omega L}{1-\omega^2 LC} \angle 90$ to LBL 1.
*LBL1	
GSB7	
RCLC	
ST02	
RCLB	
ST01	$[\psi] \leftarrow \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} [\psi]$
RCLE	
ST04	
RCLD	
ST03	
CLX	
RTN	
*LBLb	
0	
GTO2	Pass $R\angle 0$ to LBL 2.
*LBLc	
RCL0	
x	
9	
0	
GTO2	Pass $\omega L \angle 90$ to LBL 2.
*LBLd	
RCL0	
x	
1/X	
9	
0	
CHS	
GTO2	Pass $(\omega C)^{-1} \angle -90$ to LBL 2.
*LBLe	
GSB0	
CHS	
X⇄Y	Pass $\dfrac{1-\omega^2 LC}{\omega C} \angle -90$ to LBL 2.
1/X	
X⇄Y	
*LBL2	
GSB7	
RCLC	
RCLB	
RCL9	$[\psi] \leftarrow \begin{bmatrix} 1 & 0 \\ \frac{1}{Z} & 1 \end{bmatrix} [\psi]$
1/X	
RCLA	
CHS	
GSB9	
ST05	
R↓	
ST06	
RCLE	
RCLD	
RCL9	
1/X	
RCLA	
CHS	
GSB9	
ST07	
R↓	
ST08	
CLX	
RTN	
*LBL7	INPUT: $y = \lvert Z \rvert$, $x = \angle Z$
STOA	
X⇄Y	
ST09	
RCL5	
RCL6	Compute and store $\psi_{11} + Z\psi_{21}$.
GSB9	
RCL2	
RCL1	
GSB8	
STOB	
R↓	
STOC	
RCLA	
RCL9	
RCL7	
RCL8	
GSB9	Compute and store $\psi_{12} + Z\psi_{22}$.
RCL4	
RCL3	
GSB8	

REGISTERS

0	1	2	3	4	5	6	7	8	9
ω	$\lvert\psi_{11}\rvert$	$\angle\psi_{11}$	$\lvert\psi_{12}\rvert$	$\angle\psi_{12}$	$\lvert\psi_{21}\rvert$	$\angle\psi_{21}$	$\lvert\psi_{22}\rvert$	$\angle\psi_{22}$	$\lvert Z\rvert$
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
$\angle Z$	$\lvert\psi_{11\,new}\rvert$	$\angle\psi_{11\,new}$	$\lvert\psi_{12\,new}\rvert$	$\angle\psi_{12\,new}$	

Step	Key	Comments
113	STOD	
114	R↓	
115	STOE	
116	RTN	
117	*LBL8	Subroutine to add complex numbers.
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	Subroutine to multiply complex numbers.
131	R↓	
132	×	
133	R↓	
134	+	
135	R↑	
136	RTN	
137	*LBL0	INPUT: y = b, x = a
138	×	
139	LSTX	
140	RCL0	
141	×	
142	X⇄Y	
143	LSTX	
144	X²	
145	×	
146	1	
147	-	
148	CHS	
149	÷	
150	9	
151	0	OUTPUT: $y = \frac{\omega a}{1 - \omega^2 ab}$
152	RTN	$x = 90$
153	R/S	

LABELS					FLAGS
A f	B Series R	C Series L	D Series C	E Series tank	0
a	b Shunt R	c Shunt L	d Shunt C	e Shunt L-C	1
0 Used	1 Used	2 Used	3	4	2
5	6	7 Used	8 CADD	9 CMULT	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Network Transfer Functions —Output

Step	Key	Comments
001	*LBLA	Input Z_L
002	STO9	
003	X⇄Y	
004	STOA	
005	CLX	
006	R/S	
007	*LBLB	Compute Z_{in}
008	GSB4	
009	RCLB	
010	1/X	
011	RCLI	
012	CHS	
013	GSB9	
014	GTO5	
015	*LBLC	Compute V_2/V_1
016	RCL2	
017	RCL1	
018	RCL4	
019	RCL3	
020	GSB6	
021	RCLA	
022	RCL9	
023	R↑	
024	CHS	
025	R↑	
026	1/X	
027	X⇄Y	
028	GSB9	
029	GTO5	
030	*LBLD	Compute I_2/I_1
031	RCL6	
032	RCL5	
033	RCL8	
034	RCL7	
035	GSB6	
036	1/X	
037	X⇄Y	
038	CHS	
039	X⇄Y	
040	CHS	
041	GTO5	
042	*LBLE	Compute P_2/P_1
043	GSB4	
044	RCLB	
045	1/X	
046	RCLI	
047	CHS	
048	GSB9	
049	→R	
050	RCLA	
051	RCL9	
052	→R	
053	X⇄Y	
054	R↓	
055	÷	
056	STOC	
057	RCL2	
058	RCL1	
059	RCL4	
060	RCL3	
061	GSB6	
062	RCLA	
063	RCL9	
064	R↑	
065	CHS	
066	R↑	
067	1/X	
068	X⇄Y	
069	GSB9	
070	X²	
071	RCLC	
072	×	
073	F0?	
074	PRTX	
075	RTN	
076	*LBL5	IF flag 0 THEN go to LBL 0 ELSE Display y and x alternately.
077	F0?	
078	GTO0	
079	*LBL1	
080	X⇄Y	
081	R/S	
082	GTO1	
083	*LBL0	Print y and x.
084	X⇄Y	
085	PRTX	
086	X⇄Y	
087	PRTX	
088	RTN	
089	*LBL4	Compute and store $Z_L y_{21} + y_{22}$.
090	RCL6	
091	RCL5	
092	RCL8	
093	RCL7	
094	GSB6	
095	STOB	
096	R↓	
097	STOI	Compute $Z_L y_{11} + y_{12}$
098	RCL2	
099	RCL1	
100	RCL4	
101	RCL3	
102	*LBL6	
103	STOE	
104	R↓	
105	STOD	INPUT: ∠A, |A|, ∠B, |B|
106	R↓	
107	RCL9	
108	RCLA	
109	GSB9	
110	RCLD	OUTPUT: $\angle Z_L A + B$, $\lvert Z_L A + B \rvert$
111	RCLE	
112	GSB8	

REGISTERS

0	1	2	3	4	5	6	7	8	9
	$\lvert y_{11} \rvert$	$\angle y_{11}$	$\lvert y_{12} \rvert$	$\angle y_{12}$	$\lvert y_{21} \rvert$	$\angle y_{21}$	$\lvert y_{22} \rvert$	$\angle y_{22}$	$\lvert Z_L \rvert$

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
$\angle Z_L$	|Denom|	Used	∠B	|B|	∠Denom

Step	Key	Comments
113	RTN	
114	*LBLc	Compute I_2/V_1
115	RCL2	
116	RCL1	
117	RCL4	
118	RCL3	
119	GSB6	
120	1/X	
121	X⇄Y	
122	CHS	
123	X⇄Y	
124	CHS	
125	GTO5	
126	*LBLd	Compute V_2/I_1
127	RCL6	
128	RCL5	
129	RCL8	
130	RCL7	
131	GSB6	
132	RCLA	
133	RCL9	
134	R↑	
135	CHS	
136	R↑	
137	1/X	
138	X⇄Y	
139	GSB9	
140	GTO5	
141	*LBL8	Subroutine to add complex numbers.
142	→R	
143	R↓	
144	R↓	
145	→R	
146	X⇄Y	
147	R↓	
148	+	
149	R↓	
150	+	
151	R↑	
152	→P	
153	RTN	
154	*LBL9	Subroutine to multiply complex numbers.
155	R↓	
156	×	
157	R↓	
158	+	
159	R↑	
160	RTN	
161	R/S	

LABELS					FLAGS
A Z_L	B $\rightarrow Z_{in}$	C $\rightarrow V_2/V_1$	D $\rightarrow I_2/I_1$	E $\rightarrow P_2/P_1$	0 PRINT
a	b	c $\rightarrow I_2/V_1$	d $\rightarrow V_2/I_1$	e	1
0 Print y & x	1	2	3	4 $Zy_{21} + y_{22}$	2
5 Display	6 Z_L A + B	7	8 CADD	9 CMULT	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Reactive L-Network Impedance Matching

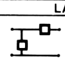
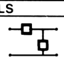
Step	Key	Comment
001	*LBLA	
002	STO1	Store R_L
003	R↓	
004	STO2	Store X_L
005	R/S	
006	*LBLB	Store R_S
007	STO3	
008	R↓	
009	STO4	Store X_S
010	R/S	
011	*LBL1	Subroutine to compute
012	RCL2	$X_{1(+)}$ and $X_{1(-)}$.
013	X²	
014	RCL1	
015	X²	
016	+	
017	RCL3	
018	×	
019	RCL1	
020	RCL3	
021	-	
022	÷	
023	LSTX	
024	1/X	
025	RCL3	
026	×	
027	RCL2	
028	×	
029	X²	
030	LSTX	
031	R↓	
032	+	
033	√X	
034	R↑	
035	X⇄Y	
036	-	
037	STO5	
038	LSTX	
039	ENT↑	
040	+	
041	+	
042	STO6	
043	RTN	
044	*LBLC	Compute $X_{1(+)}$
045	GSB1	
046	GSB5	
047	GSBE	Compute X_2
048	GSB5	
049	RTN	
050	*LBLc	Compute $X_{1(-)}$
051	GSB1	
052	RCL5	
053	GSB5	
054	GSBE	Compute X_2
055	GSB5	
056	RTN	
057	*LBLD	Exchange Z_S and Z_L.
058	GSB2	Compute $X_{1(+)}$.
059	GSB1	Compute X_2.
060	GSB5	
061	GSBE	
062	GSB5	
063	+	Save X_2 in LSTx.
064	GSB2	Exchange Z_S and Z_L.
065	LSTX	Recover X_2.
066	RTN	
067	*LBLd	Exchange Z_S and Z_L.
068	GSB2	Compute $X_{1(-)}$.
069	GSB1	
070	RCL5	
071	GSB5	
072	GSBE	Compute X_2
073	GSB5	
074	+	Save X_2 in LSTx.
075	GSB2	Exchange Z_S and Z_L.
076	LSTX	Recover X_2.
077	RTN	
078	*LBLE	Subroutine to compute
079	STO7	X_2.
080	RCL2	
081	+	
082	RCL3	
083	×	
084	RCL7	
085	RCL4	
086	+	
087	RCL1	
088	×	
089	-	
090	RCL1	
091	÷	
092	RTN	
093	*LBL2	Subroutine to exchange
094	RCL1	Z_S and Z_L.
095	RCL3	
096	STO1	
097	X⇄Y	
098	STO3	
099	RCL2	
100	RCL4	
101	STO2	
102	X⇄Y	
103	STO4	
104	RTN	
105	*LBL5	DISPLAY ROUTINE
106	F0?	IF flag 0
107	PRTX	THEN PRINT
108	F0?	
109	RTN	ELSE
110	R/S	DISPLAY.
111	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	I

LABELS					FLAGS
A $X_L \uparrow R_L$	B $X_S \uparrow R_S$	C 	D 	E	0 PRINT
a	b	c	d	e	1
0	1 X_1	2 $Z_S \rightleftarrows Z_L$	3 X_2	4	2
5 Display	6	7	8	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

Class A Transistor Amplifier Bias Optimization

Step	Key	Comments
001	*LBLA	
002	RCL9	Transfer V_{BEmax} to
003	P⇄S	secondary register.
004	STO9	
005	P⇄S	
006	RCL4	
007	2	
008	5	
009	-	Compute θ_{JA}
010	RCL5	
011	÷	
012	STO5	
013	RCL0	
014	X²	
015	×	
016	RCL4	Compute R_{L1}
017	RCL2	
018	-	
019	4	
020	.	
021	4	
022	×	
023	÷	
024	STOC	
025	.	
026	1	Compute R_{E1}
027	×	
028	STOD	
029	*LBL0	Begin iterative loop.
030	RCL0	
031	2	
032	÷	
033	ENT↑	
034	ENT↑	
035	RCLC	
036	RCLD	
037	+	Compute I_{cq}
038	÷	
039	STOI	
040	RCL5	
041	×	
042	×	Compute T_{max}
043	RCL2	
044	+	
045	RCL4	
046	X⇄Y	IF $T_{max} > T_{Jmax}$
047	X>Y?	THEN increase R_L
048	GTO1	
049	GSB3	ELSE compute V_{BEX}.
050	CHS	
051	RCL1	
052	1	
053	+	
054	GSB4	
055	RCL8	
056	+	
057	STOE	
058	1	
059	RCL1	
060	X²	
061	-	
062	2	
063	÷	
064	RCLI	
065	×	
066	RCL5	Compute T_{min}
067	×	
068	RCL0	
069	×	
070	RCL3	
071	+	
072	GSB3	
073	CHS	
074	1	
075	RCL1	Compute V_{BEN}
076	-	
077	GSB4	
078	P⇄S	
079	RCL9	
080	+	
081	P⇄S	
082	STO9	
083	RCLE	IF $V_{BEX} > V_{BEN}$
084	X>Y?	THEN reduce R_E to 0
085	GTO2	and increment R_L
086	-	ELSE
087	RCLI	Compute a new value
088	÷	for R_E.
089	RCL1	
090	÷	
091	RCLD	
092	X⇄Y	
093	STOD	
094	%CH	
095	.	
096	5	IF $\Delta R_E \geqslant .5\%$
097	X≤Y?	THEN repeat loop
098	GTO0	IF flag 1
099	F1?	THEN finish problem
100	GTO1	ELSE repeat loop
101	SF1	once more to print.
102	GTO0	
103	*LBL1	
104	CF1	
105	R/S	Stop to accept h_{FE}'s
106	STOB	
107	X⇄Y	Store h_{FEmin}
108	STOA	Store h_{FEmax}
109	RCL1	
110	2	
111	×	
112	RCLI	

REGISTERS

0	1	2	3	4	5	6	7	8	9
V_{CC}	ΔI_{cq}	T_{Amax}, R_B	T_{Amin}, V_{BB}	T_{Jmax}	P_D, θ_{JA}	I_1	ΔV_{BE}	V_{BEmin}	V_{BEN}

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
									V_{BEmax}

A	B	C	D	E	I
h_{FEmax}	h_{FEmin}	R_{Ln}	R_{En}	V_{BEX}	I_{cq}

Step	Key	Comment	Step	Key	Comment
113	x		169	x	
114	RCLD		170	RCL2	
115	x		171	x	
116	RCLE		172	LSTX	
117	+		173	RCLD	Compute A_p
118	RCL9		174	RCLB	
119	-		175	x	
120	RCLB		176	+	
121	x		177	÷	
122	RCLA	Compute R_B	178	LOG	
123	x		179	1	
124	1		180	0	
125	RCL1		181	x	
126	-		182	PRTX	
127	RCLA		183	RTN	----------
128	x		184	*LBL3	
129	1		185	F1?	IF flag 1
130	RCL1		186	PRTX	THEN PRINT T.
131	+		187	2	
132	RCLB		188	5	
133	x		189	-	Compute
134	-		190	2	
135	÷		191	.	0.0022 (x − 25)
136	RCLI		192	2	
137	÷		193	EEX	
138	STO2	--------	194	CHS	
139	RCLB		195	3	
140	÷		196	x	
141	RCLD		197	RTN	----------
142	+		198	*LBL4	
143	RCLI		199	RCLI	
144	x	Compute V_{BB}	200	x	
145	1		201	F1?	IF flag 1
146	RCL1		202	PRTX	THEN PRINT I_c.
147	-		203	RCL6	
148	x		204	÷	
149	RCL9		205	LOG	
150	+	--------	206	RCL7	
151	STO3		207	x	
152	RCL0	Compute R_1	208	+	
153	X⇄Y		209	RTN	----------
154	÷		210	*LBL2	$R_E \leftarrow 0$
155	RCL2		211	0	
156	x	--------	212	STOD	-------
157	RCL2		213	*LBL1	
158	RCL0		214	1	
159	x		215	.	$R_{Ln+1} \leftarrow R_{Ln} \times 1.1$
160	LSTX	Compute R_2	216	1	
161	RCL3		217	RCLC	
162	-		218	x	R_{Ln+1}
163	÷	--------	219	STOC	
164	RCLC		220	GTO0	----------
165	RCLD		221	R/S	
166	PRST	PRINT R_1, R_2, R_L, R_E			
167	÷				
168	RCLB				

LABELS					FLAGS
A →T, I_c . . .	B Used	C	D	E	0
a	b	c	d	e	1 Used
0 Used	1 Used	2 Used	3 Used	4 Used	2
5	6	7	8	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Transistor Amplifier Performance

```
*LBLA
2
x
2
1          Compute storage location.
-
STOI
R↓
STOi       Store h_ij
ISZI
R↓
STOi       Store θ_ij
RTN        ------------
*LBLB
STO7       Store R_L
X⇄Y
STO8       Store θ_L
RTN        ------------
*LBLb
STO5       Store R_S
X⇄Y
STO6       Store θ_S
RTN        ------------
*LBLc      Compute A_i
GSB7
X⇄Y
GSB5
X⇄Y
GSB5
SPC
RTN        ------------
*LBLC      Compute A_v
CF1
GSBe       Compute Z_in without printing.
SF1
1/X
X⇄Y
CHS
X⇄Y
RCL7
RCL8
GSB9
RCL9
RCLA
GSB9
X⇄Y
GSB5
X⇄Y
GSB5
SPC
RTN        ------------
*LBLe      Compute Z_in
GSB7
RCL7
RCL8
GSB9
RCL3
RCL4
GSB9
RCL2
RCL1
GSB8
STO0
X⇄Y
STOI
F1?        IF flag 1 THEN PRINT or DISPLAY.
GSB5
X⇄Y
F1?        IF flag 1 THEN PRINT or DISPLAY.
GSB5
F1?
SPC
RTN        ------------
*LBLD      Compute A_vs
CF1
GSBe       Compute Z_in without printing.
SF1
RCL6
RCL5
GSB8
1/X
X⇄Y
CHS
X⇄Y
RCL9
RCLA
GSB9
RCL7
RCL8
GSB9
X⇄Y
GSB5
X⇄Y
GSB5
SPC
RTN        ------------
*LBLE      Compute Z_out
RCL2
RCL1
RCL6
RCL5
GSB8
1/X
X⇄Y
CHS
X⇄Y
RCLB
RCLC
GSB9
RCL3
RCL4
GSB9
```

REGISTERS

0	1	2	3	4	5	6	7	8	9
$\lvert Z_{in} \rvert$	$h_{11} = h_i$	θ_{11}	$h_{12} = h_r$	θ_{12}	R_S	θ_S	R_L	θ_L	$\lvert A_i \rvert$
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
$\angle A_i$	$h_{21} = h_f$	θ_{21}	$h_{22} = h_o$	θ_{22}	$\angle Z_{in}$

Step	Key Entry	Comments
113	CHS	
114	RCLE	
115	RCLD	
116	GSB8	
117	1/X	
118	X⇄Y	
119	CHS	
120	GSB5	
121	X⇄Y	
122	GSB5	
123	SPC	
124	RTN	
125	*LBL5	IF flag 0
126	F0?	THEN PRINT
127	PRTX	IF flag 0
128	F0?	THEN RETURN
129	RTN	ELSE DISPLAY.
130	R/S	
131	RTN	------------
132	*LBL7	Subroutine to compute A_i.
133	RCLE	
134	RCLD	
135	RCL7	
136	RCL8	
137	GSB9	
138	0	
139	ENT↑	
140	1	
141	GSB8	
142	1/X	
143	X⇄Y	
144	CHS	
145	X⇄Y	
146	RCLB	
147	CHS	
148	RCLC	
149	GSB9	
150	STO9	
151	X⇄Y	
152	STOA	
153	X⇄Y	
154	RTN	------------
155	*LBL8	Subroutine to add complex numbers.
156	→R	
157	R↓	
158	R↓	
159	→R	
160	X⇄Y	
161	R↓	
162	+	
163	R↓	
164	+	
165	R↑	
166	→P	
167	RTN	
168	*LBL9	
169	R↓	Subroutine to multiply complex numbers.
170	×	
171	R↓	
172	+	
173	R↑	------------
174	RTN	
175	R/S	

LABELS

A θ_{ij}↑h_{ij}↑ij	B θ_L↑R_L	C →A_v	D →A_{vs}	E →Z_{out}
a	b θ_S↑R_S	c →A_i	d	e →Z_{in}
0	1	2	3	4
5 DISPLAY	6	7 A_i	8 CADD	9 CMULT

FLAGS

0	PRINT
1	NO PRINT
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☒	☐	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Transistor Configuration Conversion

Step	Key	Comments	Step	Key	Comments
001	*LBLA		057	RCLE	
002	2		058	RCLD	
003	×	Compute register to be used.	059	GSB8	$y_{12}' = -(y_{12} + y_{22})$
004	2		060	CHS	
005	1		061	STO3	
006	-		062	X⇄Y	
007	STOI		063	STO4	————————
008	R↓		064	X⇄Y	
009	STO(i)	Store h_{ij}	065	RCLC	
010	ISZI		066	RCLB	
011	R↓		067	GSB8	
012	STO(i)	Store θ_{ij}	068	RCLE	
013	RTN	————————	069	RCLD	$y_{11}' = -y_{22} + (y_{21}' + y_{12}')$
014	*LBLC	CC→CB	070	GSB8	$+ y_{11}$
015	GSB0	Compute a new y-matrix.	071	CHS	
016	*LBL3	————————	072	RCL2	$= y_{11} + y_{12} + y_{21} + y_{22}$
017	RCL1	Routine to transform	073	RCL1	
018	RCLD	$\begin{bmatrix} a_{22} & a_{21} \\ a_{12} & a_{11} \end{bmatrix}$	074	GSB8	
019	STO1		075	STO1	
020	R↓		076	R↓	
021	STOD	into	077	STO2	
022	RCL3	$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$	078	RTN	————————
023	RCLB		079	*LBLd	CE→CC
024	STO3		080	*LBLD	CC→CE
025	R↓	and then into	081	GSB0	Compute new y-matrix.
026	STOB	$\frac{1}{a_{11}} \begin{bmatrix} 1 & -a_{12} \\ a_{21} & \det a \end{bmatrix}$	082	GSB7	Transform [y] to [h].
027	RCL2		083	RTN	————————
028	RCLE		084	*LBLc	CB→CC
029	STO2		085	GSB0	Compute new y-matrix.
030	R↓		086	GTO3	Transform
031	STOE		087	*LBL0	————————
032	RCL4		088	GSB7	Transform [h] to [y]'
033	RCLC		089	RCL2	
034	STO4		090	RCL1	
035	R↓		091	RCL4	
036	STOC		092	RCL3	$y_{12}' = -(y_{11} + y_{12})$
037	GSB7		093	GSB8	
038	RTN	————————	094	CHS	
039	*LBLb	CB→CE	095	STO3	
040	*LBLB	CE→CB	096	R↓	
041	GSB0	Compute a new y-matrix.	097	STO4	————————
042	GSB7	Transform [y] to [h].	098	RCL2	
043	RTN	————————	099	RCL1	
044	*LBL0	Transform [h] to [y]'	100	RCLC	
045	GSB7		101	RCLB	
046	RCLC		102	GSB8	$y_{21}' = -(y_{11} + y_{21})$
047	RCLB		103	CHS	
048	RCLE		104	STOB	
049	RCLD	$y_{21}' = -(y_{21} + y_{22})$	105	X⇄Y	
050	GSB8		106	STOC	————————
051	CHS		107	X⇄Y	
052	STOB		108	RCL4	
053	R↓		109	RCL3	
054	STOC		110	GSB8	$y_{22}' = y_{11} + y_{12} + y_{21} + y_{22}$
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}		$\lvert\Delta\rvert$	$\angle\Delta$		

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
	h_{21}	θ_{21}	h_{22}	θ_{22}	

Step	Key	Comment
113	GSB8	
114	CHS	
115	RCLE	
116	RCLD	
117	GSB8	
118	STOD	
119	R↓	
120	STOE	
121	RTN	------------
122	*LBL7	Subroutine to convert $\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$
123	RCL2	
124	RCL1	
125	RCLD	
126	RCLE	
127	GSB9	into $\frac{1}{a_{11}} \begin{bmatrix} 1 & -a_{12} \\ a_{21} & \det a \end{bmatrix}$
128	STO6	
129	R↓	
130	STO7	
131	RCL4	
132	RCL3	
133	RCLB	
134	RCLC	
135	GSB9	
136	CHS	
137	RCL7	Compute det a
138	RCL6	
139	GSB8	
140	STO6	
141	R↓	
142	STO7	------------
143	RCL2	
144	CHS	
145	STO2	$a_{11} \leftarrow \frac{1}{a_{11}}$
146	RCL1	
147	1/X	
148	STO1	------------
149	RCL3	
150	CHS	
151	RCL4	
152	GSB9	$a_{12} \leftarrow \frac{-a_{12}}{a_{11}}$
153	STO3	
154	R↓	
155	STO4	------------
156	RCL2	
157	RCL1	
158	RCLB	
159	RCLC	
160	GSB9	$a_{21} \leftarrow \frac{a_{21}}{a_{11}}$
161	STOB	
162	R↓	
163	STOC	------------
164	RCL2	
165	RCL1	
166	RCL6	$a_{22} \leftarrow \frac{\det a}{a_{11}}$
167	RCL7	
168	GSB9	
169	STOD	
170	R↓	
171	STOE	
172	RTN	------------
173	*LBL8	Subroutine to add complex numbers.
174	→R	
175	R↓	
176	R↓	
177	→R	
178	X⇄Y	
179	R↓	
180	+	
181	R↓	
182	+	
183	R↑	
184	→P	
185	RTN	------------
186	*LBL9	Subroutine to multiply complex numbers.
187	R↓	
188	×	
189	R↓	
190	+	
191	R↑	
192	→R	
193	→P	
194	RTN	------------
195	*LBLE	Print [h]
196	RCL2	
197	GSB5	
198	RCL1	
199	GSB5	
200	RCL4	
201	GSB5	
202	RCL3	
203	GSB5	
204	RCLC	
205	GSB5	
206	RCLB	
207	GSB5	
208	RCLE	
209	GSB5	
210	RCLD	
211	*LBL5	
212	F0?	IF flag 0
213	PRTX	THEN PRINT
214	F0?	ELSE DISPLAY.
215	RTN	
216	R/S	
217	RTN	------------
218	R/S	

LABELS

A $\theta_{ij}\uparrow h_{ij}\uparrow t_{ij}$	B CB←CE	C CB←CC	D CE←CC	E PRINT [h]
a	b CB→CE	c CB→CC	d CE→CC	e
0 [h]→[y]'	1	2	3	4
5 DISPLAY	6	7 [h]⇄[y]	8 CADD	9 CMULT

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Parameter Conversion: S ⇄ Y, Z, G, H

Step	Key	Comment
001	*LBLa	
002	GSB0	Store input data.
003	R↓	
004	STOi	
005	ISZI	
006	R↓	
007	STOi	
008	RTN	
009	*LBLA	Display output data.
010	GSB0	
011	RCLi	$ij \to \theta_{ij}, M_{ij}$
012	ISZI	
013	RCLi	
014	GSB5	
015	X⇄Y	
016	*LBL5	DISPLAY ROUTINE
017	F0?	IF flag 0
018	PRTX	THEN PRINT
019	F0?	
020	RTN	ELSE
021	R/S	DISPLAY.
022	RTN	
023	*LBL0	Subroutine to compute
024	2	register location.
025	×	
026	2	
027	1	
028	-	
029	STOI	
030	RTN	
031	*LBLb	Y→S
032	STO0	
033	GSB1	$[T] = Z_0\,[Y]$
034	GTO6	Compute $[T']$; $[S] = [T']$
035	*LBLB	
036	STO0	S→Y
037	GSB6	$[T] = [S]$
038	RCL0	Compute $[T']$
039	1/X	$\xi = 1/Z_0$; $[Y] = [T']/Z_0$
040	*LBL1	
041	GSB3	
042	GSB4	$[T] \leftarrow \begin{bmatrix} \xi & 0 \\ 0 & \xi \end{bmatrix} [T]$
043	RTN	
044	*LBLc	
045	STO0	Z→S
046	1/X	$\xi = 1/Z_0$
047	GSB1	$[T] = [Z]/Z_0$
048	GSB6	Compute $[T']$
049	1	$\xi = -1$
050	CHS	$[S] = -[T']$
051	GTO1	
052	*LBLC	S→Z
053	STO0	
054	1	$\xi = -1$
055	CHS	$[T] = -[S]$
056	GSB1	

Step	Key	Comment
057	GSB6	$\xi = Z_0$
058	RCL0	$[Z] = Z_0\,[T']$
059	GTO1	
060	*LBLd	G→S
061	STO0	
062	ST×1	
063	1/X	$[T] = \begin{bmatrix} Z_0 g_{11} & g_{12} \\ g_{21} & g_{22}/Z_0 \end{bmatrix}$
064	RCLD	
065	×	
066	STOD	
067	GSB6	Compute $[T']$
068	1	$\xi = -1$
069	CHS	
070	*LBL4	
071	RCLB	
072	X⇄Y	$[T] \leftarrow \begin{bmatrix} 1 & 0 \\ 0 & \xi \end{bmatrix} [T]$
073	×	
074	STOB	
075	LSTX	
076	RCLD	
077	×	
078	STOD	
079	RTN	S→G
080	*LBLD	$\xi = -1$
081	STO0	
082	1	$[T] = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} [S]$
083	CHS	
084	GSB4	
085	GSB6	Compute $[T']$
086	RCL0	
087	ST÷1	
088	RCLD	$G = \begin{bmatrix} \frac{t_{11}'}{Z_0} & t_{12}' \\ t_{21}' & Z_0 t_{22}' \end{bmatrix}$
089	×	
090	STOD	
091	RTN	
092	*LBLe	
093	STO0	H→S
094	ST÷1	
095	RCLD	
096	×	$[T] = \begin{bmatrix} \frac{h_{11}}{Z_0} & h_{12} \\ h_{21} & h_{22} Z_0 \end{bmatrix} [H]$
097	STOD	
098	GSB6	Compute $[T']$
099	1	$\xi = -1$
100	CHS	
101	*LBL3	
102	ST×1	$[T] \leftarrow \begin{bmatrix} \xi & 0 \\ 0 & 1 \end{bmatrix} [T]$
103	ST×3	
104	RTN	
105	*LBLE	
106	STO0	S→H
107	1	$\xi = -1$
108	CHS	
109	GSB3	$T = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} [S]$
110	GSB6	
111	RCL0	
112	ST×1	Compute $[T']$

REGISTERS

0	1	2	3	4	5	6	7	8	9
Z_0	M_{11}, T_{11}'	$\theta_{11}, \angle T_{11}'$	M_{12}, T_{12}'	$\theta_{12}, \angle T_{12}'$	2/D	∠2/D			

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
	M_{21}, T_{21}'	$\theta_{21}, \angle T_{21}'$	M_{22}, T_{22}'	$\theta_{22}, \angle T_{22}'$	pointer

Step	Key	Comments
113	1/X	$[H] = \begin{bmatrix} t_{11}'Z_0 & t_{12}' \\ t_{21}' & \frac{t_{22}'}{Z_0} \end{bmatrix}$
114	RCLD	
115	x	
116	STOD	
117	RTN	
118	*LBL6	
119	RCL2	Subroutine to compute [T'].
120	RCL1	
121	GSB7	
122	STO5	
123	X⇄Y	
124	STO6	
125	RCLE	
126	RCLD	
127	GSB7	
128	RCL5	
129	RCL6	
130	GSB9	
131	STO5	
132	X⇄Y	
133	STO6	
134	RCL4	
135	RCL3	
136	RCLB	
137	RCLC	
138	GSB9	
139	CHS	
140	RCL6	
141	RCL5	
142	GSB8	
143	2	
144	÷	
145	1/X	
146	STO5	$\frac{2}{D}$
147	X⇄Y	
148	CHS	
149	STO6	
150	RCLE	
151	RCLD	
152	GSB7	
153	GSB5	
154	STOD	t_{11}'
155	X⇄Y	
156	STOE	
157	RCL2	
158	RCL1	
159	GSB7	
160	GSB5	
161	STO1	t_{22}'
162	X⇄Y	
163	STO2	
164	RCL4	
165	RCL3	
166	CHS	
167	GSB2	
168	STO3	t_{12}'

Step	Key	Comments
169	X⇄Y	
170	STO4	
171	RCLC	
172	RCLB	
173	CHS	
174	GSB2	
175	STOB	t_{21}'
176	X⇄Y	
177	STOC	
178	RCL1	
179	RCLD	Rearrange t_{11}' and t_{22}'
180	STO1	
181	X⇄Y	
182	STOD	
183	RCL2	
184	RCLE	
185	STO2	
186	X⇄Y	
187	STOE	
188	RTN	
189	*LBL5	Subroutine to multiply by 2/D and add −1 ∠ 0.
190	RCL5	
191	RCL6	
192	GSB9	
193	0	
194	ENT↑	
195	1	
196	CHS	
197	GTO8	
198	*LBL7	Subroutine to add 1 ∠ 0.
199	0	
200	ENT↑	
201	1	
202	*LBL8	
203	→R	Subroutine to add complex numbers.
204	R↓	
205	R↓	
206	→R	
207	X⇄Y	
208	R↓	
209	+	
210	R↓	
211	+	
212	R↑	
213	→P	
214	RTN	
215	*LBL2	Subroutine to multiply by 2/D.
216	RCL5	
217	RCL6	
218	*LBL9	Subroutine to multiply complex numbers.
219	R↓	
220	x	
221	R↓	
222	+	
223	R↑	
224	RTN	

LABELS

A ij→θ_{ij},M_{ij}	B S→Y	C S→Z	D S→G	E S→H
a θ_{ij}↑M_{ij}↑ij	b Y→S	c Z→S	d G→S	e H→S
0 ij→pointer	1 Used	2 Used	3 Used	4 Used
5 DISPLAY	6 T'	7 +1∠0	8 CADD	9 CMULT

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Fourier Series

Step	Key	Comment
001	*LBLa	START
002	CLRG	
003	P⇄S	
004	CLRG	
005	RAD	
006	RTN	
007	*LBLA	N↑# freqs
008	2	
009	x	
010	STOB	
011	X⇄Y	
012	STOE	
013	RTN	
014	*LBLB	J
015	STOD	Store J
016	1	
017	STO0	INITIALIZE k
018	RTN	
019	*LBLC	y_k
020	STOC	Store y_k
021	RCLB	
022	STOI	INITIALIZE pointer
023	*LBL1	BEGIN loop 1.
024	CLX	
025	RCL0	
026	RCLI	
027	RCLB	
028	-	
029	2	
030	CHS	
031	÷	
032	RCLD	
033	+	
034	RCLE	
035	÷	
036	x	
037	2	
038	x	
039	Pi	
040	x	
041	X⇄Y	
042	→R	
043	ST+i	
044	X⇄Y	
045	DSZI	
046	ST+i	
047	RCLC	
048	ENT↑	
049	DSZI	IF pointer ≠ 0
050	GTO1	THEN REPEAT loop 1.
051	1	ELSE INCREMENT k.
052	ST+0	
053	RCLE	
054	RCL0	
055	X≤Y?	IF k ≤ N
056	GTO0	THEN GO TO LBL 0
057	9	ELSE
058	1/X	DISPLAY 0.111.
059	RTN	
060	*LBL0	
061	R/S	DISPLAY new k.
062	GTOC	
063	*LBLd	PRINT POLAR
064	SF1	
065	RCLB	
066	STOI	
067	GTO2	
068	*LBLD	PRINT RECTANGULAR
069	CF1	
070	RCLB	
071	STOI	
072	*LBL2	BEGIN loop 2.
073	RCLI	
074	RCLB	
075	-	
076	2	
077	CHS	
078	÷	
079	RCLD	
080	+	
081	FIX	
082	DSP0	
083	GSB5	
084	DSP3	
085	RCLi	
086	DSZI	
087	RCLi	
088	F1?	IF print polar
089	GTO3	THEN GO TO LBL 3
090	2	ELSE
091	RCLE	Prepare to print
092	÷	rectangular.
093	x	
094	X⇄Y	
095	LSTX	
096	x	
097	*LBL4	
098	X⇄Y	
099	GSB5	
100	R↓	
101	GSB5	
102	F0?	
103	SPC	
104	DSZI	IF pointer ≠ 0
105	GTO2	THEN REPEAT loop 2.
106	RTN	
107	*LBL3	Convert (a, b) to (c, θ)
108	X⇄Y	
109	→P	
110	2	
111	RCLE	
112	÷	

REGISTERS

0	1	2	3	4	5	6	7	8	9
k, t	b	a	b	a	b	a	b	a	b

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
a	b	a	b	a	b	a	b	a	b

A	B	C	D	E	I
a	2 x # freqs	y_k	J	N	pointer

Step	Key	Comment
113	x	
114	GTO4	— — — — — — — — — — — —
115	*LBLE	t→f(t)
116	CF2	
117	STO0	
118	RCLB	
119	STOI	INITIALIZE pointer
120	CLX	— — — — — — — —
121	*LBL6	BEGIN loop 6.
122	RCLI	
123	RCLB	
124	-	
125	2	
126	CHS	
127	÷	
128	RCLD	
129	+	
130	X=0?	IF i = 0
131	SF2	THEN set flag 2.
132	2	
133	x	
134	Pi	
135	x	
136	RCL0	
137	x	
138	RCLE	
139	÷	
140	1	
141	F2?	IF flag 2
142	GSB0	THEN $a_0 \leftarrow a_0/2$.
143	→R	
144	RCLi	
145	x	
146	X⇄Y	
147	DSZI	
148	RCLi	
149	x	
150	+	
151	RCLE	
152	÷	
153	2	
154	x	
155	+	
156	DSZI	IF pointer ≠ 0
157	GTO6	THEN REPEAT loop 6
158	GSB5	ELSE DISPLAY f(t).
159	F0?	
160	SPC	
161	RTN	— — — — — — — — — — — —
162	*LBL0	Subroutine to replace 1
163	CLX	with 0.5.
164	.	
165	5	
166	RTN	— — — — — — — — — — — —
167	*LBL5	DISPLAY ROUTINE
168	F0?	IF flag 0
169	PRTX	THEN PRINT
170	F0?	ELSE DISPLAY
171	RTN	
172	R/S	
173	RTN	
174	R/S	

LABELS					FLAGS
A N↑#freqs	B J	C y_k	D RECT	E t→f(t)	0 PRINT
a START	b	c	d POLAR	e	1 POLAR
0 Used	1 Loop	2 Loop	3 →P	4 PRINT	2 Used
5 DISPLAY	6 Loop	7	8	9	3

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☐
GRAD	☐
RAD	☒

DISP	
FIX	☒
SCI	☐
ENG	☐
n	3

Active Filter Design

Step	Key	Comment
001	*LBLa	
002	STO0	Store f_0
003	RTN	------------
004	*LBLA	
005	STO1	Store A
006	RTN	------------
007	*LBLb	
008	STO2	Store α
009	RTN	------------
010	*LBLB	
011	STO3	Store C
012	RTN	------------
013	*LBLC	LOW PASS
014	RCL2	
015	2	
016	÷	
017	RCL1	
018	÷	
019	2	
020	Pi	
021	x	
022	RCL0	
023	x	
024	RCL3	
025	x	
026	STO4	
027	÷	
028	STO5	
029	GSB5	Display R_1
030	RCL3	
031	4	
032	x	
033	RCL1	
034	1	
035	+	
036	x	
037	RCL2	
038	X^2	
039	÷	
040	GSB5	Display C_2
041	RCL2	
042	2	
043	÷	
044	RCL1	
045	1	
046	+	
047	÷	
048	RCL4	
049	÷	
050	GSB5	Display R_3
051	RCL1	
052	RCL5	
053	x	
054	GSB5	Display = R_4
055	RCL3	
056	GSB5	Display C_5

Step	Key	Comment
057	RTN	------------
058	*LBLD	HIGH PASS
059	RCL3	Display C_1
060	GSB5	
061	RCL0	
062	x	
063	2	
064	x	
065	Pi	
066	x	
067	STO4	
068	RCL2	
069	X⇄Y	
070	÷	
071	2	
072	RCL1	
073	1/X	
074	+	
075	÷	
076	GSB5	Display R_2
077	RCL3	
078	GSB5	Display C_3
079	RCL1	
080	÷	
081	GSB5	Display C_4
082	RCL1	
083	2	
084	x	
085	1	
086	+	
087	RCL2	
088	÷	
089	RCL4	
090	÷	
091	GSB5	Display R_5
092	RTN	------------
093	*LBLE	BAND PASS
094	RCL3	
095	RCL0	
096	x	
097	2	
098	x	
099	Pi	
100	x	
101	STO4	
102	RCL1	
103	x	
104	RCL2	
105	x	
106	1/X	Display R_1
107	GSB5	
108	2	
109	RCL2	
110	X^2	
111	÷	
112	RCL1	

REGISTERS

0	1	2	3	4	5	6	7	8	9
f_0	A	α	C	$2\pi f_0 C$	R_{1LP}				

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

Step	Key	Comment
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	DISPLAY ROUTINE
131	F0?	IF flag 0
132	PRTX	THEN PRINT
133	F0?	
134	RTN	ELSE
135	R/S	DISPLAY.
136	RTN	
137	R/S	

LABELS					FLAGS
A A	B C	C LP	D HP	E BP	0 PRINT
a f_0	b α	c	d	e	1
0	1	2	3	4	2
5 DISPLAY	6	7	8	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

Butterworth or Chebyshev Filter Design

Step	Key	Comments
001	*LBLE	
002	1	
003	0	
004	÷	
005	10ˣ	Compute order of Butterworth filter.
006	2	
007	x	
008	1	
009	-	
010	LN	
011	STOB	
012	X⇄Y	
013	GSB9	
014	GSB7	
015	RCLB	
016	X⇄Y	
017	LN	
018	ABS	
019	÷	
020	1	
021	+	
022	2	
023	÷	
024	INT	
025	STOE	
026	RTN	
027	*LBLA	Store R
028	STO5	
029	RTN	
030	*LBLD	
031	1	
032	0	Compute order of Chebyshev filter.
033	÷	
034	10ˣ	
035	1	
036	-	
037	4	
038	x	
039	RCL6	
040	X²	
041	÷	
042	2	
043	-	
044	STOB	
045	X⇄Y	
046	GSB9	
047	GSB7	
048	ENT↑	
049	X²	
050	1	
051	-	
052	√X	
053	+	
054	STO3	
055	LN	
056	RCLB	
057	LN	
058	X⇄Y	
059	÷	
060	STOE	
061	*LBL6	Newton's method root finder.
062	RCLE	
063	RCL3	
064	RCLE	
065	Yˣ	
066	STOA	
067	ENT↑	
068	1/X	
069	+	
070	RCLB	
071	-	
072	RCLA	
073	ENT↑	
074	1/X	
075	-	
076	÷	
077	RCL3	
078	LN	
079	÷	
080	2	
081	÷	
082	-	
083	STOE	
084	LSTX	
085	ABS	
086	.	
087	0	
088	1	
089	X≤Y?	
090	GTO6	
091	RCLE	
092	2	
093	÷	
094	1	
095	+	
096	INT	
097	RTN	
098	*LBL9	Subroutine to multiply by 2π.
099	2	
100	x	
101	Pi	
102	x	
103	RTN	
104	*LBL7	Subroutine to compute normalized frequency.
105	STOA	
106	RCLD	
107	STOI	
108	GTOi	
109	*LBL4	Band Elimination.
110	GSB3	
111	GTO0	
112	*LBL2	High pass.

REGISTERS

0	1	2	3	4	5	6	7	8	9
			Used	Ripple, dB	R	ϵ	ω_0	BW	i

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
ω	Used	ω_n	1 LP 3 BP 2 HP 4 BE	n	counter

Keys	Comments
GSB1	
*LBL0	
1/X	
CHS	
GTO5	
*LBL1	Low Pass
RCLA	
RCL7	
÷	
GTO5	
*LBL3	Band Pass
RCLA	
X^2	
RCL7	
X^2	
-	
RCLA	
÷	
RCL8	
÷	
*LBL5	
ABS	
STOC	
RTN	
*LBLd	dB Ripple→ε
STO4	
1	
0	
÷	
10^x	
1	
-	
√X	
STO6	
RTN	
*LBLb	High Pass
2	
GTO0	
*LBLc	Band Pass
3	
GTO1	Band Elimination
*LBLC	
4	
*LBL1	
GSB0	
R↓	
GSB9	
STO8	
RTN	
*LBLB	Low Pass
1	
*LBL0	
STOD	
R↓	
GSB9	
STO7	
RTN	
R/S	

LABELS

A	B	C	D	E
R	LP: f_0	BE: BW↑ f_0	f_1 ↑α→n	f_1 ↑α→n
a	b HP: f_0	c BP: BW↑ f_0	d dB Ripple→ε	e
0 Used	1 Used	2 Used	3 Used	4 Used
5 Used	6 Used	7 Used	8	9 Used

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☐
SCI	☐
ENG	☒
n	3

Butterworth or Chebyshev Filter Design

Step	Key	Comment
001	*LBLE	BUTTERWORTH
002	RCLE	
003	STOI	INITIALIZE counter
004	SF1	
005	*LBL8	BEGIN loop 8.
006	RCLE	
007	RCLI	Butterworth equations
008	-	
009	1	
010	+	
011	STO9	Store i
012	2	
013	x	
014	1	
015	-	
016	Pi	
017	x	
018	2	
019	÷	$(2i - 1)\pi/2n$
020	RCLE	
021	÷	
022	SIN	
023	2	
024	x	
025	*LBL9	
026	STOA	
027	RCL5	
028	1	
029	CHS	
030	RCL9	
031	GSB5	DISPLAY i
032	Y^x	
033	Y^x	$R^{(-1)^i}$
034	x	
035	RCLD	Branch to appropriate
036	X⇄I	routine for frequency
037	GTOi	transformation.
038	*LBL1	
039	X⇄I	Low Pass
040	R↓	
041	RCL7	
042	÷	
043	GSB6	
044	GTO8	
045	*LBL2	
046	X⇄I	High Pass
047	R↓	
048	RCL7	
049	x	
050	1/X	
051	GSB6	
052	CHS	
053	GTO8	
054	*LBL3	Band Pass
055	X⇄I	
056	R↓	

Step	Key	Comment
057	RCL8	
058	÷	
059	GSB6	
060	GSB5	
061	LSTX	
062	÷	
063	1/X	
064	RCL7	
065	X^2	
066	÷	
067	GSB6	
068	CHS	
069	GTO0	
070	*LBL4	Band Elimination
071	X⇄I	
072	R↓	
073	RCL8	
074	x	
075	RCL7	
076	X^2	
077	÷	
078	GSB6	
079	GSB5	
080	LSTX	
081	÷	
082	RCL7	
083	X^2	
084	x	
085	1/X	
086	GSB6	
087	CHS	
088	*LBL0	
089	GSB5	
090	F0?	
091	SPC	
092	F1?	IF Butterworth
093	GTO1	THEN REPEAT loop 8
094	DSZI	ELSE REPEAT loop 7.
095	GTO7	
096	RTN	
097	*LBL1	
098	DSZI	
099	GTO8	
100	RTN	
101	*LBL6	Subroutine to change sign of capacitors.
102	1	
103	CHS	
104	RCL9	
105	Y^x	
106	x	
107	RTN	
108	*LBLD	CHEBYSHEV
109	1	
110	STO9	
111	CF1	
112	RCL4	

REGISTERS

0	1	2	3	4	5	6	7	8	9
				Ripple, dB	R	ϵ	ω_0	BW	i

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
G_1, G_{i-1}	a_1, a_i	γ^2	1 LP 3 BP 2 HP 4 BE	n	counter

Step	Key	Comments
113	4	
114	0	
115	÷	
116	1	
117	e^x	
118	LOG	
119	÷	
120	ENT↑	
121	+	
122	e^x	Chebyshev setup
123	1	
124	X⇄Y	
125	+	
126	LSTX	
127	1	
128	-	
129	÷	
130	RCLE	
131	STOI	
132	2	
133	×	
134	1/X	
135	Y^x	
136	ENT↑	
137	1/X	
138	-	
139	2	
140	÷	
141	X^2	
142	STOC	
143	Pi	
144	2	
145	÷	
146	RCLE	
147	÷	
148	SIN	
149	STOB	
150	2	
151	×	
152	RCLC	
153	√X	
154	÷	
155	GTO9	
156	*LBL7	- - - - - - - - - - - -
157	RCLB	BEGIN loop 7.
158	RCLE	
159	RCLI	
160	-	
161	1	Chebyshev equations
162	+	
163	STO9	
164	1	
165	-	
166	2	
167	×	
168	1	
169	+	
170	Pi	
171	×	
172	2	
173	÷	
174	RCLE	
175	÷	
176	SIN	
177	STOE	
178	×	
179	4	
180	×	
181	RCLA	
182	÷	
183	RCLC	
184	RCLE	
185	RCLI	
186	-	
187	Pi	
188	×	
189	RCLE	
190	÷	
191	SIN	
192	X^2	
193	+	
194	÷	
195	GTO9	
196	*LBL5	- - - - - - - - - - - -
197	F0?	DISPLAY ROUTINE
198	PRTX	IF flag 0
199	F0?	THEN PRINT
200	RTN	
201	R/S	ELSE
202	RTN	DISPLAY.
203	R/S	- - - - - - - - - - - -

LABELS

A	B	C	D CH'SHEV	E B'WORTH
a	b	c	d	e
0 Used	1 Used	2 Used	3 Used	4 Used
5 DISPLAY	6 Used	7 Loop	8 Loop	9 Used

FLAGS

0	PRINT
1	Butterworth
2	
3	

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☐
SCI	☐
ENG	☒
n	3

Bode Plot of Butterworth and Chebyshev Filters

Step	Key	Comments
001	*LBLa	
002	1	
003	0	Convert dB ripple to ϵ.
004	÷	
005	10^x	
006	1	
007	-	
008	√X	
009	STO6	Store ϵ
010	R↓	
011	CF0	Chebyshev
012	STOE	Store n
013	RTN	
014	*LBLA	
015	SF0	Butterworth
016	STOE	Store n
017	RTN	
018	*LBLb	
019	2	High Pass
020	GTO0	
021	*LBLc	
022	3	Band Pass
023	GTO1	
024	*LBLC	
025	4	Band Elimination
026	*LBL1	
027	GSB0	Store filter characteristic
028	R↓	and ω_0.
029	GSB9	
030	STO8	Store 2π x BW
031	RTN	
032	*LBLB	
033	1	Low Pass
034	*LBL0	
035	STOD	Store filter characteristic.
036	R↓	
037	GSB9	Multiply by 2π.
038	STO7	Store ω_0
039	RTN	
040	*LBLD	
041	STO0	Store Δf
042	GSB9	
043	STOC	Store $\Delta\omega$
044	R↓	
045	GSB9	
046	STOB	Store ω_2
047	R↓	
048	GSB9	
049	STOA	Store ω_1
050	RTN	
051	*LBLE	Initialize registers
052	0	
053	STO3	
054	STO5	
055	1	
056	STO4	
057	RCLE	
058	STOI	
059	GSB7	Compute ω_N
060	*LBL8	
061	RAD	BEGIN loop 8.
062	GSB6	Compute s_k
063	RCL1	
064	RCL9	
065	+	
066	RCL2	
067	→P	
068	ST÷4	Gain
069	X⇄Y	
070	ST-5	Phase
071	RCL2	
072	RCL1	
073	→P	
074	ST×4	Gain normalization
075	→R	
076	RCL9	
077	+	
078	RCL2	
079	→P	
080	X^2	
081	X⇄Y	
082	R↓	
083	÷	
084	ST+3	Time delay
085	DSZI	WHILE counter ≠ 0
086	GTO8	REPEAT loop 8.
087	RCLA	
088	1	
089	GSB9	
090	÷	Frequency
091	RCL4	
092	LOG	
093	2	
094	0	
095	×	
096	RND	Gain, dB
097	RCL5	
098	1	
099	→R	
100	DEG	
101	→P	Phase, degrees
102	CLX	
103	RCL3	Delay
104	PRST	Print f, |H|, θ, t
105	RCLE	
106	RCLA	
107	F1?	IF flag 1
108	GTO0	THEN GO TO LBL 0
109	RCLC	ELSE
110	+	$\omega \leftarrow \omega + \Delta\omega$
111	GTO3	
112	*LBL0	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Δf	$-\mathrm{Im}\{s_k\}$	$-\mathrm{Re}\{s_k\}$	delay	$-\Pi\ \|H(\omega)\|$	$\Sigma\theta(\omega)$	ϵ	ω_0	BW	ω_N
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
ω_1, ω	ω_2	$\Delta\omega$	1 LP 3 BP 2 HP 4 BE	n	counter

Step	Key	Comment
113	RCL8	
114	×	ω←ω x Δf
115	*LBL3	
116	STOA	Store new ω
117	X≤Y?	IF $\omega \leq \omega_2$
118	GTOE	THEN REPEAT loop E
119	RTN	ELSE stop.
120	*LBL7	----------- Subroutine to compute ω_N.
121	RCLD	
122	X⇄I	
123	GTOi	GO TO case i.
124	*LBL4	BE
125	GSB3	
126	GTO0	
127	*LBL2	HP
128	GSB1	
129	*LBL0	
130	1/X	
131	CHS	
132	GTO5	
133	*LBL1	LP
134	X⇄I	
135	RCLA	
136	RCL7	
137	÷	
138	GTO5	
139	*LBL3	BP
140	X⇄I	
141	RCLA	
142	X²	
143	RCL7	
144	X²	
145	-	
146	RCLA	
147	÷	
148	RCL8	
149	÷	
150	*LBL5	
151	STO9	Store ω_N
152	RTN	-----------
153	*LBL6	Subroutine to compute s_k.
154	F0?	IF Butterworth
155	GTO1	THEN GO TO LBL 1
156	GSB1	ELSE get Butterworth pole
157	1	and modify it.
158	RCL6	
159	1/X	
160	→P	
161	X⇄Y	
162	R↓	
163	LSTX	
164	+	
165	LN	
166	RCLE	
167	÷	
168	e^x	
169	LSTX	
170	CHS	
171	e^x	
172	+	
173	ENT↑	
174	ENT↑	
175	LSTX	
176	2	
177	×	
178	-	
179	ST×2	
180	R↓	
181	ST×1	
182	2	
183	ST÷2	
184	ST÷1	
185	RTN	-------
186	*LBL1	Subroutine to compute Butterworth pole location.
187	RCLI	
188	2	
189	×	
190	1	
191	-	
192	RCLE	
193	÷	
194	GSB9	
195	4	
196	÷	
197	1	
198	→R	
199	STO1	
200	X⇄Y	
201	STO2	
202	RTN	-----------
203	*LBLd	
204	1	
205	F1?	
206	CLX	Set logarithmic increment.
207	SF1	
208	X=0?	-------
209	CF1	
210	RTN	Set linear increment.
211	*LBL9	------- Subroutine to multiply by 2π.
212	2	
213	×	
214	Pi	
215	×	
216	RTN	
217	R/S	

LABELS

A B'WORTH n	B LP: f_0	C BE: BW↑f_0	D f_1↑f_2↑Δf	E "PLOT"
a CHEB n↑dB R	b HP: f_0	c BP: BW↑f_0	d LIN – LOG	e
0 Used	1 Used	2 Used	3 Used	4 Used
5 Used	6 Used	7 Used	8 Loop	9 Used

FLAGS

Flag	Meaning
0	B'WORTH
1	LOG
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☐	☒	DEG	☐	FIX	☒
1	☒	☐	GRAD	☐	SCI	☐
2	☐	☒	RAD	☒	ENG	☐
3	☐	☒			n	3

Resistive Attenuator Design

Step	Key	Comments
001	*LBLA	
002	STO1	Store R_{in}
003	RTN	------------
004	*LBLB	
005	STO2	Store R_{out}
006	RTN	------------
007	*LBLC	
008	RCL1	
009	RCL2	
010	÷	
011	ENT↑	Compute min loss.
012	ENT↑	
013	1	
014	-	
015	√X	
016	X⇄Y	
017	√X	
018	+	
019	X^2	
020	LOG	
021	1	
022	0	
023	×	
024	GSB5	
025	STO3	
026	RTN	------------
027	*LBLD	T calculation
028	RCL3	
029	X>Y?	IF min loss > desired loss
030	GTO9	THEN ERROR
031	X⇄Y	ELSE
032	1	Compute R_1, R_2, R_3
033	0	
034	÷	
035	10^x	
036	STO4	
037	RCL1	
038	×	
039	RCL2	
040	×	
041	√X	
042	2	
043	×	
044	RCL4	
045	1	
046	-	
047	÷	
048	STO7	
049	1	
050	RCL4	
051	+	
052	LSTX	
053	1	
054	-	
055	÷	
056	RCL1	
057	×	
058	-	
059	CHS	
060	STO5	
061	1	
062	RCL4	
063	+	
064	LSTX	
065	1	
066	-	
067	÷	
068	RCL2	
069	×	
070	RCL7	
071	-	
072	STO6	
073	GTO1	------------
074	*LBLE	Π calculation
075	RCL3	
076	X>Y?	IF min loss > desired loss
077	GTO9	THEN ERROR
078	X⇄Y	ELSE
079	1	Compute R_1, R_2, R_3
080	0	
081	÷	
082	10^x	
083	STO4	
084	1/X	
085	RCL1	
086	×	
087	RCL2	
088	×	
089	√X	
090	RCL4	
091	1	
092	-	
093	×	
094	2	
095	÷	
096	STO7	
097	1	
098	RCL4	
099	+	
100	LSTX	
101	1	
102	-	
103	÷	
104	RCL1	
105	÷	
106	RCL7	
107	1/X	
108	-	
109	1/X	
110	STO5	
111	1	
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	I

Step	Key	Comments
113	+	
114	LSTX	
115	1	
116	-	
117	÷	
118	RCL2	
119	÷	
120	RCL7	
121	1/X	
122	-	
123	1/X	
124	ST06	
125	*LBL1	--------
126	RCL4	RECALL OUTPUTS
127	LOG	
128	1	
129	0	
130	×	
131	GSB5	
132	RCL5	
133	GSB5	
134	RCL6	
135	GSB5	
136	RCL7	
137	GSB5	
138	RTN	
139	*LBL5	-------------
140	F0?	DISPLAY ROUTINE
141	PRTX	IF flag 0
142	F0?	THEN PRINT
143	RTN	ELSE
144	R/S	DISPLAY.
145	RTN	-------------
146	R/S	

LABELS					FLAGS
A R_{in}	B R_{out}	C →min loss	D Used	E Used	0 PRINT
a	b	c	d	e	1
0	1 Used	2	3	4	2
5 DISPLAY	6	7	8	9 Error	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

L12-01

Smith Chart Conversions

Step	Key	Comments
001	*LBLc	$\rho \to$ R.L.
002	1/X	
003	*LBLa	
004	LOG	
005	2	$\sigma \to$ SWR
006	0	
007	x	
008	RTN	
009	*LBLC	R. L.$\to \rho$
010	CHS	
011	*LBLA	
012	2	
013	0	
014	÷	SWR$\to \sigma$
015	10^x	
016	RTN	
017	*LBLb	$\sigma \to \rho$
018	1/X	
019	CHS	
020	*LBLB	
021	1	
022	X⇄Y	
023	+	
024	1	$\rho \to \sigma$
025	LSTX	
026	-	
027	÷	
028	RTN	
029	*LBLd	
030	STO1	Store Z_0
031	RTN	
032	*LBLD	$\Gamma \to Z$
033	1	
034	GSB7	
035	RCL1	
036	CHS	
037	x	
038	→R	
039	→P	
040	GTO9	
041	*LBLE	$Z \to \Gamma$
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	
057	RTN	
058	*LBL7	Input: $\angle$ a, |a|, k
059	ENT↑	
060	R↓	
061	R↓	
062	→R	Subroutine to compute
063	R↑	
064	-	$\frac{a \angle a + k \angle 0}{a \angle a - k \angle 0}$
065	STO6	
066	R↓	
067	R↓	
068	+	
069	+	
070	→P	
071	R↑	
072	RCL6	
073	→P	
074	R↓	
075	X⇄Y	
076	R↑	
077	÷	
078	R↓	
079	-	
080	R↑	Output: ang, mag
081	RTN	
082	R/S	

REGISTERS

0	1	2	3	4	5	6	7	8	9
	Z_0					Used			

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

LABELS					FLAGS	SET STATUS		
A SWR→σ	B ρ→σ	C R.L.→ρ	D Γ→Z	E Z→Γ	0 PRINT	FLAGS	TRIG	DISP
a σ→SWR	b σ→ρ	c ρ→R.L.	d Z_0	e	1	ON OFF 0 ☒ ☐ 1 ☐ ☒ 2 ☐ ☒ 3 ☐ ☒	DEG ☒ GRAD ☐ RAD ☐	FIX ☒ SCI ☐ ENG ☐ n 2
0	1	2	3	4	2			
5 DISPLAY	6	7 Used	8	9 Used	3			

Transmission Line Impedance

```
001  *LBLA     Open two-wire line.
002  STO0
003  R↓
004  ÷
005  2
006  ×
007  LN
008  1
009  2
010  0
011  ×
012  RCL0
013  √X
014  ÷
015  GTO5
             ------------------------
016  *LBLB     Single wire near ground.
017  STO0
018  R↓
019  4
020  ×
021  ÷
022  1/X
023  LOG
024  1
025  3
026  8
027  ×
028  RCL0
029  √X
030  ÷
031  GTO5
             ------------------------
032  *LBLC     Balanced wires near
033  STO0      ground.
034  R↓
035  STO1
036  R↓
037  STO2
038  R↓
039  STO3
040  RCL1
041  ÷
042  2
043  ÷
044  X²
045  1
046  +
047  √X
048  1/X
049  2
050  ×
051  RCL3
052  ×
053  RCL2
054  ÷
055  LOG
056  2
057  7
058  6
059  ×
060  RCL0
061  √X
062  ÷
063  GTO5
             ------------------------
064  *LBLD     Wires in parallel near
065  STO0      ground.
066  R↓
067  STO1
068  R↓
069  STO2
070  R↓
071  STO3
072  RCL1
073  ÷
074  1/X
075  2
076  ×
077  X²
078  1
079  +
080  √X
081  RCL1
082  ×
083  RCL2
084  ÷
085  4
086  ×
087  LOG
088  6
089  9
090  ×
091  RCL0
092  √X
093  ÷
094  GTO5
             ------------------------
095  *LBLE     Coaxial line
096  STO0
097  R↓
098  ÷
099  LN
100  6
101  0
102  ×
103  RCL0
104  √X
105  ÷
             -------
106  *LBL5     DISPLAY ROUTINE
107  F0?       IF flag 0
108  PRTX      THEN PRINT
109  RTN       ELSE
110  R/S          DISPLAY.
```

REGISTERS

0	1	2	3	4	5	6	7	8	9
ϵ_r	h	d	D						

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I

LABELS					FLAGS
A	B	C	D	E	0 PRINT
a	b	c	d	e	1
0	1	2	3	4	2
5 DISPLAY	6	7	8	9	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☒
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☐
3	☐	☒			n	2

Microstrip Transmission Line Calculations

Step	Key	Comment
001	*LBLA	
002	SF1	
003	STO7	Store h
004	X⇄Y	
005	STO6	Store w
006	SF0	
007	X>Y?	IF w > h
008	CF0	THEN clear flag 0
009	÷	
010	STO9	Store h/w
011	1/X	
012	STO8	Store w/h
013	1	
014	0	
015	LN	
016	STO0	Store ln 10
017	RTN	------------
018	*LBLB	
019	1	
020	X⇄Y	
021	+	
022	LSTX	Compute ϵ_{eff}
023	1	
024	-	
025	1	
026	0	
027	RCL8	
028	÷	
029	1	
030	+	
031	√X	
032	÷	
033	+	
034	2	
035	÷	
036	√X	
037	1/X	
038	STO2	Store v_r
039	F0?	IF w ≤ h
040	GTO1	THEN GO TO 1.
041	1	
042	RCL9	
043	-	
044	6	Compute Z_0 for w > h
045	Y^X	
046	.	
047	4	
048	4	
049	RCL8	
050	÷	
051	-	
052	2	
053	.	
054	4	
055	2	
056	+	
057	RCL8	
058	+	
059	2	
060	Pi	
061	×	
062	X⇄Y	
063	÷	
064	GTO2	-------
065	*LBL1	Compute Z_0 for w ≤ h.
066	8	
067	RCL8	
068	÷	
069	LSTX	
070	4	
071	÷	
072	+	
073	LN	
074	*LBL2	-------
075	6	
076	0	
077	×	
078	STOA	Store Z_0
079	×	
080	STO1	Store Z_c
081	X⇄Y	
082	PRTX	Print v_r
083	X⇄Y	
084	PRTX	Print Z_c
085	RTN	-----------
086	*LBLD	IF uniform assumption
087	√X	THEN GO TO 1.
088	F1?	
089	GTO1	
090	*LBL4	
091	RCL4	
092	×	
093	RCL7	
094	÷	
095	2	
096	×	
097	Pi	
098	×	
099	STO3	Store partial result.
100	RTN	-----------
101	*LBL1	
102	2	
103	0	
104	RCL0	
105	÷	
106	RCL9	
107	×	
108	RCLA	
109	÷	
110	STO4	
111	R↓	-----------
112	GTO4	

REGISTERS

0	1	2	3	4	5	6	7	8	9
ln 10	Z_c	v_r	α_c	A	$f/10^9$	w	h	w/h	h/w
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
Z_0					

```
*LBLE
EEX
9
÷
STO5
√X
RCL3
×                 Print αc
RCL2
÷
STOB
PRTX
LSTX
×
2
×                 Print R
RCL4
÷
RCL9
×
PRTX
2
Pi
×
RCL0
÷
RCL5
×
3
÷                 Print Q0
RCL2
÷
RCLB
÷
PRTX
RTN
*LBLC
CF1
RCL7
2
×                 Calculate ∂w/∂t
X⇄Y
÷
RCL8
Pi
2
×
×
×
X>Y?
X⇄Y
LN
Pi
÷
RCL8
+
1
+
F0?               IF w ≤ h
GTO1              THEN GO TO 1.
1
RCL9
-                 Compute A for w > h.
5
Y^X
6
×
.
4
4
+
RCL9
X²
×
1
+
×
RCLA
×
7
2
0
÷
Pi
GTO0
*LBL1             Compute A for w ≤ h.
3
2
RCL9
X²
×
1
-
×
RCLA
÷
LSTX
6
0
÷
e^x
÷
.
4
*LBL0
÷
RCL0
÷
Pi
÷
STO4              Store A
RTN
```

LABELS					FLAGS	SET STATUS		
A: w↑h	B: $\epsilon_r \to V_r, Z_C$	C: t→A	D: ρ	E: $f \to \alpha_c, R, Q_0$	0: w > h	FLAGS	TRIG	DISP
a	b	c	d	e	1: uniform	ON / OFF: 0 ☐ ☒; 1 ☐ ☒; 2 ☐ ☒; 3 ☐ ☒	DEG ☒ GRAD ☐ RAD ☐	FIX ☐ SCI ☐ ENG ☒ n 3
0: Used	1: Used	2: Used	3	4: Used	2			
5	6	7	8	9	3			

Transmission Line Calculations

Step	Key	Comment	Step	Key	Comment
001	*LBLa		057	RCL6	
002	EEX		058	+	
003	1		059	STO4	
004	0		060	RCL6	
005	÷		061	RCL8	
006	STO9	Store $f/10^{10}$	062	-	
007	2		063	STO2	
008	Pi		064	RCL5	
009	×		065	RCL3	
010	×		066	÷	
011	STO8	Store ω'	067	ST×1	
012	RTN	------------	068	RCL5	
013	*LBLA		069	RCL3	
014	STO1	Store R_0	070	×	
015	X⇄Y		071	ST×7	
016	STO2	Store v_r	072	RTN	
017	RTN	------------	073	*LBLD	------------
018	*LBLB		074	X⇄Y	
019	STOA	Store ℓ	075	STO8	Store α_D
020	2		076	R↓	
021	×		077	STO3	Store α_C
022	3		078	RCLA	
023	RCL2		079	RCL2	
024	×		080	RCL9	
025	STO3	Store $3\ v_r$	081	Pi	
026	÷		082	×	
027	STO7	Store $2\ell/3\ v_r$	083	1	
028	RTN	------------	084	.	
029	*LBLC		085	5	
030	RCL3		086	÷	
031	×		087	X⇄Y	
032	RCL1		088	÷	
033	÷		089	STO6	
034	STO5	Store $3\ v_r\ R/R_0$	090	×	
035	R↓		091	2	
036	RCL1		092	×	
037	×		093	STO7	
038	ST×3	$R_3 \leftarrow 3\ v_r\ R_0\ G$	094	RCL8	
039	RCL8		095	1	
040	RCL5		096	0	
041	→P		097	LN	
042	√X		098	2	
043	STO5		099	0	
044	X⇄Y		100	÷	
045	2		101	RCL6	
046	÷		102	÷	
047	STO6		103	ST×3	
048	RCL8		104	ST×8	
049	RCL3		105	RCL8	
050	→P		106	RCL3	
051	√X		107	-	
052	STO3		108	ENT↑	
053	X⇄Y		109	STO5	
054	2		110	RCL8	
055	÷		111	3	
056	STO8		112	×	

REGISTERS

0	1	2	3	4	5	6	7	8	9
	R_0, Z_0	v_r	Used	Used	Used	Used	$2\ell/3\ v_r$, $2\beta_0\ell$	ω', ∂_D	$f/10^{10}$

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
ℓ					

Step	Key	Comment
113	RCL3	
114	+	
115	×	
116	2	
117	÷	
118	CHS	
119	1	
120	+	
121	→P	
122	ST×1	
123	X⇄Y	
124	STO2	
125	RCL5	
126	X²	
127	2	
128	÷	
129	1	
130	+	
131	RCL3	
132	RCL8	
133	+	
134	→P	
135	ST×7	
136	X⇄Y	
137	STO4	
138	RTN	
139	*LBLE	
140	STO5	Store Z_L
141	X⇄Y	
142	STO6	Store θ_L
143	RCL4	
144	RCL7	
145	→R	
146	CHS	
147	e^x	
148	STO7	
149	X⇄Y	
150	1	
151	8	
152	0	
153	×	
154	Pi	
155	÷	
156	STO8	
157	RCL6	
158	RCL2	
159	-	
160	RCL5	
161	RCL1	
162	÷	
163	→R	
164	1	
165	+	
166	→P	
167	1/X	
168	2	
169	CHS	
170	×	
171	X⇄Y	
172	CHS	
173	X⇄Y	
174	→R	
175	1	
176	+	
177	→P	
178	RCL7	
179	×	
180	1/X	
181	X⇄Y	
182	RCL8	
183	-	
184	CHS	
185	X⇄Y	
186	→R	
187	1	
188	-	
189	→P	
190	1/X	
191	2	
192	×	
193	X⇄Y	
194	CHS	
195	X⇄Y	
196	→R	
197	1	
198	+	
199	→P	
200	RCL1	
201	×	
202	X⇄Y	
203	RCL2	
204	+	
205	GSB5	
206	X⇄Y	
207	GSB5	
208	RTN	
209	*LBL5	DISPLAY ROUTINE
210	F0?	IF flag 0
211	PRTX	THEN PRINT
212	F0?	
213	RTN	ELSE
214	R/S	DISPLAY.
215	RTN	
216	R/S	

LABELS

A $v_r \uparrow R_0$	B ℓ	C G↑R	D $\alpha_D \uparrow \alpha_C$	E $Z_L \rightarrow Z_{in}$
a f	b	c	d	e
0	1	2	3	4
5 DISPLAY	6	7	8	9

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☐
SCI	☐
ENG	☒
n	3

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

001	*LBLA		057	+	
002	2		058	RCLD	
003	×		059	X²	
004	2		060	CHS	
005	1	Input [S]	061	GSB1	
006	-		062	GSB2	
007	STOI		063	GSB5	Display $G_{2\,max}$
008	R↓		064	RTN	-----------
009	STOi		065	*LBL5	DISPLAY ROUTINE
010	RTN	------------	066	F0?	IF flag 0
011	*LBLE		067	PRTX	THEN PRINT
012	RCL1	Compute	068	F0?	
013	RCL3	u, G_u, G_{min}, G_{max}	069	RTN	ELSE
014	×	G_0, $G_{1\,max}$, G_{2max}.	070	R/S	DISPLAY.
015	RCLB		071	RTN	-----------
016	×		072	*LBL1	Subroutine to compute
017	RCLD		073	1	
018	×		074	+	$\frac{1}{1+x}$
019	1		075	1/X	
020	RCL1		076	RTN	-----------
021	X²		077	*LBL3	Subroutine to re-compute
022	-		078	RCLB	G_u.
023	1		079	X²	
024	RCLD		080	RCL6	
025	X²		081	÷	-------
026	-		082	*LBL2	Subroutine to convert to
027	×		083	LOG	decibels.
028	STO6		084	1	
029	÷		085	0	
030	STO7		086	×	
031	GSB5	Display u	087	RTN	-----------
032	GSB3		088	*LBL4	Subroutine to compute
033	GSB5	Display G_u	089	1	
034	RCL7		090	+	$\frac{1}{(1+x)^2}$
035	GSB4		091	X²	
036	GSB2		092	1/X	
037	GSB3		093	RTN	-----------
038	+		094	*LBLC	Compute r_{o1}, ρ_{o1}
039	GSB5	Display G_{min}	095	1	
040	RCL7		096	GTO6	-----------
041	CHS		097	*LBLc	Compute r_{o2}, ρ_{o2}
042	GSB4		098	2	
043	GSB2		099	3	-------
044	GSB3		100	*LBL6	
045	+		101	STOI	
046	GSB5	Display G_{max}	102	X⇄Y	
047	RCLB		103	1	
048	X²		104	0	
049	GSB2		105	÷	
050	GSB5	Display G_0	106	10^x	
051	RCL1		107	STO0	
052	X²		108	RCLi	
053	CHS		109	×	
054	GSB1		110	LSTX	
055	GSB2		111	X²	
056	GSB5	Display $G_{1\,max}$	112	RCL0	

REGISTERS

0	1	2	3	4	5	6	7	8	9
Used	s_{11}		s_{12}		G_i	$\lvert s_{21}\rvert^2/G_u$	u	r	ρ

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
	s_{21}		s_{22}		pointer

Step	Key	Comments
113	x	
114	1	
115	+	
116	÷	
117	GSB5	Display r
118	STO8	
119	LSTX	
120	1	
121	RCLi	
122	X²	
123	-	
124	RCL0	
125	x	
126	1	
127	-	
128	CHS	
129	√X	
130	X⇄Y	
131	÷	
132	GSB5	Display ρ
133	STO9	
134	RTN	-----------
135	R/S	

LABELS

A $s_{ij}\uparrow t_{ij}$	B Compute	C $G_1 \rightarrow r_{o1}, \rho_{o1}$	D	E
a	b	c $G_2 \rightarrow r_{o2}, \rho_{o2}$	d	e
0	1 Used	2 Used	3 Used	4 Used
5 Used	6 Used	7	8	9

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF
0	☒	☐
1	☐	☒
2	☐	☒
3	☐	☒

TRIG	
DEG	☒
GRAD	☐
RAD	☐

DISP	
FIX	☒
SCI	☐
ENG	☐
n	2

Bilateral Design: Stability Factor, Maximum Gain, Optimum Matching

Key	Comment
*LBLA	
2	
x	Compute pointer
2	
1	
-	
STOI	
R↓	
STOi	Store s_{ij}
ISZI	
R↓	
STOi	Store θ_{ij}
RTN	
	------------
*LBLB	
RCL2	
RCLE	Compute K, G_{max}
+	
1	
→R	
RCL1	
RCLD	
x	
x	
X⇄Y	
LSTX	
x	
RCL3	
RCLB	
x	
STO9	
CLX	
RCL4	
RCLC	
+	
RCL9	
STO7	
CLX	
1	
→R	
STO6	
R↓	
RCL7	
x	
LSTX	
ST×6	
CLX	
RCL6	
R↓	
-	
R↓	
-	
CHS	
R↑	
X⇄Y	
→P	
STO6	Store $\lvert\Delta\rvert$
X⇄Y	
STO7	Store $\angle\Delta$
RCLD	
RCL1	
GSB7	
RCL6	
X²	
1	
+	
RCL1	
X²	
-	
RCLD	
X²	
-	
2	
÷	
RCL3	
RCLB	
x	
ABS	
÷	
STO9	
GSB5	Display K
ENT↑	
x	
LSTX	
X⇄Y	
1	
-	
√X	
RCL5	
x	
CHS	
+	
RCLB	
x	
RCL3	
÷	
ABS	
LOG	
1	
0	
x	
GSB5	Display G_{max}
RTN	
	------------
*LBLc	Compute Γ_{ms}
RCL7	
RCL6	
RCLD	
RCLE	
CHS	
GSB9	
CHS	
RCL2	
RCL1	

REGISTERS

0	1	2	3	4	5	6	7	8	9
C	s_{11}	θ_{11}	s_{12}	θ_{12}	sgn	Used	Used	Used	Used

S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
	s_{21}	θ_{21}	s_{22}	θ_{22}	pointer

```
GSB8
STO0
X⇄Y
STOA
RCLD
RCL1
GSB7
GTO1
----------------
*LBLC        Compute Γml
RCL7
RCL6
RCL1
RCL2
CHS
GSB9
CHS
RCLE
RCLD
GSB8
STO0
X⇄Y
STOA
RCL1
RCLD
GSB7
----------------
*LBL1
RCL8
RCL0
÷
2
÷
ENT↑
X²
1
-
√X
RCL5
×
-
RCLA
CHS
GSB5         Display ∠Γ
X⇄Y
GSB5         Display |Γ|
RTN
----------------
*LBL7
X²
X⇄Y
X²
-
1
+            Compute sgn(B).
RCL6
X²
-
STO8
X=0?
1
ABS
LSTX
÷
STO5
RTN
----------------
*LBL8        Subroutine to add com-
→R           plex numbers.
R↓
R↓
→R
X⇄Y
R↓
+
R↓
+
R↑
→P
RTN
----------------
*LBL9        Subroutine to multiply
R↓           complex numbers.
×
R↓
+
R↑
RTN
----------------
*LBL5
F0?          DISPLAY ROUTINE
PRTX         IF flag 0
F0?          THEN PRINT
RTN          ELSE
R/S            DISPLAY.
----------------
RTN
R/S
```

LABELS					FLAGS
A $\theta_{ij}\uparrow s_{ij}\uparrow ij$	B →K, G_{max}	C $\to\Gamma_{ml}$	D	E	0 PRINT
a	b	c $\to\Gamma_{ms}$	d	e	1
0	1 Used	2	3	4	2
5 DISPLAY	6	7 Used	8 CADD	9 CMULT	3

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

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

Step	Key	Comment
001	*LBLA	
002	1	
003	0	
004	÷	
005	10^x	
006	RCLB	
007	X^2	
008	÷	
009	STOI	Store G_p
010	RCL7	
011	RCL6	
012	RCL1	
013	CHS	
014	RCL2	
015	CHS	
016	GSB9	
017	RCLE	
018	RCLD	
019	GSB8	
020	STO0	
021	X⇄Y	
022	CHS	
023	GSB5	Display ∠r
024	RCLD	
025	X^2	
026	RCL6	
027	X^2	
028	-	
029	STOA	
030	RCLI	
031	×	
032	LSTX	
033	X⇄Y	
034	1	
035	+	
036	÷	
037	RCL0	
038	×	
039	GSB5	Display r
040	RCLI	
041	RCL3	
042	×	
043	RCLB	
044	×	
045	ENT↑	
046	ENT↑	
047	RCL9	
048	ENT↑	
049	+	
050	-	
051	×	
052	1	
053	+	
054	√X	
055	RCLI	
056	RCLA	
057	×	
058	1	
059	+	
060	÷	Display ρ
061	*LBL5	DISPLAY ROUTINE IF flag 0 THEN PRINT ELSE DISPLAY.
062	F0?	
063	PRTX	
064	F0?	
065	RTN	
066	R/S	
067	RTN	
068	*LBLC	
069	STOI	Store pointer
070	GTOi	
071	*LBL1	Compute input stability circles.
072	RCLE	
073	CHS	
074	RCLD	
075	RCL6	
076	RCL7	
077	GSB9	
078	CHS	
079	RCL2	
080	RCL1	
081	GSB8	
082	X⇄Y	
083	CHS	
084	GSB5	Display ∠ r_{s1}
085	X⇄Y	
086	RCL1	
087	X^2	
088	RCL6	
089	X^2	
090	-	
091	÷	
092	GSB5	Display $\lvert r_{s1} \rvert$
093	GTO3	
094	*LBL2	Compute output stability circles.
095	RCL2	
096	CHS	
097	RCL1	
098	RCL6	
099	RCL7	
100	GSB9	
101	CHS	
102	RCLE	
103	RCLD	
104	GSB8	
105	X⇄Y	
106	CHS	
107	GSB5	Display ∠ r_{s2}
108	X⇄Y	
109	RCLD	
110	X^2	
111	RCL6	
112	X^2	

REGISTERS

0	1	2	3	4	5	6	7	8	9
$\lvert C_2 \rvert$	s_{11}	θ_{11}	s_{12}	θ_{12}	sgn(B)	$\lvert\Delta\rvert$	∠Δ	B	K
S0	S1	S2	S3	S4	S5	S6	S7	S8	S9

A	B	C	D	E	I
D_2	s_{21}	θ_{21}	s_{22}	θ_{22}	G_p

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

LABELS

A $G_p \to \angle r, r, \rho$	B $\Gamma_L \to \Gamma_{ms}$	C $i \to \angle r, r, \rho$	D	E
a	b $\Gamma_s \to \Gamma_{ml}$	c	d	e
0	1 Used	2 Used	3	4 Used
5 DISPLAY	6	7 Used	8 CADD	9 CMULT

FLAGS

0	PRINT
1	
2	
3	

SET STATUS

FLAGS	ON	OFF	TRIG		DISP	
0	☒	☐	DEG	☒	FIX	☐
1	☐	☒	GRAD	☐	SCI	☐
2	☐	☒	RAD	☐	ENG	☒
3	☐	☒			n	3

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]	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].
x ↑ y [A]	↑ 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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