

HEWLETT-PACKARD

HP-41

USERS' LIBRARY SOLUTIONS
Electrical Engineering

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INTRODUCTION

This HP-41C Solutions book was written to help you get the most from your calculator. The programs were chosen to provide useful calculations for many of the common problems encountered.

They will provide you with immediate capabilities in your everyday calculations and you will find them useful as guides to programming techniques for writing your own customized software. The comments on each program listing describe the approach used to reach the solution and help you follow the programmer's logic as you become an expert on your HP calculator.

KEYING A PROGRAM INTO THE HP-41C

There are several things that you should keep in mind while you are keying in programs from the program listings provided in this book. The output from the HP 82143A printer provides a convenient way of listing and an easily understood method of keying in programs without showing every keystroke. This type of output is what appears in this handbook. Once you understand the procedure for keying programs in from the printed listings, you will find this method simple and fast. Here is the procedure:

- At the end of each program listing is a listing of status information required to properly execute that program. Included is the SIZE allocation required. Before you begin keying in the program, press **XEQ** **ALPHA** **SIZE** **ALPHA** and specify the allocation (three digits; e.g., 10 should be specified as 010).

Also included in the status information is the display format and status of flags important to the program. To ensure proper execution, check to see that the display status of the HP-41C is set as specified and check to see that all applicable flags are set or clear as specified.

- Set the HP-41C to PRGM mode (press the **PRGM** key) and press **■** **GTO** **□** **□** to prepare the calculator for the new program.
- Begin keying in the program. Following is a list of hints that will help you when you key in your programs from the program listings in this handbook.
 - When you see " (quote marks) around a character or group of characters in the program listing, those characters are ALPHA. To key them in, simply press **ALPHA**, key in the characters, then press **ALPHA** again. So "SAMPLE" would be keyed in as **ALPHA** "SAMPLE" **ALPHA**.
 - The diamond in front of each LBL instruction is only a visual aid to help you locate labels in the program listings. When you key in a program, ignore the diamond.
 - The printer indication of divide sign is /. When you see / in the program listing, press **÷**.
 - The printer indication of the multiply sign is ×. When you see × in the program listing, press **×**.
 - The T character in the program listing is an indication of the **APPEND** function. When you see T, press **■** **APPEND** in ALPHA mode (press **■** and the K key).
 - All operations requiring register addresses accept those addresses in these forms:
 - nn (a two-digit number)
 - IND nn (INDIRECT: **■**, followed by a two-digit number)
 - X, Y, Z, T, or L (a STACK address: **□** followed by X, Y, Z, T, or L)
 - IND X, Y, Z, T or L (INDIRECT stack: **■** **□** followed by X, Y, Z, T, or L)

Indirect addresses are specified by pressing **■** and then the indirect address. Stack addresses are specified by pressing **□** followed by X, Y, Z, T, or L. Indirect stack addresses are specified by pressing **■** **□** and X, Y, Z, T, or L.

Printer Listing

```

01♦LBL "SAM
PLE"
02 "THIS IS
A "
03 "T-SAMPLE
"
04 AVIEW
05 6
06 ENTER↑
07 -2
08 /
09 ABS
10 STO IND
L
11 "R3="
12 ARCL 03
13 AVIEW
14 RTN

```

Keystrokes

```

■ LBL ALPHA SAMPLE ALPHA
ALPHA THIS IS A ALPHA
ALPHA ■ APPEND SAMPLE
■ AVIEW ALPHA
6
ENTER+
2 CHS
÷
XEQ ALPHA ABS ALPHA
STO ■ □ L
ALPHA R3= ■ ARCL 03
■ AVIEW
ALPHA
■ RTN

```

Display

```

01 LBLT SAMPLE
02T THIS IS A
03T T-SAMPLE
04 AVIEW
05 6
06 ENTER ↑
07 -2
08 /
09 ABS
10 STO IND L
11T R3=
12 ARCL 03
13 AVIEW
14 RTN

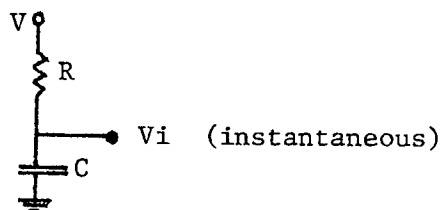
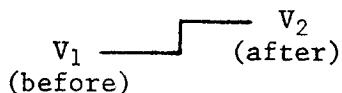
```


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RC TIMING

This program computes any one of the six variables shown, provided the other five are known.



V_1 = Voltage before step

C = Capacitance

V_2 = Voltage after step

V_i = Instantaneous voltage

R = Resistance

t = Time

All solutions are algebraically derived from this basic formula:

$$V_i = V_1 e^{-t/\tau} + V_2 (1 - e^{-t/\tau})$$

NOTE: For voltages across the resistor, remember that $V_R + V_C = V$ applies at all times.

Example:

A 555 type of integrated circuit timer uses an external RC configuration for time determination. When used as a one-shot its output pulse terminates when the capacitor charges to 2/3 of the supply voltage. Until the pulse starts, the capacitor is shorted so $V_1 = 0$. Given a supply voltage of 12V, a 47 μ F capacitor, and you need a 1 second pulse, what size resistor should you use?

Keystrokes:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 007

[XEQ] [ALPHA] RC [ALPHA]

V1?

0 [R/S]

V2?

12 [R/S]

VI?

8 [R/S]

C?

47 [EEX] 6 [CHS] [R/S]

R?

[R/S]

T?

1 [R/S]

1.000 00

[XEQ] [ALPHA] R [ALPHA]

R=19.37E3

User Instructions

				SIZE: 007
STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program			
2	Begin execution and enter data, skip unknown by pressing [R/S].		[XEQ] RC	V1?
		V ₁	[R/S]	V2?
		V ₂	[R/S]	VI?
		V _i	[R/S]	C?
		C	[R/S]	R?
		R	[R/S]	T?
		t	[R/S]	
3	Execute for desired output:			
	V ₁		[XEQ] V1	V1=
	V ₂		[XEQ] V2	V2=
	V _i		[XEQ] VI	VI=
	C		[XEQ] C	C=
	R		[XEQ] R	R=
	t		[XEQ] T	T=
4	To vary one or more parameters simply place the new value in the appropriate register			
		V ₁	[STO] 01	
		V ₂	[STO] 02	
		V _i	[STO] 03	
		C	[STO] 04	
		R	[STO] 05	
		t	[STO] 06	
	Go to step 3			

Program Listings

01♦LBL "RC"		52 XEQ 00	
02 ENG 3		53 RCL 02	
03 CF 00		54 *	V ₁
04 "V1?"		55 RCL 03	
05 PROMPT	Initialize	56 X<>Y	
06 STO 01	registers	57 -	
07 "V2?"		58 STO 00	
08 PROMPT		59 XEQ 03	
09 STO 02		60 RCL 00	
10 "V1?"		61 X<>Y	
11 PROMPT		62 /	
12 STO 03		63 STO 01	
13 "C?"		64 "V1="	
14 PROMPT		65 GTO 05	-----
15 STO 04		66♦LBL C	
16 "R?"		67 XEQ 01	
17 PROMPT		68 RCL 05	C
18 STO 05		69 *	
19 "T?"		70 RCL 06	
20 PROMPT		71 X<>Y	
21 STO 06		72 /	
22 STOP		73 STO 04	
23♦LBL "V2"	-----	74 "C="	
24 XEQ 03		75 GTO 05	-----
25 RCL 01	V ₂	76♦LBL "R"	
26 *		77 XEQ 01	
27 RCL 03		78 RCL 04	R
28 X<>Y		79 *	
29 -		80 RCL 06	
30 STO 00		81 X<>Y	
31 XEQ 00		82 /	
32 RCL 00		83 STO 05	
33 X<>Y		84 "R="	
34 /		85 GTO 05	-----
35 STO 02		86♦LBL "T"	
36 "V2="		87 XEQ 01	
37 GTO 05		88 RCL 04	t
38♦LBL "VI"	-----	89 RCL 05	
39 XEQ 03		90 *	
40 RCL 01	V _i	91 *	
41 *		92 STO 06	
42 STO 00		93 "T="	
43 XEQ 00		94♦LBL 05	
44 RCL 02		95 ARCL X	
45 *		96 AVIEW	
46 RCL 00		97 STOP	-----
47 +		98♦LBL 01	
48 STO 03		99 1	
49 "VI="		100 RCL 03	
50 GTO 05		101 RCL 01	
51♦LBL "V1"	-----	102 -	

[illegible]

DATA REGISTERS				STATUS			
00	Temporary Storage	50		SIZE	007	TOT. REG.	37
	V ₁			ENG	3	FIX	
	V ₂			DEG		RAD	
	V _i					SCI	
	C					ON	OFF X
05	R	55		FLAGS			
	t			#	INIT S/C	SET INDICATES	CLEAR INDICATES
				05		To calculate	To calculate e^{k_c}
						1 - e^{k_c}	
10		60					
15		65					
20		70					
25		75					
30		80					
35		85					
40		90		ASSIGNMENTS			
				FUNCTION	KEY	FUNCTION	KEY
45		95					

RC TIMING

PROGRAM REGISTERS NEEDED: 31

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SOLUTION BOOK:
ELECTRICAL ENGINEERING

ROW 1 (1 - 4)



ROW 2 (4 - 10)



ROW 3 (11 - 19)



ROW 4 (19 - 24)



ROW 5 (24 - 34)



ROW 6 (35 - 38)



ROW 7 (39 - 47)



ROW 8 (48 - 51)



ROW 9 (52 - 60)



ROW 10 (61 - 67)



ROW 11 (67 - 76)



ROW 12 (76 - 83)



ROW 13 (84 - 87)



ROW 14 (88 - 97)



ROW 15 (98 - 110)



ROW 16 (111 - 122)



ROW 17 (122 - 125)



FREQUENCY RESPONSE OF A TRANSFER FUNCTION

For transfer function of the form:

$$G(S) = \frac{K_1(Z_2S + 1)}{S^{N_3}(Z_4S + 1)(Z_5S + 1)\left(\frac{S^2}{\omega_7^2} + \frac{2Z_6S}{\omega_7} + 1\right)}$$

the program computes $\angle G(j\omega)$, $|G(j\omega)|$ and $\log |G(j\omega)|$ for any input frequency ω .

Parameters K_1 , Z_2 , N_3 , Z_4 , Z_5 , Z_6 and ω_7 are stored in registers 01, 02, 03, 04, 05, 06, and 07 respectively.

NOTE: For type 0 systems, enter $N_3 = 0$. Z_2 , Z_4 and/or Z_5 can be entered as 0. If there is no quadratic term, enter Z_6 as 0 and ω_7 very large compared to $\frac{1}{Z_5}$, where Z_5 is the smallest first order term used (other than zero).

Example:

Find $|G(j\omega)|$, $\angle G(j\omega)$ and $\log |G(j\omega)|$ for $G(S) = \frac{12(S + 0.6)}{S(S + 1)(S^2 + 6S + 36)}$ frequency 0.01 rad/sec.

First put $G(S)$ into proper form: $G(S) = \frac{.2(1.67S + 1)}{S(S + 1)\left[\left(\frac{S}{6}\right)^2 + \left(\frac{S}{6}\right) + 1\right]}$

Keystrokes:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 010

[XEQ] [ALPHA] FREQ [ALPHA]

.2 [R/S]

1.67 [R/S]

1 [R/S]

1 [R/S]

0 [R/S]

.5 [R/S]

6 [R/S]

.01 [R/S]

[R/S]

[R/S]

K1=?

Z2=?

N3=?

Z4=?

Z5=?

Z6=?

W7=?

W=?

G $\angle$ JW=20.00

$\angle$ G $\angle$ JW=-89.71

LOG G=1.30

[illegible]

Program Listings

01♦LBL "FRE		51 1	
02 FIX 2		52 R-P	
03 "K1=?"	Store data	53 XEQ 01	-----
04 PROMPT		54 RCL 08	
05 STO 01		55 RCL 03	S ^{N3}
06 "Z2=?"		56 Y↑X	
07 PROMPT		57 *	
08 STO 02		58 X<>Y	
09 "N3=?"		59 RCL 03	
10 PROMPT		60 90	
11 STO 03		61 *	
12 "Z4=?"		62 +	
13 PROMPT		63 CHS	
14 STO 04		64 X<>Y	
15 "Z5=?"		65 1/X	-----
16 PROMPT		66 RCL 02	
17 STO 05		67 RCL 08	
18 "Z6=?"		68 *	K ₁ (Z ₂ S + 1)
19 PROMPT		69 RCL 01	
20 STO 06		70 *	
21 "W7=?"		71 RCL 01	
22 PROMPT		72 R-P	
23 STO 07		73 XEQ 01	-----
24♦LBL "W2"		74 "G<JW>="	
25 "W=?"		75 ARCL X	
26 PROMPT		76 AVIEW	Display
27 STO 08		77 STOP	
28 RCL 06		78 STO 09	
29 RCL 07		79 X<>Y	
30 /		80 "ΔG<JW>="	
31 2	$\left[\frac{S_2^2}{\omega_7^2} + \frac{2Z_6}{\omega_7} \right] + 1$	"	
32 *		81 ARCL X	
33 RCL 08		82 AVIEW	
34 *		83 STOP	
35 1		84 RCL 09	
36 RCL 08		85 LOG	
37 RCL 07		86 "LOG G="	
38 /		87 ARCL X	
39 X↑2		88 AVIEW	
40 -		89 STOP	-----
41 R-P		90♦LBL 01	
42 RCL 05		91 X<>Y	
43 RCL 08	Z ₅ S + 1	92 RDN	Multiply
44 *		93 *	complex
45 1		94 RDN	numbers
46 R-P		95 +	
47 XEQ 01		96 R↑	
48 RCL 04		97 RTN	
49 RCL 08	Z ₄ S + 1	98 .END.	
50 *			
		00	

DATA REGISTERS				STATUS			
00		50		SIZE <u>010</u>	TOT. REG. <u>34</u>	USER MODE	
	K ₁			ENG <u> </u>	FIX <u>2</u>	SCI <u> </u>	ON <u> </u> OFF <u>X</u>
	Z ₂			DEG <u>X</u>	RAD <u> </u>	GRAD <u> </u>	
	N ₃			FLAGS			
	Z ₄						
05	Z ₅	55		#	INIT S/C	SET INDICATES	CLEAR INDICATES
	Z ₆						
	ω ₇						
	ω						
	G(jω)						
10		60					
15		65					
20		70					
25		75					
30		80					
35		85					
				ASSIGNMENTS			
				FUNCTION	KEY	FUNCTION	KEY
40		90					
45		95					

FREQUENCY RESPONSE OF
A TRANSFER FUNCTION
PROGRAM REGISTERS NEEDED: 25

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ROW 1 (1 - 3)



ROW 2 (3 - 9)



ROW 3 (9 - 15)



ROW 4 (15 - 20)



ROW 5 (21 - 24)



ROW 6 (25 - 34)



ROW 7 (35 - 47)



ROW 8 (47 - 56)



ROW 9 (57 - 68)



ROW 10 (69 - 74)



ROW 11 (74 - 80)



ROW 12 (80 - 86)



ROW 13 (86 - 96)

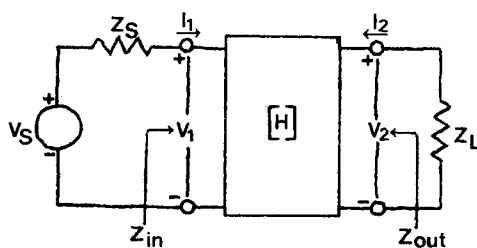


ROW 14 (97 - 98)



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

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

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:

Display:

[USER]		(set USER mode)
[///][FIX] 2		
[XEQ][ALPHA] SIZE [ALPHA] 023		
0 [ENTER+] 1100 [ENTER+] 11		
[XEQ][ALPHA] HP [ALPHA]		
0 [ENTER+] 250 [EEX] 6 [CHS]		
[ENTER+] 12 [XEQ][ALPHA] HP [ALPHA]		
0 [ENTER+] 50 [ENTER+]		
21 [XEQ][ALPHA] HP [ALPHA]		
0 [ENTER+] 25 [EEX] 6 [CHS]		
[ENTER+] 22 [XEQ][ALPHA] HP [ALPHA]		
0 [ENTER+] 1000 [ENTER]		
0 [ENTER+] 10000 [XEQ][ALPHA] Z [ALPHA]		
[A]	MAG=-40.00	(A _i)
[R/S]	Δ =0.00	
[B]	MAG=-400.00	(A _v)
[R/S]	Δ =0.00	
[C]	MAG=-200.00	(A _{vs})
[R/S]	Δ =0.00	
[D]	MAG=1,000.00	(Z _{in})
[R/S]	Δ =0.00	
[E]	MAG=52,500.00	(Z _{out})
[R/S]	Δ =0.00	

				SIZE: 023
STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program and set USER mode		[USER]	
2	Input h-parameters			
	- Angle	θ_{ij}, deg	[ENTER↑]	
	- Magnitude	h_{ij}	[ENTER↑]	
	- Designation (row, column)	ij	[XEQ] HP	
	Repeat for all 4 parameters			
3	Input termination impedances			
	- Angle of Z_S	θ_S, deg	[ENTER↑]	
	- Magnitude of Z_S	$ Z_S $	[ENTER↑]	
	- Angle of Z_L	θ_L, deg	[ENTER↑]	
	- Magnitude of Z_L	$ Z_L $	[XEQ] Z	
4	Compute:			
	- Current gain		[A]	MAG=
			[R/S]	Δ =
	- Voltage gain		[B]	MAG=
			[R/S]	Δ =
	- Voltage gain with source resistor		[C]	MAG=
			[R/S]	Δ =
	- Input impedance		[D]	MAG=
			[R/S]	Δ =
	- Output impedance		[E]	MAG=
			[R/S]	Δ =

Program Listings

01♦LBL "HP"		51 RCL 17	
02 STO 00		52 RCL 16	
03 3		53 XEQ 02	
04 -	Store matrix	54 RCL 03	
05 STO 01		55 RCL 02	
06 RDN		56 R-P	
07 STO IND		57 1/X	
00		58 X<>Y	
08 RDN		59 CHS	
09 STO IND		60 X<>Y	
01		61 XEQ 01	
10 STOP		62 GTO 20	
11♦LBL "Z"		63♦LBL B	
12 STO 14		64 XEQ b	
13 RDN		65 1/X	
14 STO 15	Store impedances	66 X<>Y	Voltage gain
15 RDN		67 CHS	
16 STO 16		68 X<>Y	
17 RDN		69 RCL 03	
18 STO 17		70 RCL 02	
19 CF 05		71 XEQ 01	
20 STOP		72 GTO 20	
21♦LBL E		73♦LBL C	
22 RCL 19		74 XEQ b	
23 RCL 22		75 RCL 17	
24 RCL 08		76 RCL 16	
25 RCL 11	Z _{out}	77 XEQ 02	Voltage gain with source resistor
26 XEQ 01		78 1/X	
27 P-R		79 X<>Y	
28 STO 02		80 CHS	
29 X<>Y		81 X<>Y	
30 STO 03		82 RCL 03	
31 RCL 19		83 RCL 02	
32 RCL 22		84 XEQ 01	
33 RCL 17		85 GTO 20	
34 RCL 16		86♦LBL D	
35 XEQ 01		87 CF 04	
36 P-R		88♦LBL 03	
37 ST+ 02		89 SF 05	
38 X<>Y		90 XEQ 00	Z _{in}
39 ST+ 03		91 RCL 15	
40 RCL 18		92 RCL 14	
41 RCL 21		93 XEQ 01	
42 RCL 09		94 RCL 09	
43 RCL 12		95 RCL 12	
44 XEQ 01		96 XEQ 01	
45 P-R		97 RCL 08	
46 ST- 02		98 RCL 11	
47 X<>Y		99 XEQ 02	
48 ST- 03		100 FS? 04	
49 RCL 08		101 RTN	
50 RCL 11		102 GTO 20	

Program Listings

103♦LBL H		155 AVIEW	
104 CF 05		156 STOP	
105♦LBL 00		157 RTN	
106 RCL 19		158♦LBL b	
107 RCL 22	Current gain	159 SF 05	
108 RCL 15		160 XEQ 00	
109 RCL 14		161 RCL 15	
110 XEQ 01		162 RCL 14	
111 P-R		163 XEQ 01	
112 1		164 STO 02	
113 +		165 X<>Y	
114 R-P		166 STO 03	
115 RCL 18		167 SF 04	
116 CHS		168 XEQ 03	
117 RCL 21		169 RTN	
118 1/X		170 .END.	
119 XEQ 01			
120 1/X			
121 CHS			
122 FS? 05			
123 RTN		70	
124 GTO 20			
125♦LBL 01			
126 X<>Y			
127 RDN			
128 *			
129 RDN			
130 +	Multiply complex numbers		
131 R↑			
132 RTN			
133♦LBL 02		80	
134 P-R			
135 RDN			
136 RDN			
137 P-R			
138 R↑	Add complex numbers		
139 R↑			
140 X<>Y			
141 RDN			
142 +			
143 RDN		90	
144 +			
145 R↑			
146 R-P			
147 RTN			
148♦LBL 20			
149 "MAG="			
150 XEQ 01			
151 X<>Y			
152 "Z="			
153♦LBL 01	Display		
154 ARCL X		00	

REGISTERS, STATUS, FLAGS, ASSIGNMENTS

DATA REGISTERS			STATUS				
00	Used	50	SIZE <u>023</u> TOT. REG. <u>62</u> USER MODE ENG <u> </u> FIX <u> </u> SCI <u> </u> ON <u>X</u> OFF <u> </u> DEG <u>X</u> RAD <u> </u> GRAD <u> </u>				
05		55	FLAGS # INIT S/C SET INDICATES CLEAR INDICATES				
	Δh_i		04		Return	Continue	
	Δh_r		05		Return	Continue	
10		60					
	h_i						
	h_r						
	R_i						
15	ΔR_i	65					
	R_s						
	ΔR_s						
	Δh_f						
	Δh_0						
20		70					
	h_f						
	h_0						
25		75					
30		80					
35		85					
			ASSIGNMENTS				
			FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	
40		90	FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	
45		95	FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	
			FUNCTION		KEY	FUNCTION	

TRANSISTOR AMPLIFIER
PERFORMANCE
PROGRAM REGISTERS NEEDED: 40

HEWLETT PACKARD
SOLUTION BOOK:
ELECTRICAL ENGINEERING

ROW 1 (1 - 7)



ROW 2 (8 - 15)



ROW 3 (16 - 23)



ROW 4 (23 - 32)



ROW 5 (32 - 39)



ROW 6 (39 - 46)



ROW 7 (47 - 54)



ROW 8 (55 - 63)



ROW 9 (63 - 71)



ROW 10 (72 - 77)



ROW 11 (77 - 85)



ROW 12 (85 - 92)



ROW 13 (93 - 99)



ROW 14 (100 - 106)



ROW 15 (107 - 115)



ROW 16 (116 - 124)



ROW 17 (124 - 135)



ROW 18 (136 - 148)



TRANSISTOR AMPLIFIER
PERFORMANCE

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ROW 19 (148 - 152)



ROW 20 (153 - 160)



ROW 21 (161 - 168)

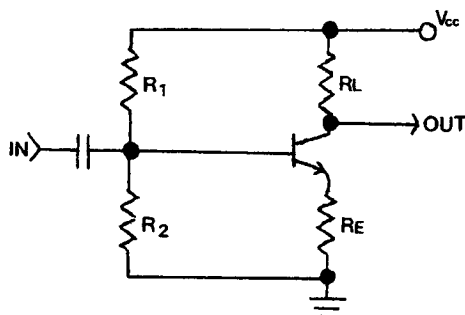


ROW 22 (169 - 170)



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 set of parameters 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 cast 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

The transistor's thermal resistance is calculated:

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

and the minimum load resistance and emitter resistance are estimated:

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

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

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

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

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

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

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

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

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

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

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

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

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

From this point, if $V_{BEX} > V_{BEN}$, then R_E is set to zero, R_L is increased by 10%, and the design procedure is repeated. Iterations continue until

$\frac{R_{E(n+1)} - R_{En}}{R_{En}} < .5\%$. If at any time the condition $T_{max} > T_{Jmax}$ occurs, R_L is increased by 10%.

When the iterative procedure is complete, T_{max} , I_{Cmax} , T_{min} , and I_{Cmin} are displayed.

Then values for

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

h_{FEmin} = minimum worst-cast 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:

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

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

Now the bias resistors R_1 and R_2 are calculated:

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

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

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

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

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

Example:

A single-stage class "A" amplifier is connected to a 30-V power supply. Calculate the maximum power output and maximum power gain obtained from a transistor over an ambient temperature range of 0°C to 70°C, with a maximum quiescent-current variation of $\pm 20\%$.

From the transistor's data sheet:

$T_{J\max}$	150°C
P_D	= 0.36 W
ΔV_{BE}	= 0.10 v from 3 to 30 mA
$V_{BE\min}$	= 0.52 v at 3 mA at 25°C
$V_{BE\max}$	= 0.72 v at 3 mA at 25°C
I_1	= 0.001 A

Keystrokes:

[XEQ] [ALPHA] SIZE [ALPHA] 017

30 [STO] 00

.2 [STO] 01

70 [STO] 02

0 [STO] 03

150 [STO] 04

.36 [STO] 05

.001 [STO] 06

.1 [STO] 07

.52 [STO] 08

.72 [STO] 09

[XEQ] [ALPHA] BIAS [ALPHA]

[R/S]

[R/S]

[R/S]

[R/S]

600 [R/S]

100 [R/S]

[R/S]

[R/S]

[R/S]

[R/S]

Display:

T=148.E0

I=18.0E-3

T=74.8E0

I=12.0E-3

H MAX?

H MIN?

RE=115.E0

RL=888.E0

R2=4.18E3

R1=45.0E3

AP=22.9E0

User Instructions

				SIZE: 017
STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program			
2	Store data			
		V_{CC}	[STO] 00	
		ΔI_{CQ}	[STO] 01	
		$T_{Amax}, ^\circ C$	[STO] 02	
		$T_{Amin} ^\circ C$	[STO] 03	
		T_{Jmax}	[STO] 04	
		P_D	[STO] 05	
		I_1	[STO] 06	
		ΔV_{BE}	[STO] 07	
		V_{BE1min}	[STO] 08	
		V_{BE1max}	[STO] 09	
3	Compute maximum and minimum temperatures			
	and currents		[XEQ] BIAS	T= (max)
			[R/S]	I= (max)
			[R/S]	T= (min)
			[R/S]	I= (min)
			[R/S]	H MAX?
4	Input maximum and minimum h_{FE} to compute	h_{FEmax}	[R/S]	H MIN?
	resistor values	h_{FEmin}	[R/S]	RE=
			[R/S]	RL=
			[R/S]	R2=
			[R/S]	R1=
	and minimum power gain		[R/S]	AP=

Program Listings

01*LBL "BIA S"		51 1	
02 ENG 2	θ_{JA}	52 RCL 01	
03 RCL 04		53 X $\uparrow$ 2	
04 25		54 -	
05 -		55 2	
06 RCL 05		56 /	
07 /		57 RCL 10	
08 STO 05		58 *	
09 RCL 00	-----	59 RCL 05	
10 X $\uparrow$ 2		60 *	
11 *	R_{L1}	61 RCL 00	
12 RCL 04		62 *	
13 RCL 02		63 RCL 03	
14 -		64 +	
15 4.4		65 XEQ 03	
16 *		66 CHS	
17 /		67 1	
18 STO 13		68 RCL 01	
19 .1	-----	69 -	
20 *	R_{E1}	70 XEQ 04	
21 STO 14		71 RCL 09	
22*LBL 00	-----	72 +	
23 RCL 00		73 STO 16	
24 2		74 RCL 15	
25 /	Loop	75 X $\gt$ Y?	
26 ENTER $\uparrow$		76 GTO 02	
27 ENTER $\uparrow$		77 -	
28 RCL 13		78 RCL 10	
29 RCL 14		79 /	
30 +		80 RCL 01	
31 /		81 /	
32 STO 10		82 RCL 14	
33 RCL 05		83 X $\lt$ $\gt$ Y	
34 *		84 STO 14	
35 *		85 XCH	
36 RCL 02		86 .5	
37 +		87 X $\leq$ Y?	
38 RCL 04		88 GTO 00	
39 X $\lt$ $\gt$ Y		89 FS? 01	
40 X $\gt$ Y?		90 GTO 01	
41 GTO 05		91 SF 01	End Loop
42 XEQ 03		92 GTO 00	
43 CHS		93*LBL 01	
44 RCL 01		94 CF 01	
45 1		95 "H MAX?"	R_B
46 +		96 PROMPT	
47 XEQ 04		97 "H MIN?"	
48 RCL 00		98 PROMPT	
49 +		99 STO 12	
50 STO 15		100 X $\lt$ $\gt$ Y	
		101 STO 11	

Program Listings

102 RCL 01		153 LASTX	
103 2		154 RCL 03	
104 *		155 -	
105 RCL 10		156 /	
106 *		157 RCL 13	
107 RCL 14		158 RCL 14	
108 *		159 "RE="	Display
109 RCL 15		160 XEQ 02	
110 +		161 "RL="	
111 RCL 16		162 XEQ 02	
112 -		163 "R2="	
113 RCL 12		164 XEQ 02	
114 *		165 "R1="	
115 RCL 11		166 XEQ 02	
116 *		167 /	
117 1		168 RCL 12	
118 RCL 01		169 *	Power gain
119 -		170 RCL 02	
120 RCL 11		171 *	
121 *		172 LASTX	
122 1		173 RCL 14	
123 RCL 01		174 RCL 12	
124 +		175 *	
125 RCL 12		176 +	
126 *		177 /	
127 -		178 LOG	
128 /		179 10	
129 RCL 10		180 *	
130 /		181 "AP="	
131 STO 02		182 *LBL 02	
132 RCL 12		183 ARCL X	
133 /		184 AVIEW	
134 RCL 14	V_{BB}	185 STOP	
135 +		186 RDN	
136 RCL 10		187 RTN	
137 *		188 *LBL 03	
138 1		189 FS? 01	
139 RCL 01		190 XEQ A	Temperature
140 -		191 25	calculations
141 *		192 -	
142 RCL 16		193 2.2 E-3	
143 +		194 *	
144 STO 03		195 RTN	
145 RCL 00		196 *LBL A	
146 X<>Y		197 "T="	
147 /		198 GTO D	
148 RCL 02	R_1	199 *LBL 04	
149 *		200 RCL 10	
150 RCL 02		201 *	
151 RCL 00	R_2	202 FS? 01	
152 *		203 XEQ I	

[illegible]

[illegible]

CLASS "A" TRANSISTOR AMPLIFIER
BIAS OPTIMIZATION
PROGRAM REGISTERS NEEDED: 46

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ROW 1 (1 - 4)



ROW 2 (5 - 15)



ROW 3 (16 - 27)



ROW 4 (28 - 40)



ROW 5 (41 - 48)



ROW 6 (49 - 61)



ROW 7 (62 - 70)



ROW 8 (71 - 81)



ROW 9 (82 - 90)



ROW 10 (91 - 95)



ROW 11 (95 - 101)



ROW 12 (102 - 113)



ROW 13 (114 - 126)



ROW 14 (127 - 139)



ROW 15 (140 - 151)



ROW 16 (152 - 160)



ROW 17 (160 - 164)



ROW 18 (164 - 170)



CLASS "A" TRANSISTOR AMPLIFIER
BIAS OPTIMIZATION

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ROW 19 (171 - 181)



ROW 20 (181 - 190)



ROW 21 (190 - 195)



ROW 22 (196 - 202)



ROW 23 (203 - 212)



ROW 24 (212 - 221)



ROW 25 (222 - 225)



ACTIVE FILTER DESIGN

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

Equations:

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

Low pass filter

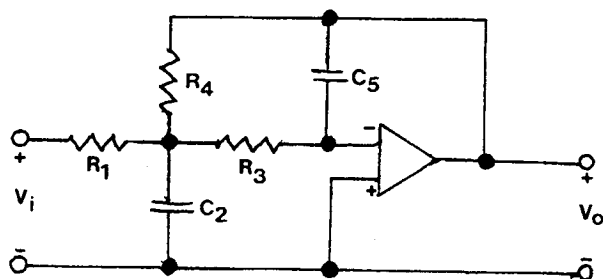
$$C_5 = C$$

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

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

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

$$R_4 = AR_1$$



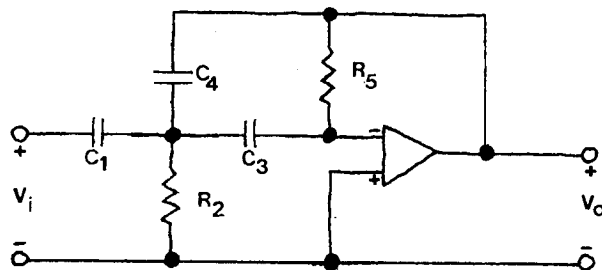
High pass filter

$$C_1 = C_3 = C$$

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

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

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



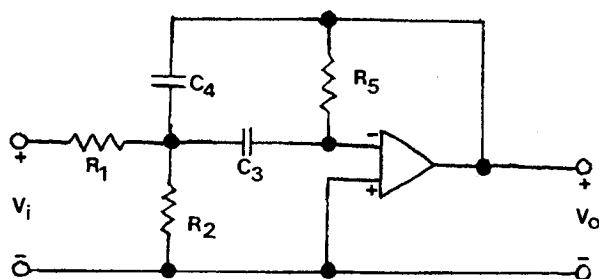
Bandpass filter

$$C_3 = C_4 = C$$

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

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

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



Example:

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

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

$$A = 10$$

$$\alpha = 1$$

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

Keystrokes:

[XEQ] [ALPHA] SIZE [ALPHA] 006
[XEQ] [ALPHA] AF [ALPHA]
10 [R/S]
10 [R/S]
1 [R/S]
1 [EEX] 6 [CHS] [R/S]
[XEQ] [ALPHA] HP [ALPHA]
[R/S]
[R/S]
[R/S]

Display:

F0?
A?
PF?
C?
1.000 -06
C1=C3=1.000E-6
C4=100.0E-9
R2=7.579E3
R5=334.2E3

[illegible]

Program Listings

01*LBL "AF"		52 *	
02 ENG 3		53 "R4="	R ₄
03 "FO?"		54 XEQ 05	
04 PROMPT		55 RCL 03	C ₅
05 STO 00	Initialization	56 "C5="	
06 "A?"		57 GTO 05	
07 PROMPT		58*LBL "HP"	-----
08 STO 01		59 RCL 03	High pass
09 "PF?"		60 "C1=C3="	C ₁ & C ₃
10 PROMPT		61 XEQ 05	
11 STO 02		62 RCL 01	
12 "C?"		63 /	C ₄
13 PROMPT		64 "C4="	
14 STO 03		65 XEQ 05	
15 STOP		66 XEQ A	
16*LBL "LP"	-----	67 RCL 02	
17 RCL 02	Low pass	68 X<>Y	
18 2		69 /	
19 /		70 2	
20 RCL 01	R ₁	71 RCL 01	R ₂
21 /		72 1/X	
22 XEQ A		73 +	
23 /		74 /	
24 STO 05		75 "R2="	
25 "R1="		76 XEQ 05	
26 XEQ 05	-----	77 RCL 03	
27 RCL 03		78 RCL 01	
28 4		79 2	
29 *		80 *	R ₅
30 RCL 01	C ₂	81 1	
31 1		82 +	
32 +		83 RCL 02	
33 *		84 /	
34 RCL 02		85 RCL 04	
35 X↑2		86 /	
36 /		87 "R5="	
37 "C2="		88 GTO 05	
38 XEQ 05		89*LBL "BP"	-----
39 RCL 02		90 XEQ A	Band pass
40 2		91 RCL 01	
41 /		92 *	R ₁
42 RCL 01	R ₃	93 RCL 02	
43 1		94 *	
44 +		95 1/X	
45 /		96 "R1="	
46 RCL 04		97 XEQ 05	
47 /		98 2	
48 "R3="		99 RCL 02	
49 XEQ 05		100 X↑2	
50 RCL 01		101 /	
51 RCL 05		102 RCL 01	R ₂

103	--		51	
104	RCL 04			
105	*			
106	RCL 02			
107	*			
108	1/X			
109	"R2="			
110	XEQ 05			
111	RCL 03	C_3 & C_4		
112	"C3=C4="		60	
113	XEQ 05			
114	2			
115	RCL 02			
116	/	R_5		
117	RCL 04			
118	/			
119	"R5="			
120	*LBL 05			
121	ARCL X	Display		
122	AVIEW		70	
123	STOP			
124	RTN			
125	*LBL A			
126	2	$2\pi f_0 C$		
127	PI			
128	*			
129	RCL 00			
130	*			
131	RCL 03			
132	*		80	
133	STD 04			
134	RTN			
135	.END.			
40			90	
50			00	

REGISTERS, STATUS, FLAGS, ASSIGNMENTS

DATA REGISTERS			STATUS			
00	f_0	50	SIZE <u>006</u> TOT. REG. <u>40</u> USER MODE ENG <u>3</u> FIX <u> </u> SCI <u> </u> ON <u> </u> OFF <u>X</u> DEG <u>X</u> RAD <u> </u> GRAD <u> </u>			
	A		FLAGS # INIT S/C SET INDICATES CLEAR INDICATES			
	α					
	C					
	$2\pi f_0 C$					
05	R1 (LP only)	55				
10		60				
15		65				
20		70				
25		75				
30		80				
35		85				
			ASSIGNMENTS			
			FUNCTION		KEY	
40		90	FUNCTION		KEY	
			FUNCTION		KEY	
			FUNCTION		KEY	
			FUNCTION		KEY	
45		95	FUNCTION		KEY	
			FUNCTION		KEY	
			FUNCTION		KEY	
			FUNCTION		KEY	
			FUNCTION		KEY	

ACTIVE FILTER DESIGN

PROGRAM REGISTERS NEEDED: 35

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ROW 1 (1 - 4)



ROW 2 (5 - 12)



ROW 3 (12 - 18)



ROW 4 (19 - 26)



ROW 5 (26 - 37)



ROW 6 (37 - 45)



ROW 7 (46 - 53)



ROW 8 (53 - 57)



ROW 9 (58 - 60)



ROW 10 (60 - 65)



ROW 11 (66 - 75)



ROW 12 (75 - 84)



ROW 13 (85 - 89)



ROW 14 (89 - 96)



ROW 15 (97 - 107)



ROW 16 (108 - 112)



ROW 17 (112 - 119)



ROW 18 (119 - 128)



ACTIVE FILTER DESIGN

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ROW 19 (129 - 135)



BUTTERWORTH FILTER DESIGN

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

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

Low Pass

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

High Pass

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

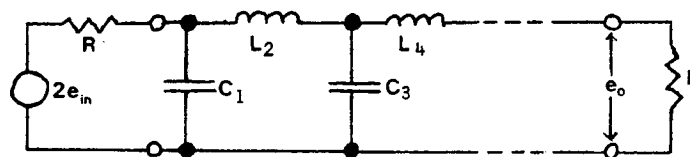
Band Pass

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

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:

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

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

where

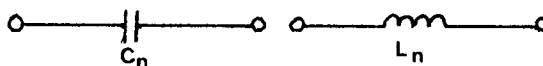
$$n = \text{INT} \left[\frac{1 + \ln(2 \times 10^{-\Delta\text{dB}/10} - 1)}{2 \ln(\omega/\omega_0)} \right]$$

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

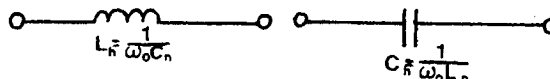
PASSBAND CHARACTERISTIC

CIRCUIT ELEMENTS

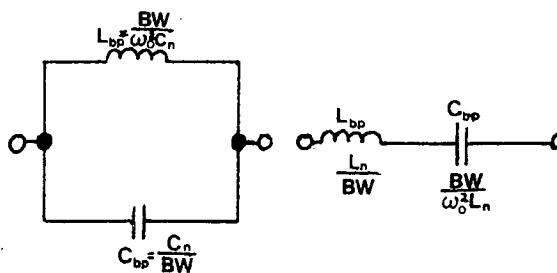
Low pass



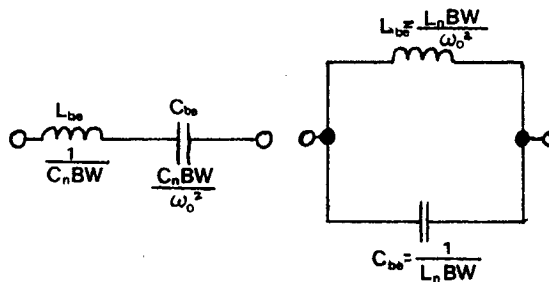
High pass



Band pass



Band elimination

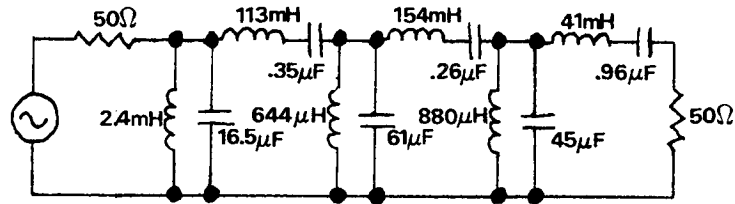


A bit of thought may be necessary to determine whether the L-C's are connected in series or parallel.

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

Example:

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:

[XEQ] [ALPHA] SIZE [ALPHA] 016

[XEQ] [ALPHA] BUT [ALPHA]

50 [R/S]

800 [R/S]

[XEQ] [ALPHA] BP [ALPHA]

100 [R/S]

900 [R/S]

30 [R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

Display:

$R=?$

$FO=?$

$BW=?$

$F1=?$

$A=?$

$N=6.000\ E0$

1.000 00

$C=16.48\ E-6$

$L=2.402\ E-3$

2.000 00

$L=112.5\ E-3$

$C=351.7\ E-9$

3.000 00

$C=61.49\ E-6$

$L=643.6\ E-6$

4.000 00

$L=153.7\ E-3$

$C=257.5\ E-9$

5.000 00

$C=45.02\ E-6$

$L=879.2\ E-6$

6.000 00

$L=41.19\ E-3$

$C=960.8\ E-9$

User Instructions

				SIZE: 016
STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program			
2	Begin execution		[XEQ] BUT	R=?
		R, Ω	[R/S]	FO=?
		f_0 , Hz	[R/S]	
3	Select filter type			
	Low pass		[XEQ] LP	F1=?
		f_1 , Hz	[R/S]	A=?
		Δ dB	[R/S]	
	Go to step 4			
	High pass		[XEQ] HP	F1=?
		f_1 , Hz	[R/S]	A=?
		Δ dB	[R/S]	
	Go to step 4			
	Band pass		[XEQ] BP	BW=?
		BW	[R/S]	F1=?
		f_1 , Hz	[R/S]	A=?
		Δ dB	[R/S]	
	Go to step 4			
	Band elimination		[XEQ] BE	BW=?
		BW	[R/S]	F1=?
		f_1 , Hz	[R/S]	A=?
		Δ dB	[R/S]	
4	Answer is displayed automatically			N=
			[R/S]	1.000 00
	(component number is displayed, then			C=
	component value.) Push [R/S] to continue		[R/S]	2.000 00
				L=

Program Listings

01♦LBL "BUT "		51 LN	
02 ENG 3	Initialization	52 ABS	
03 RAD		53 /	
04 "R=?"		54 1	
05 PROMPT		55 +	
06 STO 05		56 2	
07 "FO=?"		57 /	
08 PROMPT		58 INT	
09 XEQ 10		59 STO 15	
10 STO 07		60 STO 10	
11 STOP		61 "N="	
12♦LBL "LP"		62 ARCL X	
13 1		63 AVIEW	
14 GTO 01		64 STOP	
15♦LBL "HP"		65♦LBL 08	Loop
16 2		66 RCL 15	
17 GTO 01		67 RCL 10	
18♦LBL "BP"		68 -	
19 3		69 1	
20 GTO 01		70 +	
21♦LBL "BE"		71 STO 09	Butterworth equations
22 4		72 2	
23♦LBL 01		73 *	
24 STO 14		74 1	
25 3		75 -	
26 X>Y?		76 PI	
27 GTO 00		77 *	
28 "BW=?"		78 2	
29 PROMPT		79 /	
30 XEQ 10		80 RCL 15	
31 STO 08		81 /	
32♦LBL 00	Compute filter order	82 SIN	
33 "F1=?"		83 2	
34 PROMPT		84 *	
35 "A=?"		85♦LBL 09	
36 PROMPT		86 STO 11	
37 10		87 RCL 05	
38 /		88 -1	
39 10↑X		89 RCL 09	display i
40 2		90 PSE	$R(-1)^i$
41 *		91 Y↑X	
42 1		92 Y↑X	
43 -		93 *	
44 LN		94 GTO IND	Frequency transformation
45 STO 12		14	
46 X<>Y		95♦LBL 01	
47 XEQ 10		96 RCL 07	
48 XEQ 07		97 /	
49 RCL 12		98 XEQ 06	
50 X<>Y		99 GTO 00	
		100♦LBL 02	

Program Listings

101 RCL 07		152 GTO IND	
102 *		14	
103 1/X		153♦LBL 04	
104 XEQ 06		154 XEQ 03	Compute normalized frequency
105 CHS		155 GTO 00	
106 GTO 00		156♦LBL 02	
107♦LBL 03		157 XEQ 01	
108 SF 01		158♦LBL 00	
109 RCL 08		159 1/X	
110 /		160 CHS	
111 XEQ 06		161 GTO 05	
112 XEQ 00		162♦LBL 01	
113 ABS		163 RCL 11	
114 1/X		164 RCL 07	
115 RCL 07		165 /	
116 X↑2		166 GTO 05	
117 /		167♦LBL 03	
118 XEQ 06		168 RCL 11	
119 CHS		169 X↑2	
120 GTO 00		170 RCL 07	
121♦LBL 04		171 X↑2	
122 SF 01		172 -	
123 RCL 08		173 RCL 11	
124 *		174 /	
125 RCL 07		175 RCL 08	
126 X↑2		176 /	
127 /		177♦LBL 05	
128 XEQ 06		178 ABS	
129 XEQ 00		179 STO 13	
130 ABS		180 RTN	
131 RCL 07		181♦LBL 06	
132 X↑2		182 -1	
133 *		183 RCL 09	
134 1/X		184 Y↑X	
135 XEQ 06		185 *	
136 CHS		186 RTN	
137♦LBL 00		187♦LBL 10	
138 "L="	Display	188 2	Multiply by 2π
139 X<0?		189 *	
140 "C="		190 PI	
141 ABS		191 *	
142 ARCL X		192 RTN	
143 AVIEW		193 .END.	
144 STOP			
145 FS?C 01			
146 RTN			
147 DSE 10			
148 GTO 08			
149 RTN			
150♦LBL 07			
151 STO 11		00	

DATA REGISTERS				STATUS			
00		50		SIZE	016	TOT. REG.	58
				ENG	3	FIX	SCI
				DEG		RAD	GRAD
	temp. storage			USER MODE			
				ON OFF X			
05	R	55		FLAGS			
				#	INIT S/C	SET INDICATES	CLEAR INDICATES
	ω_0			01		Return	Continue
	BW						
	i						
10	counter	60					
	ω_n						
	temp. storage						
	1 2 filter type						
15	n	65					
20		70					
25		75					
30		80					
35		85					
				ASSIGNMENTS			
				FUNCTION		KEY	
40		90		FUNCTION		KEY	
				FUNCTION		KEY	
				FUNCTION		KEY	
45		95		FUNCTION		KEY	
				FUNCTION		KEY	
				FUNCTION		KEY	
				FUNCTION		KEY	

BUTTERWORTH FILTER DESIGN

PROGRAM REGISTERS NEEDED: 43

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ROW 1 (1 - 4)



ROW 2 (4 - 10)



ROW 3 (11 - 15)



ROW 4 (15 - 19)



ROW 5 (20 - 26)



ROW 6 (27 - 32)



ROW 7 (33 - 37)



ROW 8 (38 - 48)



ROW 9 (48 - 59)



ROW 10 (60 - 69)



ROW 11 (70 - 82)



ROW 12 (83 - 94)



ROW 13 (94 - 103)



ROW 14 (104 - 111)



ROW 15 (111 - 119)



ROW 16 (120 - 128)



ROW 17 (129 - 137)



ROW 18 (138 - 145)



BUTTERWORTH FILTER DESIGN

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ROW 19 (145 - 154)



ROW 20 (154 - 161)



ROW 21 (162 - 173)



ROW 22 (174 - 185)



ROW 23 (186 - 193)



Chebyshev Filter Design

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

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

Low Pass

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

High Pass

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

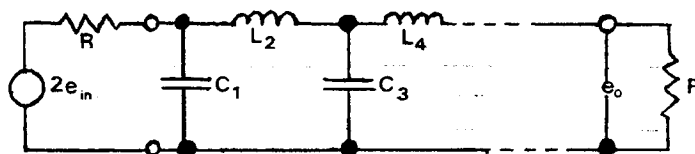
Band Pass

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

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:

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

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

where

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

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

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

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

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

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

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

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

using

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

as an initial guess where α is attenuation in dB's.

The resulting value is then increased slightly:

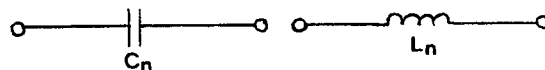
$$n \leftarrow \text{INT}(n + 1)$$

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

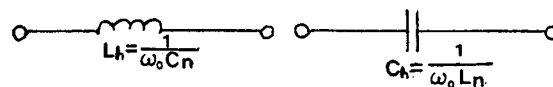
PASSBAND CHARACTERISTIC

CIRCUIT ELEMENTS

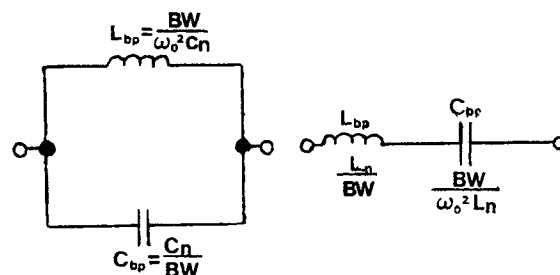
Low pass



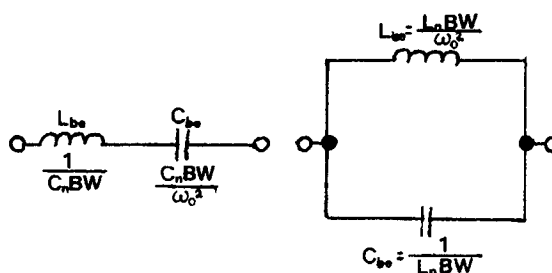
High pass



Band pass



Band elimination



A bit of thought may be necessary to determine whether the L-C's are connected in series or parallel.

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

Example:

Design a low pass Chebyshev filter with the following characteristics:

$R = 50\Omega$ $f_o = 500 \text{ Hz}$ pass band ripple = 3dB, and
30dB attenuation at 600 Hz.

Keystrokes:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 013

50 [STO] 00

500 [STO] 01

3 [STO] 03

30 [STO] 04

600 [STO] 05

[XEQ] [ALPHA] CHEB [ALPHA]

1 [R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

TYPE?

N=7.000E0

1.000 00

C=22.40E-6

2.000 00

L=12.29E-3

3.000 00

C=29.53E-6

4.000 00

L=12.79E-3

5.000 00

C=29.53E-6

6.000 00

L=12.29E-3

7.000 00

C=22.40E-6

Program Listings

<pre> 01♦LBL "CHE B" 02 ENG 3 03 RAD 04 1 05 XEQ 09 06 ST* 01 07 ST* 02 08 ST* 05 09 RCL 03 10 10 11 / 12 10↑X 13 1 14 - 15 SQRT 16 STO 06 17 RCL 04 18 10 19 / 20 10↑X 21 1 22 - 23 4 24 * 25 RCL 06 26 X↑2 27 / 28 2 29 - 30 STO 12 31 "TYPE?" 32 PROMPT 33 STO 07 34 GTO IND </pre>	Convert Hz to r/s Convert dB to ε Begin to compute filter order Filter type	<pre> 50 FS?C 02 51 RTN 52 GTO 05 53♦LBL 03 54 RCL 05 55 X↑2 56 RCL 01 57 X↑2 58 - 59 RCL 05 60 / 61 RCL 02 62 / 63 FS?C 02 64 RTN 65♦LBL 05 66 ABS 67 STO 08 68 ENTER↑ 69 X↑2 70 1 71 - 72 SQRT 73 + 74 STO 10 75 LN 76 RCL 12 77 LN 78 X<>Y 79 / 80 STO 09 81♦LBL 06 82 RCL 09 83 RCL 10 84 RCL 09 85 Y↑X 86 STO 05 87 ENTER↑ 88 1/X 89 + 90 RCL 12 91 - 92 RCL 05 93 ENTER↑ 94 1/X 95 - 96 / 97 RCL 10 98 LN 99 / </pre>	
<pre> 07 35♦LBL 04 36 SF 02 37 XEQ 03 38 GTO 00 39♦LBL 02 40 SF 02 41 XEQ 01 42♦LBL 00 43 1/X 44 CHS 45 GTO 05 46♦LBL 01 47 RCL 05 48 RCL 01 49 / </pre>	Compute ω_n	<pre> 100 2 </pre>	Newton's method root finder

Program Listings

101 /		152 PI	
102 -		153 2	
103 STO 09		154 /	
104 LASTX		155 RCL 09	
105 ABS		156 /	
106 .01		157 SIN	
107 X<=Y?		158 STO 12	
108 GTO 06		159 2	
109 RCL 09		160 *	
110 2		161 RCL 08	
111 /		162 SQRT	
112 1		163 /	
113 +		164♦LBL 10	
114 INT		165 STO 05	
115 STO 09		166 RCL 00	
116 "N="	Display n	167 -1	Display i
117 ARCL X		168 RCL 11	
118 AVIEW		169 PSE	
119 STOP		170 Y↑X	
120 1		171 Y↑X	
121 STO 11		172 *	
122 RCL 03		173 GTO IND	
123 40	Chebyshev setup	07	
124 /		174♦LBL 01	Frequency transformation
125 1		175 RCL 01	
126 E↑X		176 /	
127 LOG		177 XEQ 11	
128 /		178 GTO 00	
129 ENTER↑		179♦LBL 02	
130 +		180 RCL 01	
131 E↑X		181 *	
132 1		182 1/X	
133 X<>Y		183 XEQ 11	
134 +		184 CHS	
135 LASTX		185 GTO 00	
136 1		186♦LBL 03	
137 -		187 RCL 02	
138 /		188 /	
139 RCL 09		189 XEQ 11	
140 STO 10		190 SF 01	
141 2		191 XEQ 00	
142 *		192 1/X	
143 1/X		193 RCL 01	
144 Y↑X		194 X↑2	
145 ENTER↑		195 /	
146 1/X		196 XEQ 11	
147 -		197 CHS	
148 2		198 GTO 00	
149 /		199♦LBL 04	
150 X↑2		200 RCL 02	
151 STO 08		201 *	

202 RCL 01		253 /	
203 X↑2		254 RCL 08	
204 /		255 RCL 09	
205 XEQ 11		256 RCL 10	
206 SF 01		257 -	
207 XEQ 00		258 PI	
208 RCL 01		259 *	
209 X↑2		260 RCL 09	
210 *		261 /	
211 1/X		262 SIN	
212 XEQ 11		263 X↑2	
213 CHS		264 +	
214♦LBL 00		265 /	
215 "L="		266 GTO 10	
216 X<0?	Display L & C	267♦LBL 11	
217 "C="		268 -1	
218 ABS		269 RCL 11	
219 ARCL X		270 Y↑X	
220 AVIEW		271 *	
221 STOP		272 RTN	
222 FS?C 01		273♦LBL 09	
223 RTN		274 2	
224 DSE 10		275 *	
225 GTO 07		276 PI	
226 RTN		277 *	
227♦LBL 07	Loop	278 RTN	
228 RCL 12		279 END	
229 RCL 09			
230 RCL 10			
231 -			
232 1	Chebyshev equations	80	
233 +			
234 STO 11			
235 1			
236 -			
237 2			
238 *			
239 1			
240 +			
241 PI			
242 *		90	
243 2			
244 /			
245 RCL 09			
246 /			
247 SIN			
248 STO 12			
249 *			
250 4			
251 *			
252 RCL 05		00	

[illegible]

CHEBYSHEV FILTER DESIGN

PROGRAM REGISTERS NEEDED: 51

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ROW 1 (1 : 5)



ROW 2 (5 : 12)



ROW 3 (13 : 24)



ROW 4 (25 : 32)



ROW 5 (33 : 40)



ROW 6 (40 : 49)



ROW 7 (50 : 60)



ROW 8 (61 : 72)



ROW 9 (73 : 85)



ROW 10 (86 : 98)



ROW 11 (99 : 108)



ROW 12 (109 : 118)



ROW 13 (119 : 130)



ROW 14 (131 : 143)



ROW 15 (144 : 156)



ROW 16 (157 : 168)



ROW 17 (169 : 178)



ROW 18 (178 : 187)



CHEBYSHEV FILTER DESIGN

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ROW 19 (188 : 195)



ROW 20 (196 : 205)



ROW 21 (205 : 212)



ROW 22 (212 : 219)



ROW 23 (220 : 229)



ROW 24 (230 : 242)



ROW 25 (243 : 255)



ROW 26 (256 : 267)



ROW 27 (268 : 279)



ROW 28 (279 : 279)



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.

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

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

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

Then the new poles are given by

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

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

The network transfer function is

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

in which K is a constant chosen such that

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

The magnitude of the transfer function is

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

and its phase is

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

The normalized group delay is

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

Example:

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:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 016

[SF] 00

6 [STO] 00

800 [STO] 02

100 [STO] 03

400 [STO] 04

1600 [STO] 05

2 $\sqrt{x}$ $\sqrt{x}$ $\sqrt{x}$ [STO] 06

[XEQ] [ALPHA] BODE [ALPHA]

3 [R/S]

1 [R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

[R/S]

⋮

?

0,1-?

T=0.027

∠=161.536

MAG=-129.502

F=400.00

T=0.036

∠=158.504

MAG=-121.591

F=436.203

T=0.051

∠=154.506

MAG=-112.727

F=475.683

⋮

User Instructions

				SIZE: 016
STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program: for Butterworth		[SF] 00	
	for Chebyshev		[CF] 00	
2	Store applicable data:			
	Filter order	n	[STO] 00	
	Pass band ripple	rip	[STO] 01	
	Cutoff frequency	f_o	[STO] 02	
	Band width	BW	[STO] 03	
	Minimum frequency	f_1	[STO] 04	
	Maximum frequency	f_2	[STO] 05	
	Frequency steps	Δf	[STO] 06	
3	Begin execution		[XEQ] BODE	?
4	Input filter type:			
	1-Low pass	1	[R/S]	0,1-?
	2-High pass	2	[R/S]	0,1-?
	3-Band pass	3	[R/S]	0,1-?
	4-Band elimination	4	[R/S]	0,1-?
5	Select: Linear	0	[R/S]	
	Logarithmic	1		
			[R/S]	T=
			[R/S]	Δ =
			[R/S]	MAG=
			[R/S]	F=
6	For next increment, continue to press [R/S].			

Program Listings

01♦LBL "BOD
E"

02 FIX 3
03 RCL 01
04 10
05 /
06 10↑X
07 1
08 -
09 SQRT
10 STO 01
11 1
12 XEQ 09
13 ST* 02
14 ST* 03
15 ST* 04
16 ST* 05
17 RCL 06
18 *
19 STO 15
20 "?"
21 PROMPT
22 STO 14
23 "0.1-?"
24 PROMPT
25 SF 01
26 X=0?
27 CF 01
28♦LBL E
29 0
30 STO 09
31 STO 12
32 1
33 STO 11
34 RCL 00
35 STO 10
36 XEQ 07
37♦LBL 08
38 RAD
39 XEQ 06
40 RCL 07
41 RCL 13
42 +
43 RCL 08
44 R-P
45 ST/ 11
46 X<>Y
47 ST- 12
48 RCL 08
49 RCL 07
50 R-P
51 ST* 11

Convert dB
ripple to ϵ

Convert Hz to
r/s

Store filter
type

Set linear or
logarithmic
increment

Initialize
registers

Loop

Compute s_k

gain

phase

52 P-R
53 RCL 13
54 +
55 RCL 08
56 R-P
57 X↑2
58 X<>Y
59 RDN
60 /
61 ST+ 09
62 DSE 10
63 GTO 08
64 RCL 04
65 1
66 XEQ 09
67 /
68 RCL 11
69 LOG
70 20
71 *
72 RND
73 RCL 12
74 1
75 P-R
76 DEG
77 R-P
78 CLX
79 RCL 09
80 "T="
81 XEQ 05
82 "Z="
83 XEQ 05
84 "MAG="
85 XEQ 05
86 "F="
87 XEQ 05
88 RCL 05
89 RCL 04
90 FS? 01
91 GTO 00
92 RCL 15
93 +
94 GTO 03
95♦LBL 00
96 RCL 06
97 *
98♦LBL 03
99 STO 04
100 X<=Y?
101 GTO E
102 RTN
103♦LBL 07

gain
normalization

time delay

frequency

gain, dB

phase, degrees

Display

Increment

Program Listings

```

104 GTO IND
14
105♦LBL 04
106 XEQ 03
107 GTO 00
108♦LBL 02
109 XEQ 01
110♦LBL 00
111 1/X
112 CHS
113 GTO 04
114♦LBL 01
115 RCL 04
116 RCL 02
117 /
118 GTO 04
119♦LBL 03
120 RCL 04
121 X↑2
122 RCL 02
123 X↑2
124 -
125 RCL 04
126 /
127 RCL 03
128 /
129♦LBL 04
130 STO 13
131 RTN
132♦LBL 06
133 FS? 00
134 GTO 01
135 XEQ 01
136 1
137 RCL 01
138 1/X
139 R-P
140 X<>Y
141 RDN
142 LASTX
143 +
144 LN
145 RCL 00
146 /
147 E↑X
148 LASTX
149 CHS
150 E↑X
151 +
152 ENTER↑
153 ENTER↑
154 LASTX

```

Compute ω_n

BE

HP

LP

BP

Subroutine to
compute s_k

```

155 2
156 *
157 -
158 ST* 08
159 RDN
160 ST* 07
161 2
162 ST/ 08
163 ST/ 07
164 RTN
165♦LBL 01
166 RCL 10
167 2
168 *
169 1
170 -
171 RCL 00
172 /
173 XEQ 09
174 4
175 /
176 1
177 P-R
178 STO 07
179 X<>Y
180 STO 08
181 RTN
182♦LBL 09
183 2
184 *
185 PI
186 *
187 RTN
188♦LBL 05
189 ARCL X
190 AVIEW
191 STOP
192 RDN
193 RTN
194 .END,

```

Compute
Butterworth
pole location

$x2\pi$

Display

90

00

REGISTERS, STATUS, FLAGS, ASSIGNMENTS

[illegible]

BODE PLOT OF BUTTERWORTH AND
CHEBYSHEV FILTERS
PROGRAM REGISTERS NEEDED: 40

HEWLETT PACKARD
SOLUTION BOOK:
ELECTRICAL ENGINEERING

ROW 1 (1 - 4)

ROW 2 (5 - 14)

ROW 3 (14 - 23)

ROW 4 (23 - 28)

ROW 5 (29 - 39)

ROW 6 (39 - 48)

ROW 7 (49 - 60)

ROW 8 (61 - 68)

ROW 9 (69 - 80)

ROW 10 (80 - 84)

ROW 11 (84 - 88)

ROW 12 (89 - 98)

ROW 13 (99 - 106)

ROW 14 (107 - 115)

ROW 15 (116 - 127)

ROW 16 (128 - 136)

ROW 17 (137 - 149)

ROW 18 (150 - 160)

BODE PLOT OF BUTTERWORTH AND
CHEBYSHEV FILTERS

HEWLETT PACKARD
SOLUTION BOOK:
ELECTRICAL ENGINEERING

ROW 19 (161 - 171)



ROW 20 (172 - 182)



ROW 21 (183 - 194)

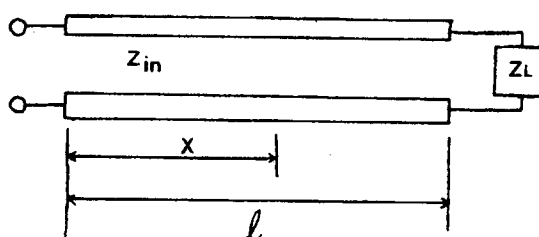


ROW 22 (194 - 194)



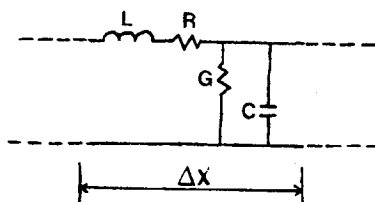
TRANSMISSION LINE CALCULATIONS

This program computes the input impedance of a 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.



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:

MODEL



Equations:

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

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

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

$$\omega = 2\pi f$$

where

L = inductance/unit length

C = capacitance/unit length

G = conductance/unit length

R = resistance/unit length

v_r = relative phase velocity

$v = 3 \times 10^8 v_r$

f = frequency, Hz

and

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

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

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

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

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

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

Then

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

where

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

l = line length

Z_L = impedance of termination

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

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

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

$$\begin{aligned}\operatorname{Re}\{Z_0\} &= \frac{R_0}{\sqrt{2(g^2 + \omega^2)}} \left[rg + \omega^2 + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}} \\ \operatorname{Im}\{Z_0\} &= \frac{\pm R_0}{\sqrt{2(g^2 + \omega^2)}} \left[-(rg + \omega^2) + \sqrt{(r^2 + \omega^2)(g^2 + \omega^2)} \right]^{\frac{1}{2}}\end{aligned}$$

in which the + sign is chosen when $g \geq r$ and the - sign is chosen when $g < r$.

Example:

A transmission line has the following properties:

$$\begin{aligned}R &= 1.2664 \, \Omega/\text{cm} \\ G &= 0.000 \, 041 \, 87 \, \text{Siemens/cm} \\ R_0 &= 55 \, \Omega \\ v_r &= 0.85\end{aligned}$$

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

Keystrokes:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 012

[XEQ] [ALPHA] LINE [ALPHA]

F?

2 [EEX] 9 [R/S]

VR?

0.85 [R/S]

RO?

55 [R/S]

L?

3.5 [R/S]

[XEQ] [ALPHA] EXACT [ALPHA]

G?

0.00004187 [R/S]

R?

1.2664 [R/S]

ZL?

75 [R/S]

Δ ZL?

30 [CHS] [R/S]

Δ ZIN=28.48

[R/S]

ZIN=48.01

User Instructions

[illegible]

Program Listings

<pre> 01♦LBL "LIN E" 02 FIX 2 03 "F?" 04 PROMPT 05 1 E10 06 / 07 STO 09 08 2 09 PI 10 * 11 * 12 STO 08 13 "VR?" 14 PROMPT 15 STO 02 16 "R0?" 17 PROMPT 18 STO 01 19 "L?" 20 PROMPT 21 STO 11 22 2 23 * 24 3 25 RCL 02 26 * 27 STO 03 28 / 29 STO 07 30 STOP </pre>	Initialization	<pre> 50 X<>Y 51 2 52 / 53 STO 06 54 RCL 08 55 RCL 03 56 R-P 57 SQRT 58 STO 03 59 X<>Y 60 2 61 / 62 STO 08 63 RCL 06 64 + 65 STO 04 66 RCL 06 67 RCL 08 68 - 69 STO 02 70 RCL 05 71 RCL 03 72 / 73 ST* 01 74 RCL 05 75 RCL 03 76 * 77 ST* 07 78 GTO "ZIN " </pre>	
<pre> 31♦LBL "EXA CT" 32 "G?" 33 PROMPT 34 "R?" 35 PROMPT 36 RCL 03 37 * 38 RCL 01 39 / 40 STO 05 41 RDN 42 RCL 01 43 * 44 ST* 03 45 RCL 08 46 RCL 05 47 R-P 48 SQRT 49 STO 05 </pre>	Exact solution	<pre> 79♦LBL "APP ROX" 80 "AD?" 81 PROMPT 82 "AC?" 83 PROMPT 84 X<>Y 85 STO 08 86 RDN 87 STO 03 88 RCL 11 89 RCL 02 90 RCL 09 91 PI 92 * 93 1.5 94 / 95 X<>Y 96 / 97 STO 06 98 * </pre>	Approximate solution

Program Listings

```

99 2
100 *
101 STO 07
102 RCL 08
103 10
104 LN
105 20
106 /
107 RCL 06
108 /
109 ST* 03
110 ST* 08
111 RCL 08
112 RCL 03
113 -
114 ENTER↑
115 STO 05
116 RCL 08
117 3
118 *
119 RCL 03
120 +
121 *
122 2
123 /
124 CHS
125 1
126 +
127 R-P
128 ST* 01
129 X<>Y
130 STO 02
131 RCL 05
132 X↑2
133 2
134 /
135 1
136 +
137 RCL 03
138 RCL 08
139 +
140 R-P
141 ST* 07
142 X<>Y
143 STO 04
144♦LBL "ZIN
"
145 "ZL?"
146 PROMPT
147 STO 05
148 "ZL?"

```

Calculate Zin

```

149 PROMPT
150 STO 06
151 RCL 04
152 RCL 07
153 P-R
154 CHS
155 E↑X
156 STO 07
157 X<>Y
158 180
159 *
160 PI
161 /
162 STO 08
163 RCL 06
164 RCL 02
165 -
166 RCL 05
167 RCL 01
168 /
169 P-R
170 1
171 +
172 R-P
173 1/X
174 -2
175 *
176 X<>Y
177 CHS
178 X<>Y
179 P-R
180 1
181 +
182 R-P
183 RCL 07
184 *
185 1/X
186 X<>Y
187 RCL 08
188 -
189 CHS
190 X<>Y
191 P-R
192 1
193 -
194 R-P
195 1/X
196 2
197 *
198 X<>Y
199 CHS

```

[illegible]

DATA REGISTERS				STATUS			
00		50		SIZE	012	TOT. REG.	56
	R ₀			ENG		FIX	2
	v _r			DEG		RAD	
	3v _r R ₀ G			SCI		GRAD	
				USER MODE			
				ON OFF X			
05	3v _r R ₀ G/R	55		FLAGS			
				#	INIT S/C	SET INDICATES	CLEAR INDICATES
	2l/3v _r						
	ω ¹						
	t/10 ¹⁰						
10	l	60					
15		65					
20		70					
25		75					
30		80					
35		85					
				ASSIGNMENTS			
				FUNCTION	KEY	FUNCTION	KEY
40		90					
45		95					

TRANSMISSION LINE CALCULATIONS

PROGRAM REGISTERS NEEDED: 45

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ELECTRICAL ENGINEERING

ROW 1 (1 - 3)

ROW 2 (4 - 13)

ROW 3 (13 - 19)

ROW 4 (19 - 31)

ROW 5 (31 - 34)

ROW 6 (34 - 44)

ROW 7 (45 - 57)

ROW 8 (58 - 70)

ROW 9 (71 - 78)

ROW 10 (78 - 80)

ROW 11 (80 - 88)

ROW 12 (89 - 99)

ROW 13 (100 - 109)

ROW 14 (110 - 121)

ROW 15 (122 - 133)

ROW 16 (134 - 144)

ROW 17 (144 - 148)

ROW 18 (148 - 158)

TRANSMISSION LINE CALCULATIONS

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ELECTRICAL ENGINEERING

ROW 19 (158 - 169)



ROW 20 (170 - 181)



ROW 21 (182 - 194)



ROW 22 (195 - 207)



ROW 23 (208 - 214)



ROW 24 (215 - 219)



TRANSMISSION LINE IMPEDANCE

This program computes high frequency characteristic impedance (Z_0) for five types of transmission lines.

<u>Transmission line configuration</u>	<u>Equation for Z_0</u>
open two-wire line	$Z_0 = \frac{120}{\sqrt{\epsilon_r}} \ln \left(\frac{2D}{d} \right)$
single wire near ground	$Z_0 = \frac{138}{\sqrt{\epsilon_r}} \log \left(\frac{4h}{d} \right)$
balanced wires near ground	$Z_0 = \frac{276}{\sqrt{\epsilon_r}} \log \left\{ \frac{2D}{d} \left[1 + \left(\frac{D}{2h} \right)^2 \right]^{-1/2} \right\}$
wires in parallel near ground	$Z_0 = \frac{69}{\sqrt{\epsilon_r}} \log \left\{ \frac{4h}{d} \left[1 + \left(\frac{2h}{D} \right)^2 \right]^{+1/2} \right\}$
coaxial line	$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \frac{D}{d}$

Example 1:

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

Keystrokes:

Display:

[XEQ] [ALPHA] SIZE [ALPHA] 004

.68 [ENTER↑] .195 [ENTER↑]

2.3 [XEQ] [ALPHA] [C] [ALPHA]

Z0=49.42

Example 2:

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

Keystrokes:

Display:

6 [ENTER↑] .0808 [ENTER↑] 1 [XEQ] [ALPHA]

[OP] [ALPHA]

Z0=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:

Display:

.1285 [ENTER↑] 6 [ENTER↑] 1 [XEQ] [ALPHA]

[SW] [ALPHA]

Z0=313.44

User Instructions

SIZE: 004

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Load program			
2	Compute impedance of open two-wire line.			
	Input: -wire spacing	D	[ENTER↑]	
	-wire diameter	d	[ENTER↑]	
	-relative permittivity	ϵ_r	[XEQ] OP	Z0=
3	Compute impedance of a single wire near ground. Input:			
	-wire diameter	d	[ENTER↑]	
	-wire height	h	[ENTER↑]	
	-relative permittivity	ϵ_r	[XEQ] SW	Z0=
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	[XEQ] B	Z0=
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	[XEQ] P	Z0=
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	[XEQ] C	Z0=

Program Listings

01*LBL "OP"	Two wire line	52 276	Wires in parallel near ground
02 STO 00		53 *	
03 RDN		54 RCL 00	
04 /		55 SQRT	
05 2		56 /	
06 *		57 GTO 05	
07 LN		58*LBL "P"	
08 120		59 STO 00	
09 *		60 RDN	
10 RCL 00		61 STO 01	
11 SQRT		62 RDN	
12 /		63 STO 02	
13 GTO 05		64 RDN	
14*LBL "SW"	Single wire near ground	65 STO 03	Coaxial cable
15 STO 00		66 RCL 01	
16 RDN		67 /	
17 4		68 1/X	
18 *		69 2	
19 /		70 *	
20 1/X		71 X↑2	
21 LOG		72 1	
22 138		73 +	
23 *		74 SQRT	
24 RCL 00		75 RCL 01	
25 SQRT		76 *	
26 /		77 RCL 02	
27 GTO 05	Balanced wires near ground	78 /	
28*LBL B		79 4	
29 STO 00		80 *	
30 RDN		81 LOG	
31 STO 01		82 69	
32 RDN		83 *	
33 STO 02		84 RCL 00	
34 RDN		85 SQRT	
35 STO 03		86 /	
36 RCL 01		87 GTO 05	
37 /		88*LBL C	Display
38 2		89 STO 00	
39 /		90 RDN	
40 X↑2		91 /	
41 1		92 LN	
42 +		93 60	
43 SQRT		94 *	
44 1/X		95 RCL 00	
45 2		96 SQRT	
46 *		97 /	
47 RCL 03		98*LBL 05	
48 *		99 FIX 2	
49 RCL 02		100 "ZO="	
50 /		101 ARCL X	
51 LOG		102 AVIEW	

Program Listings

103 STOP		51	
104 .END.			
10		60	
20		70	
30		80	
40		90	
50		00	

DATA REGISTERS				STATUS			
00	er	50		SIZE 004	TOT. REG. 24	USER MODE	
	h			ENG	FIX 2	SCI	ON OFF
	D			DEG	RAD	GRAD	
	D (rounded)						
05		55		FLAGS			
				#	INIT S/C	SET INDICATES	CLEAR INDICATES
10		60					
15		65					
20		70					
25		75					
30		80					
35		85					
				ASSIGNMENTS			
40		90		FUNCTION	KEY	FUNCTION	KEY
45		95					

TRANSMISSION LINE IMPEDANCE

PROGRAM REGISTERS NEEDED: 20

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ELECTRICAL ENGINEERING

ROW 1 (1 - 8)



ROW 2 (8 - 14)



ROW 3 (14 - 24)



ROW 4 (25 - 35)



ROW 5 (36 - 48)



ROW 6 (49 - 58)



ROW 7 (58 - 67)



ROW 8 (68 - 80)



ROW 9 (81 - 90)



ROW 10 (91 - 100)



ROW 11 (100 - 104)



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